EOSAFE: Security Analysis of EOSIO Smart Contracts

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Motivation

EOSIO market cap & DApp transactions

- EOSIO adopts DPoS consensus, which supports higher TPS
- Highest market cap: nearly 18 billion USD in Apr. 2018
- The DApp ecosystem was extremely active

EOS (EOS), the blockchain platform well-known for its delegated proof-of-stake (DPoS) consensus model which works to speed up transactions and block creation at the expense of some level of decentralization, has recently surpassed Ethereum (ETH) in daily decentralized application (dApp) users and transaction volume.

## Attack Events

EOSIO smart contracts have been attacked

<table>
<thead>
<tr>
<th>Date</th>
<th>Victim</th>
<th>Vulnerability</th>
<th>Financial Loss</th>
<th>Reference</th>
</tr>
</thead>
</table>

Representative attack events against EOSIO smart contracts

More than 100 attacks according to our collected dataset.
Vulnerability Detectors
Tools in Ethereum & EOSIO

• There are dozens of existed tools targeting on automatically detecting vulnerabilities in Ethereum smart contracts, like Osiris (https://github.com/christoftorres/Osiris), Securify2 (https://github.com/eth-sri/securify2), teEther (https://github.com/nescio007/teether) and so on.

• However, there are few tools that are able to identify vulnerabilities in EOSIO smart contracts
Background
Dispatcher: `apply` function

- EOSIO smart contracts is written in C++ and compiled into Wasm bytecode
- The `apply` is a dispatcher, handling received invocation or notification
- The signature of `apply` is fixed
  - receiver: current account
  - code: the account in which the code is executed.
  - action: name of invoked function

```c
void apply (uint64_t receiver, uint64_t code, uint64_t action) {
    if (action == N(onerror)) {
        check(code == N(eosio), " exception captured ");
    }
    auto self = receiver;
    if ((code == self || code == N(eosio.token))) {
        switch (action) {
            case N.transfer): // action == N(transfer)
                // deal with:
                // 1. direct invocation to transfer function
                // 2. notification emitted from transfer ...
        }
    }
}
```

Source code of dispatcher `apply`
Background

Transfer official/fake EOS in EOSIO

- **STEP 1**: `user` invokes the `transfer` in `eosio.token` to make a request
- **STEP 2&3**: `eosio.token` will `notify` both of them if the request is approved
- **STEP 4**: the `apply` in `dapp` will dispatch the notification to its `transfer`

**Normal situation**

- **STEP 1**: `user` invokes the `transfer` in `eosio.token` to make a request
- **STEP 2&3**: `eosio.token` will `notify` both of them if the request is approved
- **STEP 4**: the `apply` in `dapp` will dispatch the notification to its `transfer`. However, the fake EOS is worthless

**Fake EOS attack**

- **STEP 1**: `user` invokes the `transfer` in ` eosio.token1` to make a request
- **STEP 2&3**: `eosio.token1` will `notify` both of them if the request is approved
- **STEP 4**: the `apply` in `dapp` will dispatch the notification to its `transfer`. However, the fake EOS is worthless
## Goal

Concerned vulnerabilities

<table>
<thead>
<tr>
<th>Vulnerability</th>
<th>Root Cause</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake EOS</td>
<td>Lack of verification on <code>code</code></td>
<td>The malicious user could bypass the verification with worthless token</td>
</tr>
<tr>
<td>Fake receipt</td>
<td>Lack of verification on <code>to</code> in transfer</td>
<td>The malicious user could fool the victim without any cost</td>
</tr>
<tr>
<td>Rollback</td>
<td>Adopting problematic <em>bet-reveal</em> model in gambling smart contract</td>
<td>The malicious user could forecast the random number in advance</td>
</tr>
<tr>
<td>Missing permission check</td>
<td>Lack of verification on carried authority table</td>
<td>The malicious user can perform behaviors on behalf of others without authority</td>
</tr>
</tbody>
</table>

We concerned four types of vulnerabilities that are fully imported by programming error in smart contracts
Challenge #1
Existing tools on detecting vulnerabilities in Ethereum smart contracts cannot be directly adopted to detect vulnerabilities in EOSIO smart contracts

<table>
<thead>
<tr>
<th></th>
<th>Ethereum (EVM bytecode)</th>
<th>EOSIO (Wasm bytecode)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amount of Instructions</strong></td>
<td>154 (32 PUSH, 16 DUP, 16 SWAP)</td>
<td>172</td>
</tr>
<tr>
<td><strong>Types of Instructions</strong></td>
<td>-</td>
<td>- Float number related instructions</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>- Type cast related instructions</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>- <code>br_table</code> instruction</td>
</tr>
<tr>
<td><strong>Control Flow</strong></td>
<td>Relative simple</td>
<td>Multi-level nested loops</td>
</tr>
<tr>
<td><strong>Complexity of Vulnerabilities</strong></td>
<td>Do not rely on too much semantic information, like reentrancy, overflow, blockchain-state dependency vulnerabilities</td>
<td>Heavily rely on semantic information, like fake EOS, fake receipt and rollback vulnerabilities</td>
</tr>
</tbody>
</table>
Challenge #2
Symbolic execution technology would bring in some typical challenges

- **Memory modeling**: if the address is a symbol, how to effectively and precisely retrieve and store data?

- **External dependency**: the source code, even the bytecode, of the library functions cannot be obtained, how to emulate these functions’ behavior?

- **Path explosion**: the path explosion can significantly consume the resources and increase the analyzing time, especially when encountering the multi-level nested loops.
Design of EOSAFE

- Wasm Symbolic Execution Engine
- EOSIO Library Emulator
- Vulnerability Scanner
Design of EOSAFE
Wasm Symbolic Execution Engine

• Implementation:
  • We implement all 172 instructions with the help of Bit Vector in z3
  • Each feasible path corresponds to a state, maintaining the data structure in Wasm

• How to address path explosion?
  • We adopt the `timeout` and `depth` option
  • Simple but efficient

• How to address memory modeling?
  • Using a mapping structure to mimic the sparse linear array
  • We propose a memory-merging algorithm to overcome the memory overlapped problem within this structure

Interval (A+2, A+3) is overlapped after applying the store instruction
Design of EOSAFE
EOSIO Library Emulator

• To address the **external dependency**:
  • We divide commonly used external functions into five categories
  • We manually model these functions behavior

<table>
<thead>
<tr>
<th>Category</th>
<th>Imported Function Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>blockchain-state</td>
<td>tapos_block_num, current_time</td>
</tr>
<tr>
<td>memory-related</td>
<td>memcpy, memmov</td>
</tr>
<tr>
<td>control-flow-related</td>
<td>eosio_exit, eosio_assert</td>
</tr>
<tr>
<td>authority-related</td>
<td>require_auth, require_auth_2</td>
</tr>
<tr>
<td>table-related</td>
<td>db_get_i64, db_update_i64</td>
</tr>
</tbody>
</table>
Design of EOSAFE

Vulnerability Scanner

• Each vulnerability scanner consists of two steps:
  • locating suspicious functions
  • detecting vulnerabilities
• We implement four types of scanners corresponds to vulnerabilities we concerned
• This design means good scalability

\[ E_{eq_{apply}}(action, \text{"transfer"}) \land \forall a \in (A - \{self\}). \neg E_{eq_{apply}}(code, a) \]

The formal definition of fake EOS vulnerability detection logic. Specifically, if a path can lead to the transfer function and does not check the `code` field, we regard this contract is vulnerable to fake EOS vulnerability.
Evaluation

Benchmark & Comparison with the KLEE solution

A Comparison of EOSAFE and KLEE on the benchmark. (TP – True Positive, FP – False Positive, TN – True Negative, FN – False Negative, SR – Success Rate, P – Precision, R – Recall, F1 – F1 Measure)

<table>
<thead>
<tr>
<th>Type</th>
<th># Samples(Vul/Non-Vul)</th>
<th>EOSAFE SR**</th>
<th>P</th>
<th>R</th>
<th>F1</th>
<th>KLEE SR**</th>
<th>P</th>
<th>R</th>
<th>F1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake EOS</td>
<td>14 (7/7)</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>5</td>
<td>0</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Fake Receipt</td>
<td>10 (5/5)</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Rollback</td>
<td>18 (9/9)</td>
<td>94.44%</td>
<td>100.00%</td>
<td>88.89%</td>
<td>94.12%</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Permission</td>
<td>10 (6/4)*</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>5</td>
<td>0</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>52 (27/25)</td>
<td>98.08%</td>
<td><strong>100.00%</strong></td>
<td><strong>96.30%</strong></td>
<td><strong>98.11%</strong></td>
<td>10</td>
<td>0</td>
<td>25</td>
<td>17</td>
</tr>
</tbody>
</table>

* 4 pairs of the missing permission check samples are manually crafted. ** Timeout or memory error caused path explosion will be regarded as failed cases.

• From official announcement, cryptocurrency forums, and technical articles and blogs, we collected 52 victim smart contracts, which are vulnerable to at least one of our concerned vulnerabilities, as benchmark

• The benchmark is released at: https://github.com/HNYuuu/EOSafe-bench mark

• We compare EOSAFE with KLEE, which takes converted C code as input:
  • EOSAFE outperformed KLEE significantly, especially in recall
  • KLEE failed to perform the detection in most cases due to path explosion
  • The conversion from Wasm to C code requires extra human efforts on each case
Evaluation
On dataset

Vulnerability detection results in the wild.

<table>
<thead>
<tr>
<th>Type</th>
<th># Candidates</th>
<th># Vulnerable (%)</th>
<th># Unique</th>
<th># Vulnerable (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake EOS</td>
<td>47,396</td>
<td>1,457 (2.71%)</td>
<td>4,678</td>
<td>272 (4.88%)</td>
</tr>
<tr>
<td>Fake Receipt</td>
<td>47,396</td>
<td>7,143 (13.31%)</td>
<td>4,678</td>
<td>2,192 (39.33%)</td>
</tr>
<tr>
<td>Rollback</td>
<td>17,394</td>
<td>1,149 (2.14%)</td>
<td>913</td>
<td>84 (1.51%)</td>
</tr>
<tr>
<td>Permission</td>
<td>53,666</td>
<td>8,373 (15.60%)</td>
<td>5,574</td>
<td>662 (11.88%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>53,666</strong></td>
<td><strong>13,752 (25.63%)</strong></td>
<td><strong>5,574</strong></td>
<td><strong>2,759 (49.50%)</strong></td>
</tr>
</tbody>
</table>

*The percent is calculated based on all the EOSIO smart contracts with their versions.

- We collected all 53,666 smart contracts corresponding to 5,574 accounts as of Nov. 15th, 2019

- The result suggests:
  - Nearly half of smart contracts were once vulnerable to at least one kind of vulnerability, fake receipt is the most widespread one.
  - As for affected versions, missing permission check vulnerability impacts more than others.
Evaluation
Time to fix vulnerability

The time to fix the vulnerabilities.

<table>
<thead>
<tr>
<th>Type</th>
<th># Unique (Vul)</th>
<th># Latest with Vul (%)</th>
<th># Patched (%)</th>
<th>Patch Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake EOS</td>
<td>272</td>
<td>207 (76.10%)</td>
<td>65 (23.90%)</td>
<td>14.85d</td>
</tr>
<tr>
<td>Fake Receipt</td>
<td>2,192</td>
<td>1,735 (79.15%)</td>
<td>457 (20.85%)</td>
<td>24.01d</td>
</tr>
<tr>
<td>Rollback</td>
<td>84</td>
<td>28 (33.33%)</td>
<td>56 (66.67%)</td>
<td>4.24d</td>
</tr>
<tr>
<td>Permission</td>
<td>662</td>
<td>313 (47.28%)</td>
<td>349 (53.72%)</td>
<td>4.38d*</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2,759</strong></td>
<td><strong>2,080 (75.39%)</strong></td>
<td><strong>679 (24.61%)</strong></td>
<td><strong>16.84d</strong></td>
</tr>
</tbody>
</table>

*The average patch time for missing permission check is calculated on the action level.

- On average, patching a vulnerability requires **more than two weeks**
- The rollback vulnerability is patched most timely, because it has strong connections with the gambling DApps
- More than **3/4** of smart contracts were still vulnerable, especially the fake receipt vulnerability
Take-away messages

• We proposed the **first symbolic execution engine** for Wasm native code

• Based on the engine, we implemented an accurate and scalable framework: EOSAFE, which **outperforms the KLEE solution** on detecting vulnerabilities in EOSIO smart contracts

• We constructed and **released a manually checked benchmark**. Evaluation on the benchmark illustrates **promising performance** of EOSAFE

• We applied EOSAFE on over 53K smart contracts, which reveals **serious security issues** in the ecosystem, e.g., over 25% of the smart contracts are vulnerable
Thanks!

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