

# School of Informatics



## Research Methods In Security, Privacy, and Trust Detecting Ethereum Smart Contract Security Loopholes

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Abstract

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# 1 Introduction

During the predawn of the 21st century, we glimpsed a rapid technological and economic development that brought us face to face with a new technology called the blockchain. In recent years, blockchain and foremost cryptocurrencies gained much attraction due to the high monetary gains, which seem astronomical compared to traditional stock markets. It is a matter of the fact that this growth has acted as a catalyst for the technological and research eruption we have been experiencing lately. By the end of 2021, the total cryptocurrency market capitalization was 2 Trillion US Dollars[], featuring more than 16000 projects[]. Initially, the blockchain was proposed to facilitate the transfer of value completely decentralized and trust-framed over a network of peers. This was Satoshi's Nakamoto Bitcoin[] that came into existence in 2008. Since then, the research and technological trends have shifted into second-generation blockchains. Among them, the most dominant is Ethereum[]. Ethereum is a general-purpose blockchain, providing an open platform for individuals to build their applications on top of it. Their applications, i.e., Smart Contracts, are pieces of code that run decentralized on the Ethereum network. This allows developers to get involved in this new technology, creating an entirely new industry. Ethereum's ecosystem flared into a broad spectrum of Smart Contract applications, including, but not limited to, financial apps, games, digital art and music, digital voting, and patent registration.

Smart Contracts have balance measured in Ether and persistent private storage. The Smart Contract's code can manipulate changes in the program's variables and storage. On Ethereum, Smart Contracts code is in EVM[] (Ethereum Virtual Machine), a Turing complete stack-based bytecode language spanning 144 OP codes[]. Nonetheless, developers can define their code in a high-level language such as Solidity[], compiled to EVM bytecode afterward. A new transaction invocation can cause the execution of the contract's code by receiving inputs and producing outputs. Typically, when a user wants to trigger a Smart Contract needs to create a new transaction and pay some fees[]. Transaction fees depend on the code being executed on the Ethereum network.

Beyond any doubt, the Ethereum blockchain is used to manage digital assets reflecting a considerable value. Hence Smart Contracts gained the interest of malign entities. Numerous attackers perform attacks on the Ethereum applications, with the ultimate goal of stealing Ether from them. One of the most severe attacks was the infamous DAO[]. In more detail, in 2016, an autonomous decentralized organization was founded to direct a venture capital fund. This organization was formed on the Ethereum blockchain, and over 11000 investors deposited into a Smart Contract over 150 Million US Dollars[] considering the Ether price back then. Then, an unprecedented attack[] was performed on that Smart Contract, resulting in 50 Million US Dollars loss. Another critical incident happened with the Parity Wallet[], where the attack [] led to freezing 150 Million US Dollars, in terms of Ether, impermanently.

Nevertheless, it is typical for any piece of code to have bugs. Likewise, we expect Smart Contracts to behave in the same way. Potentially, five main reasons make Smart Contracts vulnerable. We might blame developers for not wholly understanding the blockchain development stack[smart check]. Also, Solidity is a relatively new language with many limitations and challenges. Thus, it is hard for developers to use it[smart check]. We consider blockchain immutability as another non-helping characteristic. Any application deployed on the Ethereum network can not be modified, so software fixes are not immediately doable[contract fuzzer]. A public blockchain allows financially motivated attackers to use their online pseudonymity to exploit any software bug[smart check]. Finally, we cannot control the Smart Contract execution environment since the network runs in a decentralized fashion[smart check]. For this reason,

Smart Contract developers need to detect possible vulnerabilities in their code before going live. A Smart Contract Auditing tool would benefit both users and developers. A developer might use the tool to detect any code issues before deploying the Smart Contract. At the same time, users can utilize the tool to check if the Smart Contract they are depositing Ether is safe and does behave maliciously.

Indeed, such tools came into existence in 2016, with the first one being OYENTE[1]. Since then, academic researchers have invested time and effort in expanding this research field, developing a plethora of tools. Some of them are general, trying to detect any vulnerability, while some others focus on a few of them. Also, they employ different analysis techniques, such as Static Analysis, Dynamic Analysis, Symbolic Execution, Fuzzing, and Machine Learning. Furthermore, researchers attempted to document and classify many of these vulnerabilities according to their behavior or functionality.

The contribution of this work is three-fold. Initially, we document and classify Smart Contract vulnerabilities reported across the most prominent studies. Next, we present the research trends of developing a Smart Contract vulnerability framework throughout the years, giving an overview of the techniques used and directions taken. Finally, we elaborate on the result reliability and scalability of the most paramount frameworks.

The structure of the following literature review has as follows ...

## 2 Methodology

In this literature review, we explore the most prominent research attempts towards creating an effective vulnerability detection tool for Ethereum Smart Contracts. The method used to filter relevant studies comprised both bottom-up and top-down strategies. Their combination significantly accelerated identifying adequate quality papers to include in this literature review.

During the bottom-up stage, we sought several papers related to frameworks that identify Smart Contract vulnerabilities. To achieve that, we employed trustworthy academic search engines such as *Google Scholar* and *IEEE Explorer*. We noticed that most of the retrieved writings had a joint primary related work, which guided us to discover this research topic's essence paper[1].

Subsequently, we aimed to find any derivative studies related to the paper arisen in the previous phase. To do so, we used a graph representation tool[2] that links relevant papers. This mechanism allowed us to identify remarkable research articles rapidly. Afterward, we manually inspected the search results and included the most reliable in our under investigation list.

Namely, we collected forty-seven papers, but we only consider nineteen of them in this literature review. The selection criteria span the context of the studies and their research contribution. We measure their contribution according to their citations and release year. According to their publication year, studies are assigned a weight ranging from 1 to 4. Papers in the span of 2016-2017, 2018, 2019, 2020 receive 1, 2, 4, 8 points, respectively, for each citation they hold. Using this metric, we evaluate the studies shown in Table 2.

| Study   | Year | Cit. | Score | Ref. |
|---|------|------|-------|------|
| Making Smart Contracts Smarter  | 2016 | 1445 | 1445  | [1]  |
| A Survey of Attacks on Ethereum Smart Contracts (SoK)   | 2017 | 1176 | 1176  | [3]  |
| Securify: Practical Security Analysis of Smart Contracts  | 2018 | 436  | 872   | [4]  |
| VerX: Safety Verification of Smart Contracts  | 2020 | 103  | 824   | [5]  |
| ZEUS: Analyzing Safety of Smart Contracts   | 2018 | 399  | 798   | [6]  |
| Finding The Greedy, Prodigious, and Suicidal Contracts at Scale   | 2018 | 357  | 714   | [7]  |
| SmartCheck: Static Analysis of Ethereum Smart Contracts   | 2018 | 291  | 582   | [8]  |
| Formal Verification of Smart Contracts  | 2016 | 525  | 525   | [9]  |
| ContractFuzzer:Fuzzing Smart Contracts for Vulnerability Detection  | 2018 | 233  | 466   | [10] |
| Slither: A Static Analysis Framework For Smart  | 2019 | 109  | 436   | [11] |
| MadMax:Surviving Out-of-Gas Conditions in Ethereum Smart Contracts  | 2018 | 213  | 426   | [12] |
| Manticore: A User-Friendly Symbolic Execution Framework for Binaries and Smart Contracts                      | 2019 | 91   | 364   | [13] |
| teether:Gnawing at Ethereum to Automatically Exploit Smart Contracts  | 2018 | 173  | 345   | [14] |
| Vandal:A Scalable Security Analysis Framework for Smart Contracts   | 2018 | 154  | 308   | [15] |
| ReGuard: Finding Reentrancy Bugs in Smart Contracts   | 2018 | 122  | 244   | [7]  |
| Ethereum Smart Contracts: Vulnerabilities and their Classifications   | 2020 | 12   | 96    | [16] |
| ETHPLOIT:From Fuzzing to Efficient Exploit Generation against Smart Contracts                                 | 2020 | 10   | 80    | [17] |
| GasFuzzer: Fuzzing Ethereum Smart Contract Binaries to Expose Gas-Oriented Exception Security Vulnerabilities | 2020 | 8    | 64    | [18] |
| SoliAudit: Smart Contract Vulnerability Assessment Based on Machine Learning and Fuzz Testing                 | 2019 | 13   | 52    | [19] |

Table 1: List of papers that are analyzed in this literature review, sorted by their score

### 3 Literature Review

#### 3.1 Smart Contract Attack Surface

One of the most important aspects of Smart Contract vulnerability detection tools is understanding and realizing models that precisely describe a vulnerability. Different authors have unique approaches on how to classify potential faulty code. For example, according to their overall behavior, Nikolic et al. [Finding greedy ...] categorize Smart Contract into Greedy, Prodigious, and Suicidal. Namely, each category represents an abstract representation of a group of more explicit vulnerabilities. On the other hand, some other authors prefer to distinguish vulnerabilities based on the domain they affect. For example, a few studies, like GasFuzzer [gas fuzzer], choose to examine only gas-oriented vulnerabilities. Subsequently, it is abundantly clear that there is a broad spectrum of Smart Contract vulnerabilities, and there is not a single universally accepted classification of them. In 2017 Atzei et al. [sok] published a survey including the most well-known security pitfalls of the Ethereum Smart Contracts. In more detail, they report twelve points, taxonomizing them into three categories (Solidity-Level, EVM-Level, and Blockchain-Level). Four years and over ten million blocks later, new vulnerabilities arose. Hence, within the context of this literature review, we have collected reported vulnerabilities across different studies and present a thorough list of them, trying to categorize them into seven groups.

We categorize vulnerabilities according to their domain. In the first place, we noticed that a

| Class                               | No. | Vulnerability Name               |
|-------------------------------------|-----|----------------------------------|
| Syntax Violations                   | 1   | Interface violation              |
|                                     | 2   | Compiler version inconsistency   |
|                                     | 3   | Variable visibility modifiers    |
|                                     | 4   | Function visibility level        |
|                                     | 5   | Argument validation              |
|                                     | 6   | Costly coding scheme             |
|                                     | 7   | Redundant Fallback Function      |
|                                     | 8   | Code format/style violation      |
| Internal Vulnerabilities            | 9   | Ether Freezing                   |
|                                     | 10  | Destroybale Contract             |
|                                     | 11  | Internal variable access control |
|                                     | 12  | Contract balance access control  |
|                                     | 13  | Exposed secret                   |
| External Vulnerabilities            | 14  | Reentrancy                       |
|                                     | 15  | Denial of Service                |
|                                     | 16  | Poor exception handling          |
|                                     | 17  | Gasless Send                     |
|                                     | 18  | Non isolated external calls      |
|                                     | 19  | Delegate calls                   |
| Arithmetic Vulnerabilities          | 20  | Integer under/over flow          |
| Gas related Vulnerabilities         | 21  | Denial of Service                |
|                                     | 22  | Integer under/over flow          |
|                                     | 23  | Unbounded mass operations        |
| Transaction related Vulnerabilities | 24  | Transaction ordering dependency  |
|                                     | 25  | Transaction state dependency     |
| Block related Vulnerabilities       | 26  | Block state dependency           |

Table 2: List of vulnerabilities according to their domain

few frameworks tend to include in their auditing report warnings related to Smart Contract syntax or related good programming practices. Thus, we included a category to wrap up all of these suggestions. Furthermore, we have classes referring to internal, external, and arithmetic bugs. Finally, we introduce two more categories to enclose transaction and block dependency exposures. Ultimately, we report twenty-two vulnerabilities over these domains (Note: a vulnerability might be part of multiple domains). Table 2 depicts the category and vulnerability mappings. The following subsections describe each vulnerability in more detail.

**Interface Violations:** Interface violations refer to implementing particular digital assets on the Ethereum blockchain without fully aligning with the defacto community accepted requirements. For example, ERC-20 tokens [eth website to erc20] need to expose a particular API interface to help third-party services communicate with their Smart Contract flawlessly. If a developer decides to implement a non-ERC-20 compliant token, it might be considered suspicious and thus malicious.

**Compiler version inconsistency:** Solidity source code files include a header line stating the versions of compiler they can be compiled with. A similar to Javascript notation can be used to indicate the minor compiler version (caret character). This notation can produce execution inconsistency in different execution environments. For this reason, it is better to declare a stable compiler version precisely. Nevertheless, we can argue with this proposal from Tikhomirov et al. since using a stable compiler version might make a Smart Contract obsolete and incapable of running on newer EVM versions.

**Variable visibility modifiers:** Many developers migrating from traditional programming languages mistake the *private* variable modifier as not visible to others. This is a misunderstanding since every Smart Contract state variable is visible to anyone. The term *private* means that other Smart Contract instances can not access this variable.

**Function visibility level:** In Solidity, a function can have three visibility levels. These are external, internal, and public. Likewise to the previous coding pitfall, many developers might misinterpret the meaning of these modifiers and use them wrong.

**Argument validation:** It is a common practice to adopt for every Smart Contract function. For example, when we receive a string of a maximum of eight characters long, we should check that its length is valid. However, this practice can require more computational complexity and yield more gas fees. It should be used when needed.

**Costly coding schemes:** In Solidity, different data structures have different gas costs, but they can achieve the same result most of the time. For instance, a developer should use pure bytes instead of using a byte array because they have lower gas fees. Moreover, loops are the most common coding scheme to avoid since a loop of an unknown length comes with high execution cost.

**Redundant Fallback Function:** Solidity supports a fallback/receive function triggered when no function signature matches the transaction data. This function deposits the incoming value to the contract balance when a transaction has value but no data. Similarly, it handles any transaction that has unknown function signatures. A fallback/receive function should be implemented only when needed; otherwise, it is redundant.

**Code format/style violation:** Smart Contract developers should use tidy and easy-to-read styling patterns throughout the code.

**Ether Freezing:** A Smart Contract, as mentioned earlier, has its balance of Ether. Different types of applications require the user to deposit Ether to participate in a lucky draw or an online game etc. Some Smart Contract will accept deposits, but under specific conditions, it might lock Ether forever, acting as a black hole. Something similar happened in 2017 with Parity wallet Smart Contract. The bug occurred because the Parity wallet transferred funds using an external library. That library was accidentally removed from the blockchain, and thus all Ether in Parity wallet became inaccessible. Further, according to Nikolic et al. another case where funds can be locked in a Smart Contract is when the contract is removed from the blockchain, and some users continue to send Ether to it. These Ether will be lost as well.

**Destroyable Contract:** Smart Contracts, out of the box, give the ability to their owners or an authorized entity to destroy them. The funds enclosed in the Smart Contract will be returned to the owner by default. However, if an arbitrary account can destroy the Smart Contract, it alarms a vulnerability. This abnormal code behavior might have been maliciously constructed and helped an attacker harvest any Ether in the Smart Contract's balance when combined with other attacks.

**Internal variable access control** With the term internal variable access control, we refer to insecure Smart Contract implementation that allows an adversarial entity to alter the internal state of the Smart Contract. This kind of behavior can be combined with the earlier mentioned Destruction vulnerability. For instance, an attacker leverages his ability to alter the Smart Contract owner variable before the Destruction. Besides that, attackers might straightforwardly access the contract's private variables value or logic, revealing an important secret.

**Contract balance access control** Like internal variable access control, a Smart Contract that can be invoked to transfer money to an arbitrary account appears questionable. We define

arbitrary accounts as addresses that have never deposited Ether into a Smart Contract but can withdraw value from it.

**Delegate calls**

**Reentrancy**

**Denial of Service**

**Poor exception handling**

**Gasless Send**

**Non isolated external calls**

**Integer under/over flow**

**Unbounded mass operations**

**Transaction ordering dependency**

**Transaction state dependency**

**Block state dependency**

### 3.2 Static Analysis

### 3.3 Dynamic Analysis

### 3.4 Symbolic Execution

### 3.5 Fuzzing

### 3.6 The Machine Learning Approach

## 4 Summary & Conclusion

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