Detecting Standard Violation Errors in Smart Contracts

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Abstract

We present SOLAR, a new analysis tool for automatically detecting standard violation errors in Ethereum smart contracts. Given the Ethereum Virtual Machine (EVM) bytecode of a smart contract and a user specified constraint or invariant derived from a technical standard such as ERC-20, SOLAR symbolically executes the contract, explores all possible execution paths, and checks whether it is possible to initiate a sequence of malicious transactions to violate the specified constraint or invariant. Our experimental results highlight the effectiveness of SOLAR in finding new errors in smart contracts. Out of the evaluated 779 ERC-20 and 310 ERC-721 smart contracts, SOLAR found 255 standard violation errors in 197 vulnerable contracts with only three false positives. 237 out of the 255 errors are zero-day errors that are not reported before. Our results sound the alarm on the prevalence of standard violation errors in critical smart contracts that manipulate publicly traded digital assets.

1 Introduction

Following the success of the cryptocurrencies [25, 32], blockchain has recently evolved into a technology platform that powers secure, decentralized, and consistent transaction ledgers at Internet-scale. Smart contract deployment is one of the most important features of many new blockchain systems such as Ethereum [32]. Users can develop smart contracts at a high level programming language to encode arbitrarily complicated transaction rules. These developed contracts are compiled to a low level Ethereum Virtual Machine (EVM) bytecode and are eventually deployed to Ethereum. The contracts and the transaction rules are then faithfully executed and enforced by all participants of the Ethereum network, eliminating any potential counter-party risk of the encoded transactions in future.

Because smart contracts are in fact programs that directly manipulate critical information such as digital assets, financial records, and even identities, ensuring the correctness of these contracts is essential. Unfortunately, human programmers often make mistakes and errors and the consequence of programming errors in smart contracts is particularly severe. For example, an anonymous attacker exploited an integer overflow vulnerability of the BeautyChain smart contract in Ethereum to illegally generate a massive amount of BECTokens, the underlying digital assets of the contract. This attack caused the market cap of BECTokens, which was two billion dollars at the time of the attack, to evaporate in days [9]. Another famous example is the DAO attack which caused 50 million dollars in losses and a community dividing hard fork of Ethereum to recover the stolen fund [14].

On one hand, to alleviate the correctness problem of smart contracts, the blockchain community has created many technical standards for common kinds of smart contracts such as digital assets, identity tokens, and domain name services [1–4]. A technical standard typically defines a set of interface functions that a contract following the standard should implement, together with specifications for each of the interface functions. This community driven effort is partially successful. For example, most smart contracts that manage digital assets are now developed under relevant technical standards such as ERC-20 [3] and ERC-721 [4]. However, it is unclear how many of such deployed contracts actually conform to the standards, because a programming error may still cause a contract implementation to deviate from its intended behavior.

On the other hand, previous research has been focusing on developing analysis tools for Ethereum smart contracts to detect potentially dangerous low-level runtime errors such as integer overflows and contract reentrance [24, 28]. However, these tools often report an excessive amount of false warnings because 1) many reported low-level warnings are actually benign errors and 2) these analysis tools do not accurately handle storage access instructions in Ethereum Virtual Machine (EVM). Also these tools have a limited scope and cannot detect logic errors where the implementation simply deviates from the intended specifications without any runtime error. Furthermore most of these tools require the access of the smart contract source code and cannot apply to the EVM...
bytecode directly. These drawbacks limit the applications of any prior art.

1.1 SOLAR

We present SOLAR, a novel symbolic execution analysis tool for detecting standard violation errors in Ethereum smart contracts. Given a set of constraints and invariants derived from the standard to which a contract conforms, SOLAR validates whether it is possible for the contract to violate the given constraints and invariants. If so, SOLAR generates an error report that include the initial contract state and the sequence of transactions to trigger the violation.

Instead of focusing on low-level runtime errors, SOLAR takes advantages of the standardization effort by the blockchain community. SOLAR exploits the fact that smart contracts following a common technical standard such as ERC-20 are essentially sharing the same set of specifications defined by the standard. SOLAR therefore provides an expressive language to allow users to develop invariants and safety constraints derived from a technical standard. Once developed, these invariants and constraints can then be applied to check all smart contracts that conform to the same standard. Unlike previous tools, SOLAR does not suffer from the problem of benign errors, because all errors that SOLAR detects correspond to deviations between a contract implementation and the corresponding standard.

SOLAR models the behavior of a smart contract as a state machine where external transactions invoke associated contract functions to drive the state transition. Given a constraint of a sequence of transactions, SOLAR symbolically executes the associated contract functions. During the symbolic execution, SOLAR queries an SMT solver to determine whether there is a possible assignment scheme of the initial contract state and the transaction input parameters to cause the contract execution violating the specified constraint.

To build a symbolic execution engine for EVM bytecode, it is important to accurately and efficiently handle storage load and store instructions. There are two kinds of storages in EVM, a persistent contract state that contains non-volatile data across different transactions and a volatile memory that contains temporary data during the process of one transaction. One challenge SOLAR faces is that load and store instructions of the contract persistent state in EVM are often paired with special cryptographic hash instructions to compute the address locations of the loaded/stored object. Naively processing these cryptographic computations would generate complicated symbolic expressions that SMT solvers cannot solve. Another challenge SOLAR faces is that the bit width of the stored volatile memory values is different from other parts of EVM. The volatile memory operates with 8-bit values, while the stack and the persistent state all operate with 256-bit values. Naively processing load and store instructions of the volatile memory would generate a large number of bit extraction and concatenation operations in symbolic expressions and would significantly slow down the performance of the symbolic execution engine.

To address the challenge of cryptographic computations associated with persistent state loads and stores, SOLAR operates with a customized addressing mechanism for the persistent state when running the symbolic execution. This customized mechanism enables SOLAR to replace cryptographic computations with lightweight computations. In the same time, it still guarantees the free of address collisions so that the program remains functionally equivalent. To address the challenge introduced by the volatile memory bit width, SOLAR uses a symbolic cache to track all 256-bit values stored into the volatile memory. For the common case where the 256-bit value is later loaded from the volatile memory as a whole, the cache will detect this and return the cached value to skip processing bit extraction and concatenation instructions. These two techniques together enable efficient and accurate symbolic execution for EVM bytecode.

1.2 Experimental Results

We evaluated SOLAR with a benchmark set of the top 779 ERC-20 and the top 310 ERC-721 smart contracts from Etherscan [5], the most popular Ethereum blockchain explorer. ERC-20 and ERC-721 are two important smart contract standards which define the specifications for implementing fungible and non-fungible digital assets. Many of the evaluated contracts manage digital assets that are publicly traded on crypto-exchanges. We applied SOLAR to check whether these contracts satisfy the total supply invariant and the transfer functionalities defined by the ERC-20 and ERC-721 standards.

Our experimental results highlight the effectiveness of SOLAR in finding security errors in Ethereum smart contracts. SOLAR found in total 255 standard violation errors in these 1089 contracts. Note that 237 out of the found 255 errors are zero-day errors, i.e., to the best of our knowledge, we believe that these errors are not reported before. We compared the results of SOLAR with Mythril [24], the state-of-the-art contract analysis tool developed by the Ethereum community. For the same set of smart contracts, Mythril reported 1115 high severity errors from 512 ERC-20 contracts and 595 errors from 217 ERC-721 contracts. However, our manual analysis show that most of these reported errors are false positives and/or benign errors. We sampled 100 smart contracts to manually compare the results of SOLAR and Mythril. Among the 100 sampled contracts, SOLAR reported 36 errors from 24 contracts with no false positive, while Mythril reported 127 errors from 60 contracts with only one true positive (which is also found by SOLAR as well).

1 64 of the Mythril reported errors in the sampled 100 contracts are false positives caused by the inaccuracy of the Mythril symbolic execution engine.
Our experimental results sound the alarm on the prevalence of standard violation errors, i.e., even the top smart contracts that manipulate critical digital assets often do not fully conform to their corresponding standards. Out of the 255 found errors, 7 errors correspond to severe vulnerabilities that can be exploited by any user in the blockchain and the underlying digital assets are immediately threatened; 47 errors correspond to owner backdoors which are only exploitable by the contract owners; 20 errors correspond to subtle constraint violations that are not immediately exploitable given the current blockchain state but they may become exploitable as the blockchain state changes; the remaining 181 errors are non-exploitable standard deviations in customized features but they may cause undesirable experience if other users or contracts interact with them.

1.3 Contributions

This paper makes the following contributions:

- **SOLAR:** This paper presents a novel security analysis tool, SOLAR, which enables users to specify customized constraints and invariants to detect EVM smart contract errors that cause deviations between a contract implementation and the corresponding specification.

- **Symbolic Execution for EVM Bytecode:** This paper presents a symbolic execution framework for EVM byte code. In particular, it presents novel techniques for efficiently handling EVM instructions that access the persistent state and the volatile memory.

- **Evaluation of SOLAR:** This paper presents a systematical evaluation of SOLAR on a benchmark set of 1089 smart contracts. SOLAR found 255 errors in total and 237 out of the 255 errors are zero-day errors.

- **Standard Violation Alarm:** This paper is the first to identify the prevalence of standard violation errors in critical smart contracts that manipulate publicly traded digital assets. The total market cap of these vulnerable zero-day smart contracts is more than nine hundred million dollars at the time of writing this paper. This paper also presents analyses and case studies on these standard violation errors we found to guide future efforts to eliminate such errors in smart contracts.

The remainder of this paper will be organized as follows. Section 2 presents a motivating example to illustrate SOLAR. Section 3 presents the technical design of SOLAR. Section 4 discusses the implementation of SOLAR. We evaluate SOLAR with experiments and analyze standard violation errors we found with SOLAR in Section 5. We finally discuss related work in Section 6 and conclude in Section 7.

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```solidity
contract BecToken {
    uint256 public totalSupply;
    mapping(address => uint256) public balanceOf;

    function transfer(address _to, uint256 _value) public returns (bool) {
        require(_to != address(0));
        require(_value > 0 && _value <= balanceOf[msg.sender]);
        require(_value + balanceOf[_to] > balanceOf[_to]);
        balanceOf[_to] = balanceOf[_to] + _value;
        Transfer(msg.sender, _to, _value);
        return true;
    }

    function batchTransfer(address[] _receivers, uint256 _value) public whenNotPaused returns (bool) {
        uint cnt = _receivers.length;
        /* Integer overflow */
        uint256 amount = uint256(cnt) * _value;
        require(cnt > 0 && cnt <= 20);
        require(_value > 0 && _value <= 20);
        require(_value > 0 && balanceOf[msg.sender] >= amount);
        balanceOf[msg.sender] = balanceOf[msg.sender].sub(amount);
        for (uint i = 0; i < cnt; i++) {
            balanceOf[_receivers[i]] = balanceOf[_receivers[i]].add(_value);
            Transfer(msg.sender, _receivers[i], _value);
        }
        return true;
    }
}
```

Figure 1: Simplified source code from BECToken.

2 Example

In this section, we present a motivating example of how SOLAR detects an invariant violation error in the smart contract of BECToken. Figure 1 presents the simplified source code of this example. BECToken is an ERC-20 contract deployed on Ethereum blockchain. ERC-20 is a technical standard that defines a set of contract interface functions to implement a digital token asset. Specifically in an ERC-20 contract, the public property or the function balanceOf() should return the amount of tokens that the given address owns (line 3 in Figure 1); the function transfer() should transfer the specified amount of tokens from the address of the message sender to the specified receiver address (lines 5-13); the public property or the function totalSupply() should return the total amount of the circulated tokens (line 2). An ERC-20 contract should also satisfy the following invariant: the sum of token balances of all addresses should equal to the total supply at any time.

In Figure 1, the public balanceOf map stores the balance of each address; the public totalSupply variable stores the

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2 February 12, 2019
was two billion USD at the time of the attack, evaporated in

This overflowed value in turn would enable the attacker to

variable as the handle of the being checked contract;

typically published by the developers as well. In fact, Figure 1

does not cause integer overflow errors.

check at line 4 to make sure that the computation of the sum

total transferred amount. Specifically, if an attacker creates a

transfers containing two addresses, amount would be-

come zero after the overflow (recall that amount has 256 bits).

This overflowed value in turn would enable the attacker to

bypass the security check at line 20. The consequence of this

attack is that the attacker could therefore send a large amount

of tokens that he or she does not own, effectively generating

attack in 2018 April, who sent massive amount of generated

coins to crypto-exchanges for profit at the expense of other

honest token holders. The market cap of BECToken, which

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coins to crypto-exchanges for profit at the expense of other

honest token holders. The market cap of BECToken, which

is a general-purpose invariant that not just the BECToken

contract but all ERC-20 contracts should satisfy.

Generate Function Constraints: Because the invariant in

Figure 2 should be satisfied before and after every function

invocation, SOLAR automatically generates a function

constraint from the invariant for each interface function of

BECToken. Figure 3 presents the generated constraint for

batchTransfer(). At lines 1-7, the generated constraint en-

sures that the invariant holds for the initial state of the con-

tract before the invocation of batchTransfer(). At lines

8-11, the constraint invokes batchTransfer() with a sym-

bolic array of receiving addresses and a symbolic integer

amount. caller = SymAddr() at line 11 also makes the

transaction initiated by a symbolic address as well. Note

that symbolic values here mean that these values are external

inputs and reflect the fact that anyone can initiate a transac-

tion to call batchTransfer() with arbitrary parameters. At

lines 12-18, the generated constraint checks the total supply

invariant again to check that the invariant is satisfied after

the batchTransfer() call. Note that users can also write

constraints like those in Figure 3 directly. Such capability

is useful when the user wants to use SOLAR to check dedi-

cated properties of one function rather than general invariants.

In our experiments, we utilized this capability of SOLAR to

check function specific properties of our benchmark contracts.

See Section 5 for more details.

Symbolic Execution: SOLAR then runs symbolic execution

analysis on the contract EVM bytecode to check each of

the generated constraint. The symbolic execution engine

of SOLAR initializes program values in the global states

as fresh symbolic variables similar to input parameters of

batchTransfer(). The global states include variables like

totalSupply and balances in lines 2 and 3 in Figure 1 and

blockchain states like the block height and timestamp that

might be queried by the contract program. SOLAR then sym-


describe how SOLAR could detect this vulnerability. We

first provide SOLAR the total supply invariant we want to check

as Figure 2. In SOLAR, users write invariants in a syntax

similar to Python. In Figure 2, the C keyword is a predefined

variable as the handle of the being checked contract; ADDRSL

is another predefined variable to represent the set of all possible

addresses. The invariant in Figure 2 iterates over all addresses,

calls balanceOf() to retrieve the balance of each address,

and then checks whether the sum of these balances equals to

the result returned by totalSupply(). There is also a special

check at line 4 to make sure that the computation of the sum

does not cause integer overflow errors.

Note that the user does not need the access of the con-

tract source code in Figure 1 to write this invariant. The user

only needs to know the contract Application Binary Interface

(ABI), which is specified by smart contract standards and is

typically published by the developers as well. In fact, Figure 1

Figure 2: User specified invariant.

Figure 3: Constraints generated by SOLAR.
We next formally present the design of the SOLAR symbolic execution engine.

### 3 Design

We next formally present the design of the SOLAR symbolic execution engine.

#### 3.1 Core Language

A smart contract transaction is a tuple \( T = \langle P, A \rangle \), where \( P \) is the combined bytecode program of the invoked contract function and \( A \) is an input stack that contains all transaction input parameters including the sender account address.

Figure 4 presents the syntax of a simplified stack based virtual machine language that we will use to illustrate the symbolic execution engine of SOLAR in this section. Similar to the Ethereum Virtual Machine (EVM) and other standard virtual machine languages, a program in this language is a map that maps integers (i.e., program counters) to instructions. The program executes with an execution stack. Given an initial execution stack that contains input transaction values and an initial state of the persistent blockchain storage, the program execution starts with the program counter being zero and ends when the execution reaches the `stop` instruction. All program values during the execution are integers and similar to EVM all integers have a fixed width of 256 bits. All computations during the execution also happen with 256 bits, e.g., an equal comparison instruction will produce a 256 bit integer zero if the two operands are not equal and a 256 bit integer one if the operands are equal.

The language has four execution stack manipulation instructions, `push` for pushing an extra constant into the stack, `pop` for popping the top value from the stack, `swap` for swapping the last two elements, and `dup` for duplicating the top value of the stack. The language also has various arithmetic and comparison instructions such as `add` and `eq`, each of which pops values from the execution stack as operands and push the computation result back. `jumpi` is the jump instruction which checks the top value at the stack and conditionally jumps to a specified program counter.

Instructions `addrof` and `addrofmap` are used to compute the address of a variable, an array, or a map. Each of these instructions is followed with either `sload` or `sstore`, which are instructions for accessing the persistent state of the contract. The persistent state of the contract is a flat map that maps 256 bit integer addresses to 256 bit integer values. `addrof` or `addrofmap` fetches a global variable slot index and an array index or a map key form the stack, computes a cryptographic hash, and pushes the hash result to the stack as the address. The following `sload` or `sstore` then accesses the memory at the computed address. Note that for brevity, the language in Figure 4 omits many features of EVM such as the volatile memory, the ether account balance, the gas system, and miscellaneous blockchain states. Our SOLAR implementation supports all these features. We will describe how SOLAR handles the volatile memory in Section 3.4 and the remaining EVM features in Section 4.

The `assume` and `check` instructions in Figure 4 represent the corresponding functions in the user specified constraints. We include them in the language so that we can illustrate how SOLAR verifies the constraints. Note that our current
implementation SOLAR performs symbolic executions on both of the EVM bytecode of the checked contract and the user specified constraints together. See Section 4.2.

3.2 Semantics for Symbolic Execution

**Execution Environment:** The environment of the symbolic execution is a tuple \( \sigma = (pc, K, \xi, \psi) \). \( pc \) is the current program counter value which could be an integer, nil (indicating normal termination), or err (indicating errors). \( K \) is a stack of symbolic expressions to represent the execution stack. The symbolic execution differs from the normal execution in that each concrete program value in the normal execution is instead replaced by a symbolic expression. This symbolic expression tracks the sequences of computations of generating the program value from initial state values and input values.

The symbolic array \( S \) represents the persistent state. A symbolic array has two operations Store() and Load(). Store\((S, E_1, E_2)\) updates a symbolic array by storing the symbolic expression \( E_2 \) at the symbolic index (expression) \( E_1 \) and returns the updated array. Load\((S, E_1)\) returns the symbolic expression that corresponds to the last stored value at the symbolic index (expression) \( E_1 \). The symbolic expression \( \psi \) denotes the current path constraint. The path constraint in the symbolic execution denotes the constraint that the initial state values and the input values must satisfy to make the current execution path feasible. See Figure 4 for the syntax of symbolic variables, expressions, and arrays.

**Small Step Semantics:** Figure 5 presents the rules of the small step semantics for our symbolic execution. Each rule is of the form \( \sigma = [ \Gamma ] \Rightarrow \sigma' \). It denotes that given the original execution state \( \sigma \), after executing the instruction \( I \) the new execution state can be \( \sigma' \). The rules for push, pop, swap, dup, add, and eq are self-explanatory. They fetch operands from the current execution stack and update the stack with the results accordingly.

The rule for assume updates the path constraint with the assumed constraint. There are two rules for jumpi, one for the true branch and the other one for the false branch. Besides changing the program counter, these rules also update the path constraints to indicate additional constraints on the input and initial state values for exercising the corresponding execution paths. The rule for check is similar to jumpi and assume. But if the checked constraint fails, the rule updates the program counter to err.

The rules for addrof and addrofmap take two operands from the stack and use a hash function Hash to compute the address for the followed store instructions. The rule for sstore updates the symbolic array with a Store operation and the rule for sload pushes a fresh symbolic variable \( x \) to the stack to represent the loaded value and puts an additional constraint to ensure that \( x \) equals to the value that a Load operation on \( S \) returns. Note that Hash denotes a special hash function that converts two symbolic expressions (corresponding to the global variable index and the array index or the map key) into a single 256 bit address. This faithfully matches the behavior of the EVM bytecode generated by the compiler of Solidity [7], the most popular high-level language for developing Ethereum smart contracts. The compiler generates code to use SHA3 [32] function to determine the final address of a stored object.

3.3 Main Algorithm

Figure 6 presents our main symbolic execution algorithm. The input to the algorithm is a list of transactions, because a user specified constraint can check the behavior of multiple transactions in sequence. \( \Gamma \) in Figure 6 maintains the set of active execution states and we initialize \( \Gamma \) with the input stack of the first transaction as the execution stack and a fresh symbolic array as the persistent state at line 1. Each iteration of the main loop at lines 3-14 selects one active state \( \sigma \) from \( \Gamma \) and symbolically executes on \( \sigma \) for one step with the rules in Figure 5. For each possible result state \( \sigma' \), it first invokes the underlying SMT solver to determine whether the path constraint is satisfiable at line 7. If not, then it is discarded as an impossible state. Then it checks whether the program counter reaches err, which indicates a constraint violation. If so, it will generate an error report. If not, it pushes the new state back to \( \Gamma \).

When selecting states in line 4 in Figure 6, SOLAR uses the depth first strategy and always selects the newly-generated state. Instead of bounding the number of loop iterations to make the symbolic execution in Figure 6 computationally tractable, SOLAR provides each transaction limited gas and the transaction aborts if the gas is exhausted. The rationale is that most errors can be triggered with a limited number of iterations and a small size of array.

3.4 Storage Access Optimization

**Address Scheme:** Handling the cryptographic hash functions in the address computation in EVM is challenging. If we encode SHA3 computations directly into the symbolic expression, the resulted expressions will be too complicated for any SMT solver to solve. One naive approach is to give up and return a fresh symbolic variable to represent the loaded value when facing complicated symbolic addresses. This approach is adopted by previous work like Mythril [24]. It makes the analysis results inaccurate and may introduce many false positives. Another naive approach is to concretize address values to avoid handling cryptographic computations symbolically. This approach is adopted by other previous work [28], but such concretization may cause the symbolic expression size to grow exponentially when analyzing contracts with multiple storage accesses.

SOLAR instead replaces the address scheme in the addrof and addrofmap with a customized function shown as Fig-
else if  

GenerateReport  

with additional bits to fit both of the global slot index and the key value. This guarantees no collision of different storage objects in EVM bytecode with the following heuristics. In our current implementation, SOLAR keeps the computed addresses as 256 bit vectors to simplify the resulting symbolic expressions.

Figure 7: Customized address scheme function.

Figure 5: Small-Step Operational Semantics of Instructions for Symbolic Values

Input : A list of n transactions T₁, T₂, ..., Tₙ, where Tᵢ = (Pᵢ, Aᵢ) 
1 σ₀ ← (0, A₁, s, true), where s is a free symbolic array 
2 Γ ← {σ₀, 1} 
3 while Γ ≠ ∅ do 
4 Select and remove a state (⟨ pc, K, S, ψ ⟩, i ) from Γ 
5 Σ’ ← {σ’ | ⟨ pc, K, S, ψ ⟩ = [ Pᵢ(pc) ] ⇒ σ’} 
6 for σ’ = (pc’, K’, S’, ψ’) ∈ Σ’ do 
7 if not Satisfiable(ψ’) then 
8 [ continue ] 
9 if pc’ = err then 
10 [ GenerateReport(σ’) ] 
11 else if pc’ ≠ nil then 
12 [ Γ ← Γ ∪ { ⟨ σ’, i ⟩ } ] 
13 else if i ≠ n then 
14 [ Γ ← Γ ∪ { ⟨ ⟨ 0, Aᵢ+1, S’, ψ’ ⟩, i + 1 ⟩ } ]

Figure 6: Main loop

The intuition is to avoid collisions of different global objects without using expensive cryptographic hash functions. SOLAR expand the address space of the persistent storage with additional bits to fit both of the global slot index and the key value. This guarantees no collision of different storage objects and it is functionally equivalent to the original contract behavior (as long as attackers cannot find collisions in SHA3 to trigger object collisions in the original contract). More importantly, the computation in Figure 7 is much cheaper for an SMT solver to handle.

In the current implementation, SOLAR bounds the size of any dynamically sized objects (i.e., arrays and maps) to three. This enables SOLAR to focus on exploring new states that more likely contain errors than less productive states in iterative structures. Although the bound in theory may cause the analysis to miss some errors, in practice we found no error requiring more than three elements in dynamically sized objects to trigger in our experiments.

This bound also enables SOLAR to further reduce the number of bits used in the computation in Figure 7. The bound limits the maximum index of the stores for arrays (E₂ in Figure 7). For common map cases, the map keys are Ethereum account addresses. SOLAR collects all possible account addresses into an address pool (see Section 4.3) and normalize them into bounded integer indexes as well. With these two optimizations, SOLAR actually does not need to shift 256 bits to avoid collisions. In our current implementation, SOLAR keeps the computed addresses as 256 bit vectors to simplify the resulting symbolic expressions.

Note that SOLAR distinguishes maps from other dynamic objects in EVM bytecode with the following heuristics. In EVM, the maps are not stored sequentially and the map keys participate the cryptographic computation for determining the final addresses of mapped values. In contrast, other objects like array are stored sequentially. SOLAR therefore statically analyzes EVM instruction sequences before each load and store to determine the data type of the accessed object.

Volatile Memory: Besides global persistent state δ described in this section, EVM also contains volatile memory to store temporary data which will be wiped after each transaction execution finishes. SOLAR models memory using a symbolic array similar to the global persistent state. Note that unlike the persistent state, the memory does not use complicated cryptographic hash functions for computing addresses so that the address scheme is continuous and simpler.
However, one challenge of handling the memory is that unlike the rest of EVM programs which use 256 bit integer values, the memory maps 256 bit address to 8 bit values. Therefore storing a 256 bit value from stack to the memory requires the system to break the value into 32 bytes and store each of them separately. Naively processing these data transfer instructions will cause the symbolic execution engine to generate numerous redundant bit operations for symbolic expressions if the checked constraints contain intensive memory operations. Appendix B presents such an example. Such redundant operations will slow down the underlying SMT solver dramatically. To address this challenge, SOLAR maintains a cache to optimize volatile memory access during symbolic executions. SOLAR detects instruction patterns like Appendix B which store and load 256 bit values into and from the memory. When the program stores a symbolic 256 bit value into the memory, the cache records the address and the 256 bit symbolic value. When the program loads a symbolic 256 bit value from the memory, SOLAR queries the SMT solver to determine whether the loaded address corresponds to only one possible cached address from the cache. If so, SOLAR returns the corresponding symbolic value from cache directly without generating redundant bit extraction and concatenation operations.

**Results:** Our experimental results show that our storage access optimizations increase the efficiency of the system dramatically. In our experiments, the combination of the address scheme optimization and the volatile memory optimization enable SOLAR to find out 67 more errors and/or to generate much less false positives than other alternative approaches. See Section 5.

4 Implementation

We built SOLAR on top of Manticore [28], an open source symbolic execution framework. The original Manticore does not fully support EVM instructions, does not support user defined constraints, and handles storage access addressing inefficiently with concretization. Besides the algorithms described in Section 3, SOLAR is extended to support all EVM instructions described in Ethereum yellow paper [32]. SOLAR uses boolector [26] as its underlying SMT solver to check satisfiability of the generated symbolic constraints during symbolic executions.

4.1 EVM Bytecode

**Indirect Jump:** One difference between EVM and the core language in Section 3 is that the jump instructions in EVM are indirect, i.e., an EVM jump instruction fetches the jump target address from the execution stack. To handle such jump instructions, SOLAR checks whether the destination from the stack is symbolic. If so, SOLAR gets all possible values from the SMT solver and forks the current execution state for each jump destination. In practice, the current implementation of the Solidity compiler guarantees that the jump destination is always constant.

**Miscellaneous Blockchain State:** Global blockchain states such as timestamp and block height are initialized as fresh symbolic variables. This is consistent with the fact that a transaction may occur at any time and any state in Ethereum. SOLAR updates these state values accordingly when new transactions are generated. Each transaction is assigned with enough gas to execute and SOLAR leverages the gas limit system so that the system will stop after certain iterations.

4.2 User Constraints

User defined policies consist of 1) contract function calls, 2) assumptions, and 3) safety constraints. SOLAR allows users to write Python scripts to interact with a contract. Calling a contract function is similar to normal function calls, and the return value is deserialized from transaction return data. SOLAR then translates those function calls into transactions and symbolically executes them in sequential order. A user can use `assume(expr)` to define the preconditions and assumptions of transaction arguments and initial states. The user can also use `check(expr)` to define safety constraints that transaction executions must satisfy. SOLAR handles assumptions and constraints in the same way as `assume and check` instructions described in Section 3.

4.3 Address Pool

In the Python script of a user defined constraint, the `ADDRS` keyword represents an address pool that the script can interact with (as shown in Figure 3). When SOLAR starts, it first populates the address pool with a fixed number of random addresses. SOLAR then statically analyzes the EVM bytecode and detects additional addresses using the following heuristic. Different from other integer types, addresses in EVM are 160 bits and the usage of each address is accompanied by a bit operation to extract the last 160 bits from a 256 bit integer from the stack. SOLAR collects all detected concrete addresses into the address pool as well.

4.4 Inter-Contract Call

Smart contracts in Ethereum can call functions defined in other contracts. There are two usage scenarios of such inter-contract calls. The first one is to reuse code in library contracts. The second one is to send transactions to other smart contracts. To handle an inter-contract call, SOLAR first assumes the call belongs to the first scenario. SOLAR fetches and executes the bytecode from the Ethereum blockchain. To keep the search space included a reasonable size, SOLAR takes advantage of storage access optimization. If the callee address is a symbolic value and from the global storage, SOLAR fetches the current
stored value from the Ethereum blockchain instead of solving all possible values. If this address concretization fails, then SOLAR conservatively assumes that the call belongs to the second scenario and SOLAR will use a fresh symbolic value to represent the returned value.

**Reentrance Errors:** One limitation of relying on user-specified constraints is that the user constraints may not specify side effect that an external contract call could trigger. The constraints therefore may miss reentrance errors. To this end, SOLAR implements the “no write after external call” rule similar to previous work [30] and can detect reentrance errors with this rule. Specifically, the symbolic execution engine in SOLAR will generate a reentrance error warning if there is an execution path that the contract first 1) calls a non-library external function and then 2) modifies the persistent state.

5 Evaluation

We next evaluate SOLAR with a set of 1089 real world smart contracts. The goal this evaluation is to answer the following questions:

1. How effective is SOLAR in finding standard violation errors in Ethereum smart contracts?
2. What kinds of errors SOLAR find and how many of them are zero-day errors?
3. How does SOLAR compare with previous smart contract analysis tools?
4. How much improvement do the storage access optimizations in Section 3.4 have on the performance of SOLAR?

5.1 Methodology

**ERC-20 and ERC-721:** ERC-20 [3] and ERC-721 [4] are two important smart contract standards, which define the contract interface and specification for implementing fungible and non-fungible digital assets respectively. Those two standards are well-established and followed by many smart contracts in Ethereum. Many of the underlying digital assets of these contracts are publicly traded in crypto-exchanges. Given the importance and the popularity of ERC-20 and ERC-721, we therefore focus our evaluation on contracts following these two standards.

**Collect Benchmark Contracts:** To collect a representative data set, we downloaded all ERC-20 and ERC-721 token contracts listed by Etherscan [5] on November 29, 2018 and obtained in total 1089 contracts. We limit our study on these top contracts in Etherscan because 1) we want to focus our analysis on important contracts that manipulate critical digital assets and 2) many of the remaining ERC-20 and ERC-721 contracts in the blockchain are experimental or duplicate. Besides the contract bytecode, we downloaded the application binary interface (ABI) of each contract as well as the contract source code. The ABI lists all public functions defined by a contract, which enables SOLAR to call contract functions and build symbolic transaction inputs. We downloaded the source code from Etherscan in order to analyze and classify the vulnerabilities. Note that this is for our manual analysis and SOLAR does not require the source code to check a contract.

**Specify Constraints:** We developed one invariant and two constraints based on the semantic of ERC-20 interfaces [3]:

- **Total Supply:** The total supply invariant requires that no matter which function is executed, the sum of account balances equals the total supply of the token.
- **Transfer:** The transfer() function succeeds if and only if sufficient tokens are supplied and the balances of the receiver and sender should be updated accordingly.
- **Approval:** The transferFrom() function succeeds if and only if the token owner authorizes the message sender to do so and has a sufficient balance. Both account balances and allowance of the sender should be updated if the function transferFrom() returns true.

Similarly, we developed one constraint based on the semantic of ERC-721 interfaces [4]. The transferFrom() function succeeds if and only if the token owner authorizes the message sender to do so. A detailed explanation on how a user checks the invariants and the constraints using SOLAR will be provided in Appendix C.

**Apply SOLAR:** We apply SOLAR to downloaded contracts to check the developed constraints. In our experiments, we turned off the reentrance error detector in SOLAR to focus on constraint violation errors. All experiments are performed on a slurm cluster with two eight-core Intel Xeon E5-2680 processors and 96GB rams on each node. Specifically, SOLAR allocates 20 minutes and 3GB memory for each contract. For each error, SOLAR reports the function name, the violated constraint, and a concrete transaction trace that triggers the violation.

Note that in order to evaluate the effectiveness our optimizations in SOLAR for handling storage load and store instructions (see Section 3.4), we implemented a baseline version of SOLAR that does not enable the optimizations. For the persistent state, the baseline implementation attempts to concretize the address values whenever it encounters a load and store instruction paired with cryptographic functions. For the volatile memory, the baseline implementation naively process every load and store instruction without the cache. We apply this baseline version of SOLAR to all of our benchmark contracts and compare the results with the normal version of SOLAR.

**Apply Mythril:** We compare our results with Mythril [24], the state-of-the-art open source security tool developed by
We evaluate $S$ with the default configuration to analyze all collected smart contracts.

**Analyze Detected Errors:** We manually analyze each reported error 1) to determine whether it is a true positive, benign error, or false positive 2) to classify the error based on who can trigger the error and the severity of the error and 3) to check whether the error is reported before and contact the contract owner and relevant stake holders about the issues we found. Note that we classify a report as a benign error if the error is not exploitable and is intended in the context. For example, an integer overflow that is later filtered by a check or an assertion before introducing any side effect is counted as a benign error.

$S$ reports 255 standard violation errors and 197 vulnerable contracts. We classify the 255 errors into four categories:

- **Severe:** Severe errors can be exploited by anyone and may lead to financial loss of contract participants.
- **Backdoor:** Backdoor errors provide the contract owner exploitable privileges that are not consistent with the standard.
- **Attackable:** Attackable errors are theoretically exploitable, but the attack has to be performed at specific time period or an attacker may need to acquire a large amount of digital assets.
- **Deviation:** Some contracts implement their own features that are not consistent with the standards. Although we believe these errors are not exploitable, they may cause financial loss to a user who interacts with these contracts, if the user assumes the contracts conform to the standards.

Mythril reports plenty of issues. Even for high severity issues, Mythril reports 1115 errors from 513 ERC-20 contracts and 595 errors from 217 ERC-721 contracts, which makes it impossible to analyze them all manually. We therefore sample 100 ERC-20 contracts and analyze the errors reported by Mythril on the sampled contracts. A detailed comparison can be found in Section 5.3.

### 5.2 Results

We evaluate $S$ for all 1089 smart contracts for policies described in Appendix C. Figure 8 summarizes our experimental results. Each row presents the results of the corresponding invariant or constraint. Note that the fifth row summarizes all errors from ERC-20 contracts. For columns 2-5, each column represents the results for one type of errors, severe errors, owner backdoors, attackable errors, and standard deviations. Each cell presents two numbers. The first one is the number of found errors and the second one is the number of zero-day errors that are not reported before. The sixth column shows the number of contracts that do not implement all required functions to perform the analysis. These contracts are not conforming to the standards to implement all necessary functions. And the seventh column represents the number of false positives reported by $S$. Note that $S$ does not report any benign error in our experiments. The last column presents the average execution time of $S$ to report an error.

**Severe:** $S$ found 7 errors that are classified as "Severe". There are three types of severe errors:

1. Contracts implement the approve() function without providing the functionality that allows a user to revoke the approval, which may lead to token loss if a user sets the wrong approval.
2. Contracts allows a user to transfer others token without approval.
3. The totalSupply variable is defined multiple times in different parent contracts and transaction functions refer to inconsistent totalSupply instances.

**Backdoor:** 47 out of 255 errors are classified as owner backdoors. All of those errors provide the admin privileges to modify balances of other accounts that are not allowed in the ERC-20 standard.

**Attackable:** $S$ detects 20 theoretically attackable errors that the possibilities to exploit such contracts are rare. However, reusing the source code of such contracts may increase the risk of being attacked.

**Deviation:** Some contracts implement their customized features and deviate from the ERC-20 standard. Such deviations might be intended and are not exploitable on their own, but such contracts might be misused if the user assumes the contract follows the standard. We classified 181 errors as standard deviations. They can be further classified into two types. Firstly, a contract may implement its own logic beside ERC-20 interfaces such as locked token or transaction fees. Secondly, many contracts do not implement ERC-20 interfaces as specified. For example, some contracts implement the transfer() function without any return value. Based on the EVM specification, the function returns 0 if no return value is given which means the transfer() function returns false even if the transaction succeeds. Such a contract is vulnerable if it interacts with other contracts, and they use the return value to check if a transaction succeeds.

**Baseline Algorithm:** The baseline algorithm analyzes 6335 functions without any exceptions and reports in total 188 errors, which is roughly twenty percent less than $S$. We further examine that all errors reported by the baseline algorithm are covered by $S$. The baseline algorithm fails to report many errors that $S$ does report because it
runs out of the time without the optimizations for handling the persistent state and volatile memory.

Our results show that SOLAR is effective in finding standard violation errors. SOLAR flags 255 from 197 vulnerable tokens and the tokens have a market capitalization of 2 billion US dollars. 237 out of the 255 errors are new errors that are not reported before. Our results also show that the symbolic execution engine of SOLAR is fast due to our optimizations for handling storage address schemes. We observe that 78% of functions can be verified within 20 minutes by SOLAR. Without the optimization, only 68% of functions can be verified within 20 minutes.

### 5.3 Comparison With Mythril

We run Mythril on all benchmark contracts. Due to the high volume of reports generated by Mythril, we randomly sampled 100 smart contracts to manually compare the results of Mythril with SOLAR. Out of the 127 issues reported by Mythril, there is only one true positive, which corresponds to a severe vulnerability that is also reported by SOLAR. The remaining 126 reported issues are either benign errors or false positives.

Mythril generates 64 false positives for the 100 contracts, because Mythril fails to handle load instructions to persistent state with symbolic addresses. In such cases, Mythril always returns a new unbounded symbolic value. If this unbounded value is further used for arithmetic operations, Mythril will very likely generate a false report. This again highlights the importance of handling persistent state accurately for symbolic execution of EVM bytecodes. Mythril also generates 62 benign errors for the 100 contracts. The most common cases correspond to integer overflows that are later filtered by assertions or if statements before introducing any side effects. For those errors not reported by Mythril, they contain logical errors that cannot be detected based on low level EVM semantics. Figure 9 presents one example of such logical errors, which we will describe in details in Section 5.4.

Our results show that SOLAR is more accurate and effective than Mythril. SOLAR is able to find significantly more errors with much less false positives than Mythril in our experiments. This is because SOLAR has a more accurate symbolic execution engine and SOLAR detects high level standard violations instead of low level EVM errors, many of which could be benign.

### 5.4 Case Studies

We next present one representative case for each type of standard violation errors that SOLAR found. We also present a case where SOLAR generates a false positive due to the imprecision of the supplied constraints.

#### Severe

Figure 9 shows the `transferFrom()` function from RemiCoin found by approval policy. There is a logic error at line 4 that the conditional statement returns false if the allowance is greater or equal than `value`. The correct behavior is to return false if the allowance is smaller. This error allows an attacker to transfer one account’s tokens to the other without proper approval. Note that SOLAR successfully detected this error, but Mythril cannot. This is because this logic error is not associated with any other low-level runtime error.

```python
function transferFrom(address from, address to, uint value) returns (bool success) {
    require(msg.sender == ico);
    require(value != 0);
    require(totalSupply > _value <= TOKEN_LIMIT);
    balances[_holder] += _value;
    totalSupply += _value;
    Transfer(from, to, value);
    return true;
}
```

Figure 9: The RemiCoin contract code snippet.

---

1 contract address: 0x7dc4f41294697a7903c4027f6ac528c5d14cd7eb

---
function migrate(uint256 amount) {
  Token(previousToken).transferFrom(msg.sender, this, amount);
  pendingMigrations[msg.sender].dateTimeCreated = now;
  pendingMigrations[msg.sender].amount = amount;
}

function claimMigrate() {
  balances[msg.sender] += pendingMigrations[msg.sender].amount;
  totalSupply += pendingMigrations[msg.sender].amount;
  delete pendingMigrations[msg.sender];
}

constructor() public {
  initialSupply = 4000000000;
  totalSupply_ = initialSupply * 10 ** decimals;
  balances[owner] = totalSupply_;
}

function balanceOf(address _holder) public view {
  return balances[_holder] + lookupInfo[_holder].lockupBalance;
}

function transfer (address _to, uint256 _value) {
  return (bool success) {
    uint256 fee = fee();
    if (accounts[msg.sender] < _value) return false;
    if (_value > fee && msg.sender != _to) {
      accounts[msg.sender] = safeSub(accounts[msg.sender], _value);
      accounts[_to] = safeSub(accounts[_to], _value);
      tokensCount -= tokensCount, burnFee);
      Transfer (msg.sender, fund, fee);
      Transfer (msg.sender, _to, safeSub(_value, fee));
    }
    return true;
  }
}

Figure 11: The simplified RexToken code snippet.

Backdoor: To allocate tokens on the fly, many tokens implement a mint function that allows the contract admin to issues new tokens to others. However, missing security checks may leave backdoors that allow the contract admin to modify balances of other accounts to an arbitrary number. Figure 10 shows the mint function from ATL. The mint() function allows the contract owner to allocate tokens to an address _holder. The function first verifies that the transaction is from contract owner (line 2), and the value is not zero (line 3). The contract sets a token limit that the total supply of this token should not be more than TOKEN_LIMIT (line 4). The function then updates the balance of _holder and totalSupply.

SOLAR found two issues from this function. Suppose the owner calls mint() with a large _value. First, the guard that token's total supply should less than TOKEN_LIMIT can be bypassed by an overflow attack. This allows the owner to allocate more tokens than the contract allows. Second, _holder's balance can be overflowed and can be set to any number at line 5. This effectively allows the owner to change a user's balance to an arbitrary number (e.g., to confiscate tokens from a user).

Attackable: Figure 11 shows the migrate() and claimMigrate() functions from RexToken. Those two functions allow RexToken users to migrate their tokens stored in previous contracts to this contract. While executing the claimMigrate() function, it increases the balance of the sender and the total supply of the token respectively without any overflow check at lines 7 and 8. SOLAR marks this contract as vulnerable because the total supply invariant can be violated if the sender has large amount of token in previous contract. Although this is theoretically exploitable, we investigated these two contracts on Etherscan main chain and such exploitations are not possible with the current contract state.

Deviation: Figure 12 shows the simplified transfer() function from ParagonCoinToken. Unlike other ERC-20 tokens, ParagonCoinToken computes a transaction fee each time a user transfer tokens to the other (line 6-7), which breaks the transfer policy that all tokens should be transferred to receiver's account. We believe this a deviation from ERC-20 standard. Note that a user can change the constraint to avoid treating this constraint as vulnerable if desired.

False Positive: Figure 13 shows the balanceOf() function from PRASMToken. SOLAR reports that this contract may break the specified constraints if an integer overflow occurs when computing the balance at line 8 in Figure 13. This is unfortunately a false positive because the total supply of this contract is fixed as a constant after being initialized during the contract construction at line 4. Therefore, the sum of balances[_holder] and lockupBalance at line 8 will never overflow. SOLAR generates this false positive because the general purpose constraints we used do not capture the precondition of the total supply. In fact, a more precise set of constraints will enable SOLAR to eliminate all three false positives in our experiments.

5.5 Summary

Our experimental results show that standard violation errors are prevalent in Ethereum smart contracts. Over one sixth of evaluated ERC-20 and ERC-721 contracts contain one or more standard violation errors. We found that for many
contracts that are supposed to follow a standard, their implementations in the end deviate from the intended standard behavior. This surprising result calls for more efforts from the community to validate the consistency between the contract standards and the actual implementations. We also have the following important findings in our experiments.

Severe Logic Errors: Logic errors like Figure 9 in a smart contract can cause severe vulnerabilities that immediately threaten the security of the underlying digital assets represented by the contract. This poses a challenge to standard analysis tools that focus on specific types of low-level runtime errors. SOLAR can successfully detect these logic errors, while previous tools like Mythril [24] may miss them. This is because in these logic error cases, the implementation simply does not match the intended behavior and no low-level runtime error is triggered.

Neglected Owner Backdoors and Corner Cases: SOLAR finds a large amount of owner backdoor errors. This shows that software errors in the owner privileged functions are often neglected by the community. This is undesirable because, in ERC-20 and ERC-721 contracts, the owner corresponds the issuer of the digital assets. Therefore, the analogies of these owner backdoors are intentional or unintentional hidden text in a legal contract for financial assets.

SOLAR also finds a large amount of theoretically attackable contracts. This shows that the smart contract developer has a tendency to ignore corner cases. For example, one vulnerable contract casts a balance value of 256-bit integers directly down to 128-bit integers without proper checks, assuming the balance will always be less than 128 bits. Consider the fact that smart contract code is often copied and reused by multiple contracts, such code may eventually be exploited when relevant conditions are satisfied.

Error-prone Customized Features: We also found that the implementations of customized features in smart contracts are often vulnerable or inconsistent with the corresponding standards. We believe the smart contract developers should proceed with extreme caution when designing and implementing customized features.

Developer Irresponsiveness: Last but not least, we found that smart contract developers/owners are not very responsive for error reports. One explanation is that developers and owners do not have the capability to quickly fix a reported issue. Ethereum does not allow any update to a deployed smart contract. The rationale is that the smart contract corresponds to the law that all participants should follow and that no one should be able to change the law. The only way to fix a vulnerable contract is to deploy a new contract and to persuade every participant to accept the new contract instead of the old one. Another explanation is that as the issuers of publicly traded digital assets, developers and owners may be economically incentivized to hide a smart contract error if the exploitation chance is low.

6 Related Work

Smart Contract Security: Researchers recently have proposed several automated program analysis techniques to help detect security errors and vulnerabilities in the smart contracts. Oyente [22] implements a symbolic execution tool that detects vulnerability patterns of transaction-ordering dependency attacks, timestamp attacks, reentrance attacks, and mishandled exception attacks. Mythril [24] and Manticore [28] are open source symbolic execution frameworks for detecting integer overflows and reentrance errors. Kolluri et al. use symbolic execution techniques to detect races of smart contract transactions [19]. Maian [27] analyzes traces with symbolic execution to detect vulnerable contracts that handles ether transfers. A more recent work, Zeus [18], converts solidity source code into a customized low level virtual machine language that is compatible with LLVM [21] and then uses existing taint analysis and symbolic execution tools in LLVM to detect common vulnerability patterns and fairness issues. SOLAR differs from these symbolic execution tools in that instead of focusing on specific patterns of runtime errors, SOLAR validates the consistency between a contract implementation and the corresponding standard. SOLAR also works with optimizations on handling EVM storage access instructions for more efficient symbolic execution of EVM byte code directly. Together, these differences enable SOLAR to find significant more errors (including logic errors) with much less false positives in our experiments.

ContractFuzzer [17] proposes a fuzzing framework for detecting seven kinds of vulnerabilities from Ethereum smart contracts. Comparing to SOLAR, fuzzing techniques may miss many errors (i.e., introduce false negatives) because they only exercise a limited number of execution paths. Securify [30] provides a domain-specific static analysis framework for smart contracts, that translates EVM bytecode into Data-log and use off-the-shelf verifier to check predefined security properties like that no storage write should occur after function calls and that all ether transfers should be protected by conditions. TEEither [20] uses static analysis to detect control flow paths that lead to attackable instructions that attackers can exploit to steal ether. Comparing to SOLAR, these static analysis techniques target specific patterns of errors, while SOLAR can detect any deviation between an implementation and the corresponding standard.

KEVM [16] formally defines the EVM semantics in K and EVM* [8] translates EVM bytecode to F*. Building EVM semantics allows a user of K or F* to build their own policy for further verification. VeriSolid [23] is a model-based approach that allows a user to specify a transition model as well as security rules. Similarly, Vandal [11], a static analysis framework, translates EVM bytecode to logic relations and detects vulnerabilities described in Soufflé language. Unfortunately, these verification tools either cannot handle full EVM
byte code or require significant human interventions during the verification process.

**Contract Development Tools:** Libraries such as openzeppelin-solidity [6] provide safe arithmetic operations which avoid integer overflow and underflow attacks. It also provides a reference implementation of standard protocols. However, using such libraries is not mandatory. Ironically, BecToken included SafeInt library in its contract code, but it does not use the library for all arithmetic operations. Moreover, such libraries cannot prevent contracts from logic errors such as missing authorization.

Breidenbach et al. propose the hydra framework, automates the process of discovering bugs and distributing bounties [10], which incentivizes the bug disclosure. Erays [33] is a reverse engineering tool that decompiles EVM bytecode into high-level solidity-like pseudocode. A user can further analyzes the security issues inside the contract without accessing to the contract source code. Wang et al. propose a test oracle for ether-related transactions that examines the invariant between balances from a bookkeeping variable and the ether values among accounts [31].

**Symbolic Execution:** Symbolic execution techniques [12,13,15,29] have been used to improve software security for many years. KLEE [12,13] is a popular symbolic execution engine on LLVM framework for traditional computer programs. DIODE [29] proposes goal-directed conditional branch enforcement technique to quickly explore execution paths to detect integer overflow errors.

### 7 Conclusion

We presented SOLAR, a novel analysis tool for detecting standard violation errors for Ethereum smart contracts. SOLAR operates with an optimized symbolic execution engine and utilizes the standardization effort of the community. As a result, SOLAR is significantly more effective than previous tools in our experiments, finding more errors with much less false positives. Furthermore, our results show that standard violation errors are prevalent even in those critical smart contracts that manipulate digital assets. This calls for more community efforts to enforce the consistency between smart contract implementations and contract standards.

### References


Figure 14: Concrete example exploits the batchTransfer() function.

A Error Triggering Input

Figure 14 shows a concrete error triggering transaction SOLAR generates for exploiting the error we described in Section 2.

B Memory Operations

Figure 15 shows an example of storing and loading memory data without any optimization. To store a 256-bit integer value, a naive approach would first generate 32 extract instructions and 32 store instructions. Each pair of extract and store instructions extract a 8-bit integer from value and store the integer to the memory. Similarly, to load a 256-bit integer from memory, the system would generate 32 select instructions to load a 256-bit integer from the memory. Each instruction loads a 8-bit integer from memory. It then would concatenate 32 8-bit integers into a 256-bit integer.

C Invariants and Constraints

In this section, we describe how a user checks the invariants and the constraints using SOLAR.

Total Supply: As described in Section 2 and Figure 3, ERC-20 tokens are designed as assets that can be sent and received and in practice many ERC-20 tokens are traded publicly and have market value. If the total supply changes unexpectedly due to software errors, it may have significant impact on the market value of each token. We applied SOLAR to check if any public function in our benchmark contracts will break the total supply invariant.

Transfer: The transfer() function defines the most fundamental functionality of an ERC-20 token, that allows a user to transfer his balances to other users. To secure a token transfer, the contract must guarantee that the sender has enough token to transfer. Otherwise, the token transfer should fail.

Figure 16 shows the function to build transfer policy, where acc[0] and acc[1] are two symbolic accounts and value is a symbolic value. Before calling the function transfer(), account acc[0] owns pre_bal[0] tokens and 3

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>ADDRs.length</td>
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</tr>
<tr>
<td>ADDRs[0]</td>
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<tr>
<td>ADDRs[1]</td>
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<tr>
<td>_receivers.length</td>
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<td>_receivers[1]</td>
<td>ADDRs[1]</td>
</tr>
<tr>
<td>_value</td>
<td>0x67518339e369a3d591d3569ab0d8832ff198</td>
</tr>
</tbody>
</table>

Figure 15: Constraints from MSTORE and MLOAD instructions without simplification.

acc[1] owns pre_bal[1] tokens. acc[0] creates a transaction that transfers value tokens to acc[1]. post_bal[1] and post_bal[1] are tokens owned by acc[0] and acc[1] after calling the transfer() function. At line 11-18, the generated constraints check if the transfer function breaks the security rule defined above.

Token Approval (ERC-20): The approve() and the transferFrom() functions allow a user to authorize a third party to spend his token. A user calls the approve() function to allow a third party to spend tokens in his account and the third party uses the transferFrom() function to transfer the token.

Figure 17 shows the security policies built for approve() and transferFrom() scheme. At line 8 account acc[0] calls the function approve() to authorize acc[2] to spend up to values[0] tokens. acc[2] then calls the transferFrom function to transfer acc[0]'s token to acc[1]'s account.

A secure transferFrom() transaction should check the following conditions. 1) acc[0] has enough tokens to perform the transaction; 2) the transferred token is smaller than acc[0]'s allowance; 3) the allowance and the account balances should be updated correspondingly if the transfer succeeds (line 15-26).
Figure 16: Policies for transfer function.

Token Approval (ERC-721): Similar to ERC-20, ERC-721 allows a user to transfer his ownership of a token to other users. Different from ERC-20, ERC-721 uses the approve() function to authorize a third party to transfer a single token and setApprovalForAll to authorize a third party to manage all assets.

In Figure 18, SOLAR assumes that acc[0] is not authorized to transfer token tid and acc[1] is not the owner of tid (line 5-12). acc[0] then creates a transaction that transfers the ownership of tid from owner to acc[1] (line 13). A vulnerable contract would allow the transaction and modify the ownership correspondingly.

Figure 17: Policies for approve and transferFrom functions (ERC-20).

Figure 18: Policies for approve and transferFrom functions (ERC-721).