Smart Contract Vulnerabilities: Does Anyone Care?

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Contributions. Our contributions are:

contracts.

• This paper presents the first broadly scoped analysis of the real-life prominence of security exploits against smart

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We propose a Datalog-based formulation for performing analysis over Ethereum Virtual Machine (EVM) execution traces. We use this highly scalable approach to analyze a total of more than 16 million transactions from the Ethereum blockchain to search for exploits. We should highlight that our analyses run *automatically* based on the facts that we extract and the rules that define the vulnerabilities we cover in this paper.

We analyze the vulnerabilities reported in six recently published studies and conclude that, although the number of contracts and the amount of money supposedly at risk is very high, the amount of money which has actually been exploited is several orders of magnitude lower.

 We discover out of 21,270 vulnerable contracts worth a total of 3,088,102 ETH, merely 49 contracts containing Ether may have been exploited for an amount of 9,066 ETH, which represents as little as 0.29% of the total amount at stake.

• We hypothesize that the reasons for these vast differences are multi-fold: lack of appetite for exploitation, the sheer difficulty of executing some exploits, fear of attribution, other more attractive exploitation options, etc. Further analysis of the vulnerable contracts and the Ether they contain suggests that a large majority of Ether is held by only a small number of contracts, and that the vulnerabilities reported on these contracts are either false positives or not applicable in practice, making exploitation significantly less attractive as a goal.

To make many of the discussions in this paper more concrete, we present a thorough investigation of the high-value contracts in Appendix A.

ABSTRACT

In the last year we have seen a great deal of both academic and practical interest in the topic of vulnerabilities in smart contracts, particularly those developed for the Ethereum blockchain. In this paper we survey the 21,270 vulnerable contracts reported by six recent academic projects. Contrary to what might have been believed given the reported number of vulnerable contracts, there has been precious little in terms of *actual exploitation* when it comes to these vulnerabilities. We find that at most 504 out of 21,270 contracts have been subjected to exploits. This corresponds to at most 9,066 ETH (~1.8 million USD ¹), or only 0.29% of the 3 million ETH (600 million USD) claimed in some of the papers. While we are certainly not implying that smart contract vulnerability research is without merit, our results suggest that the potential impact of vulnerable code had been greatly exaggerated.

1 INTRODUCTION

When it comes to vulnerability research, especially as it pertains to software security, it is frequently difficult to estimate what fraction of discovered or reported vulnerabilities are exploited in practice. However, public *blockchains*, with their immutability, ease of access, and what amounts to a replayable execution log for smart contracts present an excellent opportunity for just such an investigation. In this work we aim to contrast the vulnerabilities that are reported in smart contracts on the Ethereum [18] blockchain with the actual exploitation of these contracts.

We collect the data shared with us by the authors of six recent papers [27, 34, 35, 38, 43, 52] that focus on finding smart contract vulnerabilities. These academic datasets are significantly bigger in scale than reports we can find in the wild and because of the sheer number of affected contracts -21,270 - represent an excellent study subject.

To make our approach more general, we express five different frequently reported vulnerability classes as Datalog queries computed over relations that represent the state of the Ethereum blockchain, both current and historic. The Datalog-based exploit discovery approach gives more scalability to our process; also, while others have used Datalog for static analysis formulation, we are not aware of it being used to capture the dynamic state of the blockchain over time.

We discover that the amount of smart contract exploitation which occurs in the wild is notably lower than what might be believed, given what is suggested by the sometimes sensational nature of some of the famous crypto-currency exploits such as TheDAO [46] or the Parity wallet [16] bugs.

$^1\mathrm{We}$ use the exchange rate on 2019-05-12: 1 ETH = 200 USD. For consistency, any monetary amounts denominated in USD are based on this rate.

2 BACKGROUND

The Ethereum [18] platform allows its users to run "smart contracts" on its distributed infrastructure. Ethereum *smart contracts* are programs which define a set of rules for the governing of associated funds, typically written in a Turing-complete programming language called Solidity [23]. Solidity is similar to JavaScript, yet some notable differences are that it is strongly-typed and has built-in constructs to interact with the Ethereum platform. Programs written in Solidity are compiled into low-level untyped bytecode to be executed on the Ethereum platform by the Ethereum Virtual Machine (EVM). It is important to note that it is also possible to write EVM contracts without using Solidity.

To execute a smart contract, a sender has to send a transaction to the contract and pay a fee which is derived from the contract's computational cost, measured in units of *gas*. Consumed gas is

Name	Contracts analyzed							Report month	Citation
Oyente	19K	8.8K	✓	✓		✓		2016-10	[38]
ZEUS	22.4K	21K	✓	✓	✓	✓	✓	2018-02	[34]
Maian	34K	3.7K			✓			2018-03	[43]
SmartCheck	4.6K	4.6K	✓	✓	✓		✓	2018-05	[51]
Securify	25K	5K	✓	✓	✓	✓		2018-06	[52]
ContractFuzzer	7K	460	✓	✓				2018-09	[33]
Vandal	141K	85K	✓	✓				2018-09	[17]
MadMax	92K	6K			√		✓	2018-10	[27]

Figure 1: A summary of smart contract analysis tools presented in prior work.

credited to the miner of the block containing the transaction, while any unused gas is refunded to the sender. In order to avoid system failure stemming from never-terminating programs, transactions specify a gas limit for contract execution. An out-of-gas exception is thrown once this limit has been reached.

Smart contracts themselves have the capability to "call" another account present on the Ethereum blockchain. This functionality is overloaded, as it is used both to call a function in another contract and to send Ether (ETH), the underlying currency in Ethereum, to an account. A particularity of how this works in Ethereum is that calls from within a contract do not create any new transactions and are therefore not directly recorded on-chain. This means that merely looking at the transactions without executing them does not provide enough information to follow the flow of Ether.

2.1 Current Industrial Practice

Smart contracts are generally designed to manipulate and *hold* funds denominated in Ether. This makes them very tempting attack targets, as a successful attack may allow the attacker to directly steal funds from the contract. Hence, in order to ensure a sufficient degree of smart contract security, a wide variety of practices that operate at different stages of the development life-cycle have been adopted in the industry.

Analysis tools. A large number of tools have been developed to analyze smart contracts [21, 38, 52]. Most of these tools analyze either the contract source code or its compiled EVM bytecode and look for known security issues, such as re-entrancy or transaction order dependency vulnerabilities. We present a summary of these different works in Figure 1. The second and third columns respectively present the reported number of contracts analyzed and contracts flagged vulnerable in each paper. The "vulnerabilities" columns show the type of vulnerabilities that each tool can check for. We present these vulnerabilities in Subsection 2.2 and give a more detailed description of these tools in Section 7.

Testing. Like any piece of software, smart contracts benefit from automated testing and some efforts have therefore been made to make the testing experience more straightforward. Truffle [20] is a popular framework for developing smart contracts, which allows to write both unit and integration tests for smart contracts in JavaScript. One difficulty of testing on the Ethereum platform is that the EVM does not have a single main entry point and bytecode is executed when fulfilling a transaction.

There are mainly two methods used to work around this. The first is to use a private Ethereum network, or a test-net, where it is easy to control the state. The smart contracts are deployed and executed on the private network in the same way they would be deployed on the main Ethereum network. The other approach is to use a standalone implementation of the EVM. Ganache [22] is one of the most popular such standalone implementation of the EVM built for development purposes and is developed by the same authors as Truffle. Although this provides a more lightweight way to run tests, it also requires the implementation to perfectly mimic the original one, which is error-prone.

Auditing. As smarts contracts can have a high monetary value, *auditing* contracts for vulnerabilities is a common industrial practice. Audit should preferably be performed while contracts are still in testing phase but given the relatively high cost of auditing (usually around 30,000 to 40,000 USD [12]) some companies choose to perform audits later in their development cycle. In addition to checking for common vulnerabilities and implementation issues such as gas-consuming operations, audits also usually check for divergences from the whitepaper and other high-level logic errors, which are impossible for current automatic tools to detect.

Bounty programs. Another common practice for developers to improve the security of their smart contracts is to run bounty programs. While auditing is usually a one-time process, bounty programs remain ongoing throughout a contract's lifetime and allow community members to be rewarded for reporting vulnerabilities. Companies or projects running bounty programs can either choose to reward the contributors by paying them in a fiat currency such as US dollars, a cryptograms — typically Bitcoin or Ether — or other crypto assets. Some bounty programs, such as the one run by the 0x project [7], offer bounties as high as 100,000 USD for critical vulnerabilities.

2.2 Vulnerability Types

In this subsection, we briefly review some of the most common vulnerability types that have been researched and reported for EVM-based smart contracts. We provide a two-letter abbreviation for each vulnerability, which we shall use throughout the remainder of this paper.

Re-Entrancy (RE). The vulnerability is exploited when a contract tries to send Ether before having updated its internal state. If the destination address is another contract, it will be executed and can therefore call the function to request Ether again and again [34, 38, 52]. This vulnerability was used in The DAO exploit [46], essentially causing the Ethereum community to decide to rollback to a previous state using a hard-fork [40]. We provide more details about The DAO exploit in Section 7

Unhandled Exceptions (UE). Some low-level operations in Solidity such as send, which is used to send Ether, do not throw an exception on failure, but rather report the status by returning a boolean. If this return value were to be unchecked, a contract would continue its execution even if the payment failed, which could be easily lead to inconsistencies [17, 34, 38, 51].

Locked Ether (LE). Ethereum smart contracts can have a function marked as payable which allows it to receive Ether, increasing the balance of the contract. Most of the times, the contract will also

Name	Contracts analyzed	Vulnerabilities found	Ether at stake at time of report
Oyente	19,366	7,527	1,289,177
Zeus	1,120	855	729,376
Maian	NA	2,691	14.13
Securify	29,694	9,185	719,567
MadMax	91,800	6,039	1,114,692
teEther	784,344	1,532	0.756

Figure 2: Summary of the contracts in our dataset.

have a function which sends Ether. For example, a contract might have a payable function called deposit, which receives Ether, and a function called withdraw, which sends Ether. However, there are several reasons for which the withdraw function may become unable to send funds anymore.

One reason is that the contract may depend on another contract, which has been destructed using the SELFDESTRUCT instruction of the EVM — i.e. its code has been removed and its funds transferred. For example, the withdraw function may require an external contract to send Ether. However, if the contract it relies on has been destructed, the withdraw function would not be able to actually send the Ether, effectively locking the funds of the contract. This is what happened in the Parity Wallet bug in November 2017, locking millions of USD worth of Ether [16]. We provide more details about the Parity Wallet bug in Section 7

There are also cases where the contract will *always* run out of gas when trying to send Ether, locking the contract funds. More details about such issues can be found in [27].

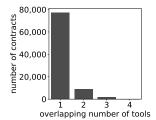
Transaction Order Dependency (TO). In Ethereum, multiple transactions are included in a single block, which means that the state of a contract can be updated multiple times in the same block. If the order of two transactions calling the same smart contract changes the final outcome, an attacker could exploit this property. For example, given a contract which expects participant to submit the solution to a puzzle in exchange for a reward, a malicious contract owner could reduce the amount of the reward when the transaction is submitted.

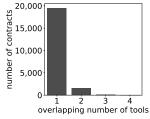
Integer Overflow (IO). Integer overflow and underflow is a common type of bug in many programming languages but in the context of Ethereum it can have very severe consequences. For example, if a loop counter were to overflow, creating an infinite loop, the funds of a contract could become completely frozen. This can be exploited by an attacker if he has a way of incrementing the number of iterations of the loop, for example, by registering new users of the contract.

3 DATASET

In this paper, we analyze the vulnerable contracts reported by the following six academic papers: [38], [34], [43], [52], [27] and [35]. To collect information about the addresses analyzed and the vulnerabilities found, we reached out to the authors of the different papers.

Oyente [38] data was publicly available [37]. The authors of the other papers were kind enough to provide us with their dataset.





(a) Overlapping contracts analyzed.

(b) Overlapping vulnerabilities flagged.

Figure 3: Histograms that show the overlap in the contracts analyzed and flagged by different papers.

Tools	Total	Agreed	Disagreed	% agreement
Oyente/Securify	774	185	589	23.9%
Oyente/Zeus	104	3	101	2.88%
Zeus/Securify	108	2	106	1.85%

Figure 4: Agreement among tools for re-entrancy analysis.

We received all the replies within less than a week of contacting the authors.

We also reached out to the authors of [51], [33] and [17] but could not obtain their dataset, which is why we left these papers out of our analysis.

Our dataset is comprised of a total of 110,177 contracts analyzed, of which 21,270 contracts have been flagged as vulnerable to at least one of the five vulnerabilities described in Section 2. Although we received the data directly from the authors, the numbers of contracts analyzed usually did not match the data reported in the papers, which we show in Figure 1. We believe the two main results for this are: authors improving their tools after the publication and authors not including duplicated contracts in their data they provided us. Therefore, we present the numbers in our dataset, as well as the Ether at stake for vulnerable contracts in Figure 2. The Ether at stake is computed by summing the balance of all the contracts flagged vulnerable. We use the balance at the time at which each paper was published rather than the current one, as it gives a better sense of the amount of Ether which could potentially have been exploited.

Taxonomy. Rather than reusing existing smart contracts vulnerabilities taxonomies [13] as-is, we adapt it to fit the vulnerabilities analyzed by the different tools in our dataset. We do not cover any vulnerability which is not analyzed by at least two of the six tools we analyze. We settle on the five types of vulnerabilities described in Section 2: re-entrancy (RE), unhandled exception (UE), locked Ether (LE), transaction order dependency (TO) and integer overflows (IO). As the papers we analyze use different terms and slightly different definitions for each of these vulnerabilities, we map the relevant vulnerability to one of the five types of vulnerabilities we analyze. We show how we mapped these vulnerabilities in Figure 5.

Excluded data. We exclude teEther [35] and Maian [43] from our analysis for two reasons. First, the amount of Ether at stake is too low to make an impact on our final results. The amount of Ether at stake for both tools combined represent a total of 14.89 Ether, which is six orders of magnitude less than the total. Second, it is vastly

	Oyente	ZEUS	Securify	MadMax
RE	re-entrancy	re-entrancy	no writes after call	_
UE	callstack	unchecked send	handled exceptions	_
TO	concurrency	tx order dependency	transaction ordering dependency	_
LE	_	failed send	Ether liquidity	unbounded mass operation
				wallet griefing
Ю	_	integer overflow	_	integer overflows

Figure 5: Mapping of the different vulnerabilities analyzed.

Figure 6: Sample execution trace information.

harder given the vulnerabilities analyzed by these tools to reliably assess if they have been exploited. Indeed, for a vulnerability such as being able to destruct the contract, there is no general way of knowing if the person who performed such a call should have been allowed to do so. Given this lack of reliability and the very low amount of money at stake, we decided to keep this data out of further analysis.

Overlapping vulnerabilities. In this subsection, we analyze our dataset to see how much the contracts analyzed by the different tools and the vulnerabilities found overlap. Although most papers, except for [38], are written around the same period, we find that only 13,751 contracts out of the total of 110,177 have been analyzed by at least two of the tools. In Figure 3a, we show a histogram of how many different tools analyze a single contract. In Figure 3b, we show the number of tools which flag a single contract as vulnerable to any of the analyzed vulnerability. The overlap for both the analyzed and the vulnerable contracts is clearly very small. We assume one of the reasons is that some tools work on Solidity code [34] while other tools work on EVM bytecode [38, 52], making the population of contracts available different among tools.

We also find a lot of contradiction in the analysis of the different tools. We choose re-entrancy to illustrate this point, as it is unambiguous and is supported by three of the tools we analyze. In Figure 4, we show the agreement between the three tools which support re-entrancy detection. The *Total* column shows the total number of contracts analyzed by both tools in the *Tools* column and flagged by at least one of them as vulnerable to re-entrancy. Oyente and Securify agree on only 23% of the contracts, while Zeus does not seem to agree with any of the other tools. This reflects the difficulty of building static analysis tools targeted at the EVM. While we are not trying to evaluate or compare the performance of the different tools, this gives us yet another motivation to find out the impact of the reported vulnerabilities.

4 METHODOLOGY

In this section, we describe in details the different analysis we perform in order to check for exploits of the vulnerabilities described in Section 2. To check for potential exploits, we mainly perform bytecodelevel transaction analysis, whereby we look at the code executed by the contract when carrying out a particular transaction. We use this type of analysis to detect re-entrancy (RE), unhandled exceptions (UE) and integer overflows (IO). We also use transaction pattern analysis, where we analyze the flow of the transactions both from and to the contract, either to filter or to refine our results. We use this type of analysis to refine the results of locked Ether (LE) and to filter transactions when looking for transaction order dependency (TO) exploits.

To perform both analyses, we first retrieve transaction data for all the contracts in our dataset. To simplify the retrieval process, we use data provided by Etherscan [8], a well-known Ethereum blockchain explorer service, rather than scanning the entire Ethereum blockchain ourselves.

Next, to perform bytecode-level analysis, we extract the execution traces for the transactions which may have affected contracts of interest. We use EVM's debug functionality, which gives us the ability to replay transactions and to trace all the executed instructions. To speed-up the data collection process, we patch the Go Ethereum client [11], opposed to relying on the Remote Procedure Call (RPC) functionality provided by the default Ethereum client.

The extracted traces contain a list of executed instructions, as well as the state of the stack at each instruction. We show a truncated sample of the extracted traces in Figure 6 for illustration. The op key is the current instruction, pc is the program counter, depth is the current level of call nesting, and finally, stack contains the current state of the stack. We use single-byte values in the example, but the actual values are 32 bytes (256 bits).

To analyze the traces, we encode them into a Datalog representation; Datalog is a language implementing first-order logic with recursion [32], which has been used extensively by the programming language community. We use the following domains to encode the information about the traces as Datalog facts:

- ullet V is the set of program variables;
- A is the set of Ethereum addresses;
- $\bullet~\mathbb{N}$ is the set of natural numbers, \mathbb{Z} is the set of integers.

We show an overview of the facts that we collect and the relations that we use to check for possible exploits in Figure 7. We should highlight that our analyses run *automatically* based on the facts that we extract and the rules that define various violations described in subsequent sections.

4.1 Re-Entrancy

In the EVM, as transactions are executed independently, re-entrancy issues can only occur *within* a single transaction. Therefore, for re-entrancy to be exploited, there must be a call to an external

Fact	Description
is_output($v_1 \in V, v_2 \in V$)	v_1 is an output of v_2
$size(v \in V, n \in \mathbb{N})$	v has n bits
$is_signed(v \in V)$	v is signed
${\sf in_condition}(v \in V)$	v is used in a condition
$call(a_1 \in A, a_2 \in A, p \in \mathbb{N})$	a_1 calls a_2 with p Ether
expected_result($v \in V, r \in \mathbb{Z}$)	v's expected result is r
$actual_result(v \in V, r \in \mathbb{Z})$	v's actual result is r
coll manult(n.c.V. n.c.NI)	v is the result of a call
$call_result(v \in V, n \in \mathbb{N})$	and has a value of n
$call_entry(i \in \mathbb{N}, a \in A)$	contract a is called when
call_entry($i \in \mathbb{N}, u \in A$)	program counter is i
call ovit(i $\subset \mathbb{N}$)	program counter is i when
$call_exit(i \in \mathbb{N})$	exiting a call to a contract
$tx_sstore(b \in \mathbb{N}, i \in \mathbb{N}, k \in \mathbb{N})$	storage key k is written in
$tx_sstore(b \in 14, t \in 14, K \in 14)$	transaction i of block b
$+v$ closed $(h \in \mathbb{N} : \in \mathbb{N} : h \in \mathbb{N})$	storage key k is read in
$tx_sload(b \in \mathbb{N}, i \in \mathbb{N}, k \in \mathbb{N})$	transaction i of block b

(a) Datalog facts.

```
\begin{split} & \text{Datalog rules} \\ & \text{depends}(v_1 \in V, \ v_2 \in V) : \text{-} \text{ is\_output}(v_1, \ v_2). \\ & \text{depends}(v_1, \ v_2) : \text{-} \text{ is\_output}(v_1, \ v_3), \text{ depends}(v_3, \ v_2). \\ & \text{call\_flow}(a_1 \in A, \ a_2 \in A, \ p \in \mathbb{Z}) : \text{-} \text{ call}(a_1, \ a_2, \ p). \\ & \text{call\_flow}(a_1, \ a_2, \ p) : \text{-} \text{ call}(a_1, \ a_3, \ p), \\ & \text{call\_flow}(a_3, \ a_2, \ \_). \\ & \text{inferred\_size}(v \in V, \ n \in \mathbb{N}) : \text{-} \text{size}(v, \ n). \\ & \text{inferred\_size}(v, \ n) : \text{-} \text{depends}(v, \ v_2), \text{size}(v_2, \ n). \\ & \text{inferred\_signed}(v) : \text{-} \text{depends}(v, \ v_2), \text{is\_signed}(v_2). \\ & \text{influences\_condition}(v \in V) : \text{-} \text{in\_condition}(v). \\ & \text{influences\_condition}(v) : \text{-} \text{depends}(v_2, \ v), \\ & \text{in\_condition}(v_2). \\ \end{split}
```

(b) Basic Datalog relation definitions.

Type of vulnerability	Query
Re-Entrancy	$\begin{array}{l} call_flow(a_1,\ a_2,\ p_1),\\ call_flow(a_2,\ a_1,\ p_2),\\ a_1\neq a_2 \end{array}$
Unhandled Exceptions	$\begin{array}{c} {\sf call_result}(v,\ 0), \\ {\sf \neg influences_condition}(v) \end{array}$
Transaction Order Dependency	$tx_sstore(b, t_1, i),$ $tx_sload(b, t_2, i), t_1 \neq t_2$
Locked Ether	$\begin{aligned} & \texttt{call_entry}(i_1, a), \\ & \texttt{call_exit}(i_2), i_1 + 1 = i_2 \end{aligned}$
Integer Overflow	$\begin{aligned} &actual_result(v,\ r_1),\\ &expected_result(v,\ r_2), r_1 \neq r_2 \end{aligned}$

(c) Datalog queries for detecting different vulnerability classes.

Figure 7: Datalog setup.

```
if (!addr.send(100)) { throw; }
```

(a) Failure handling in Solidity.

```
; preparing call
(0x65) CALL
; call result pushed on the stack
(0x69) PUSH1 0x73
(0x71) JUMPI ; jump to 0x73 if call was successful
(0x72) REVERT
(0x73) JUMPDEST
```

(b) EVM instructions for failure handling. Figure 8: Correctly handled failed send.

contract, which invokes, directly or indirectly, a re-entrant callback to the calling contract. We therefore start by looking for CALL instructions in the execution traces, while keeping track of the contract currently being executed.

When CALL is executed, the address of the contract to be called as well as the value to be sent can be retrieved by inspecting the values on the stack [54]. Using this information, we can record $call(a_1, a_2, p)$ facts described in Figure 7a. Using these, we then use the query shown in Figure 7c to retrieve potentially malicious re-entrant calls.

Soundness and completeness. Our analysis for re-entrant calls is sound and complete. As the EVM executes each contract in a single thread, a re-entrant call must come from a recursive call. For example, given A, B, C and D being functions, a re-entrant call could be generated with a call path such as $A \to B \to C \to A$. Our tool searches for such mutually-recursive calls; it supports an arbitrarily-long calls path by using a recursive Datalog rule, making the analysis sound. Our query will match transactions only if such a call path has been executed, making the analysis complete. However, it is important to note that some re-entrant call might be part of the normal functioning of a contract, and not exploitation.

4.2 Unhandled Exceptions

When Solidity compiles contracts, methods to send Ether, such as send, are compiled into the EVM CALL instructions. We show an example of such a call and its instructions counterpart in Figure 8. If the address passed to CALL is an address, the EVM executes the code of the contract, otherwise it executes the necessary instructions to transfer Ether to the address. When the EVM is done executing, it pushes either 1 on the stack, if the CALL succeeded, or 0 otherwise.

To retrieve information about call results, we can therefore check for CALL instructions and use the value pushed on the stack after the call execution. The end of the call execution can be easily found by checking when the depth of the trace turns back to the value it had when the CALL instruction was executed; we save this information as $call_{result}(v, n)$ facts.

As shown in Figure 8b, the EVM uses the JUMPI instruction to perform conditional jumps. At the time of writing, this is the only instruction available to execute conditional control flow. We therefore mark all the values used as a condition in JUMPI as in_condition. We can then check for the unhandled exceptions by looking for call results, which never influence a condition using the query shown in Figure 7c.

Soundness and completeness. The analysis we perform to check for unhandled exceptions is sound and complete. All failed calls in the execution of the program will be recorded, while we accumulate facts about the execution. We then use a recursive Datalog rule to check if the call result is used directly or indirectly in a condition. This is essentially a runtime analysis version of the static analysis performed by the tools we analyze [34, 52].

4.3 Locked Ether

Although there are several reasons for funds locked in a contract, we focus on the case where the contract relies on an external contract, which does not exist anymore, as this is the pattern which had the largest financial impact on Ethereum [16]. Such a case can occur when a contract uses another contract as a library to perform some actions on its behalf. To use a contract in this way, the DELEGATECALL instruction is used instead of the CALL, as the latter does not preserve call data, such as the sender or the value.

The next important part is the behavior of the EVM when trying to call a contract which does not exist anymore. When a contract is destructed, it is not completely removed per-se, but its code is removed. When a contract tries to call a contract which has been destructed, the call is a no-op rather than a failure, which means that the next instruction will be executed and the call will be marked as successful. To find such patterns, we collect Datalog facts about all the value of the program counter before and after every DELEGATECALL instruction. In particular first mark the program counter value at which the call is executed — call_entry($i_1 \in \mathbb{N}$, $a \in A$). Then, using the same approach as for unhandled exceptions, we skip the content of the call and mark the program counter value at which the call returns — call_exit($i_2 \in \mathbb{N}$).

If the contract called does not exist anymore, $i_1 + 1 = i_2$ must hold. Therefore, we can use the Datalog query shown in Figure 7c to retrieve the address of the destructed contracts, if any.

Soundness and completeness. The approach we use to detect locked ether is sound and complete. All vulnerable contracts must have a DELEGATECALL instruction. If the issue is present and the call contract has indeed been destructed, it will always result in a no-op call. Our analysis records all of these calls and systematically check for the program counter before and after the execution, making the analysis sound and complete.

4.4 Transaction Order Dependency

The first insight to check for exploitation of transaction ordering dependency is that at least two transactions to the same contract must be included in the same block for such an attack to be successful. Furthermore, as shown in [38] or [52], exploiting a transaction ordering dependency vulnerability requires manipulation of the contract's storage.

The EVM has only one instruction to read from the storage, SLOAD, and one instruction to write the storage, SSTORE. In EVM, the location of the storage to use for both of these instructions is passed as an argument, and referred to as the storage *key*. This key is available on the stack at the time the instruction is called. We go through all the transactions of the contracts and each time we encounter one of these

Instruction	Description
SIGNEXTEND	Increase the number of bits
SLT	Signed lower than
SGT	Signed greater than
SDIV	Signed division
SMOD	Signed modulo

Figure 9: EVM instructions that operate on signed operands.

instructions, we record either $tx_sload(b \in \mathbb{N}, i \in \mathbb{N}, k \in \mathbb{N})$ or $tx_sstore(b \in \mathbb{N}, i \in \mathbb{N}, k \in \mathbb{N})$ where in each case b is the block number, i is the index of the transaction in the block and k is the storage key being accessed.

The essence of the rule to check for transaction order dependency issues is then to look for patterns where at least two transactions are included in the same block with one of the transactions writing a key in the storage and another transaction reading the same key. We show the actual rule in Figure 7c.

Soundness and completeness. Our approach to check for transaction order dependencies is sound but not complete. With the definition we use, for a contract to have a transaction order dependency it must have two transactions in the same block, which affect the same key in the storage. We check for all such cases, and therefore no false-negatives can exist. However, finding if there is a transaction order dependency requires more knowledge about how the storage is used and our approach could therefore result in false positives.

4.5 Integer Overflow

The EVM is completely untyped and expresses everything in terms of 256-bits words. Therefore, types are handled entirely at the compilation level, and there is no explicit information about the original types in any execution traces.

To check for integer overflow, we accumulate facts over two passes. In the first pass, we try to recover the sign and size of the different values on the stack. To do so, we use known invariants about the Solidity compilation process. First, any value which is used as an operand of one of the instructions shown in Figure 9 can be marked to be signed with <code>is_signed(v)</code>. Furthermore, <code>SIGNEXTEND</code> being the usual sign extension operation for two's complement, it is passed both the value to extend and the number of bits of the value. This allows to retrieve the size of the signed value. We assume any value not explicitly marked as signed to be unsigned. To retrieve the size of unsigned values, we use another behavior of the Solidity compiler.

To work around the lack of type in the EVM, the Solidity compiler inserts an AND instruction to "cast" unsigned integers to their correct value. For example, to emulate an uint8, the compiler inserts AND value 0xff. In the case of a "cast", the second operand m will always be of the form $m=16^n-1$, $n\in\mathbb{N}$, $n=2^p$, $p\in[1,6]$. We use this observation to mark values with the according type: uintN where $N=n\times 4$. Variables size are stored as size(v,n) facts.

During the second phase, we use the $inferred_signed(v)$ and $inferred_size(v, n)$ rules shown in Figure 7b to retrieve information about the current variable. When no information about the size can be inferred, we over-approximate it to 256 bits, the size of an EVM word. Using this information, we compute the expected

Contract address	Last transaction	Amount exploited
0xd654bdd32fc99471455e86c2e7f7d7b6437e9179	2016-06-10	5,885
0x675e2c143295b8683b5aed421329c4df85f91b33	2015-12-31	50.49
0x02b2101903eb6a51518e63e84b785180859fda9d	2016-04-10	43.41
0x8dd7693ead649aa369bc188049112fd7486a3b6b	2015-11-09	28.59
0x233820087a752349ee20daab1c18e0b7c546d3f6	2016-05-15	13.38
0xcd3e727275bc2f511822dc9a26bd7b0bbf161784	2017-03-25	10.34

Figure 10: RE: Contracts victim of re-entrancy attack.

value for all arithmetic instructions (e.g. ADD, MUL), as well as the actual result computed by the EVM and store them as Datalog facts. Finally, we use the query shown in Figure 7c to find instructions which overflow.

Soundness and completeness. Our analysis for integer overflow is neither sound nor complete. The types are inferred by using properties of the compiler using a heuristic which should work for most of cases but can fail. For example, if a contract contains code which yields AND value 0xff but value is an uint32, our type inference algorithm would wrongly infer that this variable is an uint8. Such error during type inference could cause both false positives and false negatives. However, this type of issue occurs only when the developer uses bit manipulation with a mask similar to what the Solidity compiler generate. We find that such a pattern is rare enough to not skew our data, and give an estimate the possible number of contracts which could follow such a pattern in Section 5.5.

5 ANALYSIS OF INDIVIDUAL VULNERABILITIES

As described in Section 3, the combined amount of Ether contained within *all* the flagged contracts exceeds 3 million ETH, worth 600 million USD. In this section, we present the results for each vulnerability, one by one; our results are have been obtained using the methodology described in Section 4; the goal is to show how much of this money is actually at risk.

For each vulnerability, we perform our analysis in two steps. First, we run our tool to automatically find the total amount of Ether at risk and report this number. This is the amount we use to later give a total upper bound across all vulnerabilities. In the second step, we manually analyze the contracts at risk to try to find interesting exploit patterns, if any. As analyzing all the contracts manually would be impractical, for each vulnerability we report all the contracts with a potential amount of Ether at risk greater than 10 ETH. We choose 10 ETH as a threshold because we think it is low enough to not miss any important attack, while being high enough to filter out most of the contracts. It is therefore appropriate for manual inspection effort. It is important to note that the filter used in this step affects in no way the total amount we report, and is used purely for practical purposes.

5.1 RE: Re-Entrancy

There are 4,336 contracts flagged as vulnerable to re-entrancy by [34, 38, 52], with a total of 411,604 transactions.

However, a common pattern when exploiting re-entrancy is to first send a transaction to an attacker contract, which will in

Contract address	Amount at risk
0x7011f3edc7fa43c81440f9f43a6458174113b162	52.90
0xb336a86e2feb1e87a328fcb7dd4d04de3df254d0	42.27
0x9e15f66b34edc3262796ef5e4d27139c931223f0	10.50

Figure 11: UE: Contracts affected by unhandled exceptions.

turn call the vulnerable contract. In such a case, the vulnerable contract is called in a transaction sent to another contract and there is no direct call to the vulnerable contract recorded on the blockchain. Therefore, we separately retrieve all the transactions which indirectly call the contracts to avoid missing any re-entrant call. This results in 34,742 more transactions, for a total of 446,346 transactions to analyze.

After running the analysis described in Section 4 on all the transactions, we found a total of 113 contracts which contain reentrant calls. To look for the amount at risk, we compute the sum of the Ether sent between two contracts in transactions containing re-entrant calls. The total amount of Ether exploited using reentrancy is of 6,075 ETH, which is considerable as it represents around 1,200,000 USD.

Manual analysis. To manually analyze the contracts, we look for contracts where at least 10 ETH has been lost. This gives us a total of *only* 6 contracts, as shown in Figure 10. Interestingly, one of these five potential attacks has a substantial amount of Ether at stake: 5,881 ETH, which corresponds to around 1,180,000 USD. This address has already been detected as vulnerable by some recent work focusing on re-entrancy [44]. It appears that the contract, which is part of the Maker DAO [10] platform, was found vulnerable by the authors of the contract, who themselves performed an attack to confirm the risk [2].

Sanity checking. As a sanity check, we also add to our set of analyzed contracts the address of a contract called SpankChain [6], which is known to recently have been compromised by a reentrancy attack. We confirm that our approach successfully marks this contract as having been the victim of a re-entrancy attack and correctly identifies the attacker contract.

5.2 UE: Unhandled Exceptions

There are 11,426 contracts flagged vulnerable to unhandled exceptions by [34, 38, 52]. This is a total of more than 3 million transactions, which is *an order of magnitude* larger than what we found for re-entrancy issues.

We find a total of 268 contracts where failed calls have not been checked for, which represent roughly 2% of the flagged contracts. The next goal is to find an upper bound on the amount of Ether at risk because of these unhandled exceptions. We assume that the upper bound on the money at risk is the minimum value of the balance of the contract at the time of the unhandled exception and the total of Ether which have failed to be sent. More formally, we note $\{f_1^{(a)}, \cdots, f_n^{(a)}\}$ the set of transactions with unhandled exceptions for an address a. $\{b_1^{(a)}, \cdots, b_n^{(a)}\}$ are the respective blocks of each transaction. We can compute an upper bound of the Ether at risk for an address a using (1).

Contract address	Last send	Balance
0x7da82c7ab4771ff031b66538d2fb9b0b047f6cf9	2017-11-15	369,023
0x4a412fe6e60949016457897f9170bb00078b89a3	2018-01-25	4,000
0x90420b8aef42f856a0afb4ffbfaa57405fb190f3	2018-01-08	636.7
0x49edf201c1e139282643d5e7c6fb0c7219ad1db7	2017-05-20	44.23
0x40a05d4ce308bf600cb275d7a3e9113518f59c54	2017-09-11	39.48

Figure 12: LE: Top inactive contracts flagged with locked Ether funds (The send date is *from* the contract).

$$upper_bound(a) = \sum_{i=1}^{n} \min \left\{ f_i^{(a)}, \text{balance} \left(a, b_i^{(a)} \right) \right\}$$
 (1)

We can then sum the upper bound of each address to obtain a total upper bound. This gives us a total of 141.08 Ether at risk for unhandled exceptions.

Manual analysis. We now look at all the contracts with more than 10 ETH at risk, which yields a total of 3 contracts. We summarize their addresses and the amount at risk in Figure 11.

Investigation of the contract at 0x7011f3edc7fa43c81440f9f43a6458174113b162:

The contract 0x7011f3edc7fa43c81440f9f43a6458174113b162 has failed to send a total of 52.90 Ether and currently still holds a balance of 69.3 Ether at the time of writing. After investigation, we find that the contract is an abandoned pyramid scheme [5]. The contract has a total of 21 calls which failed, all trying to send 2.7 Ether, which appears to have been the reward of the pyramid scheme at this point in time. Unfortunately, the code of this contract was not available for further inspection but we conclude that there is a high chance that some of the users in the pyramid scheme did not correctly obtain their reward because of this issue.

5.3 LE: Locked Ether

There are 7,271 contracts flagged vulnerable to locked Ether by [52], [27], [43] and [34]. The 7,271 contracts hold a total value of more than 1 million ETH, which is worth around 200 million USD.

Self-destructed contracts. We first analyze the transactions of the contracts that could potentially be locked by conducting analysis at the bytecode-level. Our tool shows than *none* of the contracts are actually affected by the pattern we check for — i.e., dependency on a contract which had been destructed.

Parity wallet. Despite having been known for more than a year, contracts affected by the Parity wallet bug [16] were not flagged by the tools that we analyzed. As this is one of the most famous cases of locked Ether, we use the contracts as a sanity check to make sure our tool is detecting this issue correctly.

To find the contracts, we simply have to use the Datalog query for locked Ether in Figure 7c and insert the value of the Parity wallet address as argument *a*. Our results for contracts affected by the Parity bug indeed matches what others had found in the past [26], with the contract at address <code>0x3bfc20f0b9afcace800d73d2191166ff16540258</code> having as much as 306,276 ETH locked.

Contract address	First issue	Balance
0xbf4ed7b27f1d666546e30d74d50d173d20bca754	2016-07-21	5,774,963
0x755cdba6ae4f479f7164792b318b2a06c759833b	2016-10-21	344,206
0x3da71558a40f63b960196cc0679847ff50fad22b	2016-09-06	13,818
0xd79b4c6791784184e2755b2fc1659eaab0f80456	2016-05-03	2,013
0xf45717552f12ef7cb65e95476f217ea008167ae3	2016-03-15	1,064

Figure 13: TOD: Top contracts potentially victim of transaction ordering dependency attack.

Transaction pattern analysis. It is worth pointing out that some tools, such as MadMax [27], check for other types of issues, which could also lock Ether. To try to check for such issues ourselves, we search for contracts with high monetary value, which have been inactive for a notably long period of time to see whether Ether is indeed locked.

We find a total of 15 contracts, which follow this pattern. We show the 5 contracts with the highest balance in Figure 12. We manually inspect the top three contracts, which contain a substantial amount of Ether, as well as the contracts, which have never *sent* any Ether. These top three contracts are all implementing multi-sig wallets, which are typically used to store Ether for long periods of time, thus explaining the inactivity. After further manual inspection, we concluded that none of the contracts had been exploited, nor were exploitable.

The first contract, which never sent any Ether, at address 0x5a5eff38da95b0d58b6c616f2699168b480953c9 has its code publicly available. After inspection, it seems to be a "lifelog" and the fact it is not sending Ether seems to be there by-design; in other words, the funds are not locked. Although we were not able to inspect the other contract because its code was not available, we did not find any vulnerability report for this address.

5.4 TO: Transaction Order Dependency

There are 1,877 contracts flagged vulnerable to transaction ordering dependency by [38] and [34]. However, as 642 of these contracts have no transactions except for the contract creation transaction, we only analyze the remaining 1,235 contracts.

For this vulnerability type, we first filter the contracts by simply looking at the transactions, as many transactions are unlikely to affect the result of the analysis. Hence, we filter out all contracts that do not have *at least two transactions* within the same block, as transaction order dependency could not possibly have been exploited in such a case.

This already reduces the number of candidate contracts to only 229, which shows that more than 80% of the contracts which have been flagged were mostly inactive contracts. We then run the analysis that we described in Section 4 on the remaining contracts. This results in a total of 48 contracts left which could have been affected by transaction-order dependency.

To estimate the amount of Ether at risk, we simply sum up the total value of Ether sent, including by internal transactions, during all the flagged transactions. This gives a total of 189 ETH at risk for transaction-order dependency.

Manual analysis. For each contract, we find the block where transaction order dependency could have happened with the highest balance and select all contracts with a balance higher than 10

Contract address	First issue	Balance
0x2935aa0a2d2fbb791622c29eb1c117b65b7a9085	2015-10-08	3,197
0x709c7134053510fce03b464982eab6e3d89728a5	2016-12-20	195.6
0x6dfaa563d04a77aff4c4ad2b17cf4c64d2983dc8	2016-06-24	178.6
0x0096800019bf4eca0bed5a714a553ecf844884c5	2016-06-21	174.0
0x9f53cdb4ea5b205a2fcd079f54af7196b1288938	2016-06-29	106.5

Figure 14: IO: Top contracts potentially victim of integer overflows.

ETH. This gives us a total of 14 contracts. We show the addresses of the 5 contracts with the highest balance at the time of the issue in Figure 13. The *First issue* column is the date on which the transaction order issue had been seen for the first time. The *Balance* column is the balance of the contract at the time the first issue occurred. Looking at the date, it is clear that this issue has not been seen in the wild for a long time, at least within the range of the contracts flagged by the tools we analyzed. We manually investigated the top five contracts in the list but did not find *any* evidence of transaction order-related exploits.

5.5 IO: Integer Overflow

There are 2,472 contracts flagged vulnerable to integer overflow, which accounts for a total of more than 1 million transactions. We run the approach we described in Section 4 to search for actual occurrences of integer overflows.

It is worth noting that for integer overflow analysis we rely on properties of the Solidity compiler. To make sure that the contracts we analyze were compiled using Solidity, we fetched all the available source codes for contracts flagged as affected by integer overflow from Etherscan [8]. Out of 2,472 contracts, 945 had their source code available. All of the contracts with their source code available were written in Solidity. 59 were written in Solidity 0.2 or lower and 886 were written using Solidity 0.3 or higher.

Effects of our formulation. As mentioned in Section 4.5, some types of bit manipulation in Solidity contracts which could result in our type inference heuristic failing. We use the source codes we collected here to verify up to what extent this could affect our analysis. We find that bit manipulation by itself is already fairly rare in Solidity, with only 244 out of the 2,472 contracts we collected using any sort of bit manipulation. Furthermore, most of the contracts using bit manipulation were using it to manipulate a variable as a bit array, and only ever retrieved a single bit at a time. Such a pattern does not affect our analysis. We found only 33 contracts which used 0xFF or similar values, which could actually affect our analysis. This represents about 1.3% of the number of contracts for which the source code was available.

We find a total of 141 contracts with transactions where an integer overflow might indeed have occurred. To find the amount of Ether at stake, we analyze all the transactions which resulted in integer overflows. We approximate the amount by summing the total amount of Ether transferred in and out during a transaction containing an overflow. We find that the total of Ether at stake is 2,661 ETH. This is most likely an over-approximation but we use this value as our upper-bound.

Manual analysis. We first inspect some of the results we obtained a little further to get a better sense of what kind of cases lead to

overflows. We find that a very frequent cause of overflow is rather underflow of unsigned values.

Investigation of the contract at 0xdcabd383a7c497069d0804070e4ba70ab6ecdd51:

This contract was flagged positive to both unhandled exceptions and integer overflow by our tool. After inspection, it seems that at block height 1,364,860, the owner tried to reduce the fees but the unsigned value of the fees overflowed and became a huge number. Because of this issue, the contract was then trying to send large amount of Ether. This resulted in failed calls which happened not to be checked, hence the flag for unhandled exceptions.

Next, we look for contracts which had at least 10 ETH at the time of the overflow. We find a total of 23 contracts with this condition. We show the 5 contracts with the highest balance at the time of the overflow in Figure 14. The top contract in this list had a large balance at the time of the issue but it had already been self-destructed and we could therefore not inspect further. We did not, however, find any report mentioning this contract.

5.6 Summary

We summarize all our findings, including the number of contracts originally flagged, the amount of Ether at stake, and the amount actually exploited in Figure 15. The Contracts exploited column indicates the number of contracts which we believe to have been exploited and Contracts with Ether exploited refers to the number of contracts which contained at least 10 ETH at the time of exploitation. The Exploited Ether column shows the maximum amount of Ether that potentially could have been exploited and the next column shows the percentage this amount represents compared to the total amount at stake. The Total row accounts for contracts flagged with more than one vulnerability only once.

Overall, we find that the situation is *many orders of magnitude* less critical than most papers we review in Section 2 make it sound. The amount of money which was actually exploited is *not even remotely close* to the 5 billion USD [27] or even 500 million [34] USD, which were supposedly at risk.

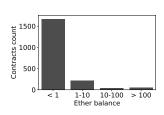
Below, we summarize the main takeaways regarding each vulnerability we examined in this paper.

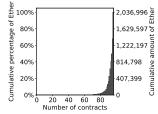
Re-Entrancy. This is by far the most dangerous issue of all the ones we have analyzed, accounting for more than 65% of the total exploitations we observed. Although some proposals have been made to add a protection against this in the Solidity compiler [41, 48], we think that this issue should instead be handled at the interpreter level. Sereum [44] is an attempt to do this, and we think that such an addition would help make the Ethereum smart contracts ecosystem considerably more secure.

Unhandled Exceptions. As we can see in Figure 15, the amount of Ether *actually exploited* is very low compared to other vulnerabilities. Although unhandled exceptions used to be a real issue a few years ago, the Solidity compiler has since then made a lot of progress and any unchecked call to send, or similar pattern, now generates a warning at compile time. Therefore, we think that this issue has already been given enough attention and is handled well

Vulnerable				Exploited contracts			Exploited Ether	
Vuln.	Vulnerable	Total Ether	Transactions	Contracts	Contracts w/Ether	% w/Ether	Exploited	% of Ether
	contracts	at stake	analyzed	exploited	exploited	exploited	Ether	exploited
RE	4,336	1,027,585	411,604	113	6	0.14%	6,075	0.59%
UE	11,426	208,528	3,063,510	268	6	0.053%	141.1	0.068%
LE	7,271	1,135,313	8,550,292	0	0	0%	0	0%
TO	1,877	207,926	2,817,260	57	14	0.75%	189.0	0.091%
Ю	2,472	508,750	1,214,206	141	23	0.93%	2,661	0.52%
Total	21,270	3,088,102	16,056,872	504	49	0.0023%	9,066	0.29%

Figure 15: Understanding the exploitation of potentially vulnerable contracts.





- (a) Ether held in analyzed contracts with non-zero balance
- (b) Cumulative Ether held in the 96 analyzed contracts with more than 10 ETH.

Figure 16: Ether held in contracts: describing the distribution.

enough by the current generation of development tools, at least as it pertains to EVM contracts developed in Solidity.

Locked Ether. In this work, we mainly cover locked Ether caused by self-destructed library contracts, such as the one seen by the Parity wallet bug [16]. This particular issue has generated much attention by the community because of the amount of money involved. However, we believe that the pattern of delegating to a library is a common pattern when working with smart contracts, and that such contracts should not be treated as "vulnerable". Indeed, we show that this issue did not happen even a single time in our dataset. We believe that the focus should lie on keeping library contracts safe opposed to not using them at all.

Transaction Order Dependency. While this vulnerability has received a lot of focus in the academic community [38, 52] it has rarely been observed in reality. Our data confirms that this is very rarely exploited in practice. One of the reason is that this vulnerability is simply quite hard to exploit: in order to reliably arrange the order of the transactions, the attacker needs to be a miner. Given that almost 85% of Ether is mined by mining pools [49], it would require the mining pool operator to be dishonest. Pragmatically speaking, there is generally not enough financial incentives for mining pools to perform such an attack, in part because more lucrative alternative opportunities may exist for them if they are dishonest.

Integer Overflow. While this remains a very common issue with smart contracts, it is both difficult to automatically detect such issues and to evaluate the impact that they may actually have. The Solidity compiler now emits warning or errors for cases working directly on integral literals but does not check anything else than that. A case as simple as $\mathbf{uint8}\ n=255;\ n++;$ would not get any warnings or errors. We believe that this is a place where static analysis tools such as [34] or [27] can be very valuable to avoid smart contracts that fail in unexpected ways.

6 DISCUSSION

In this section, we discuss some of the factors we think might be impacting the actual exploitation of smart contracts.

We believe that a major reason for the difference between the number of vulnerable contracts reported and the number of contracts exploited is the distribution of Ether among contracts. Indeed, only about 2,000 out of the 21,270 contracts in our dataset contain Ether, and most of these contracts have a balance lower than 1 ETH. We show the balance distribution of the contracts containing Ether in our dataset in Figure 16a. Furthermore, the top 10 contracts hold about 95% of the total Ether. We show the cumulative distribution of Ether within the contracts containing more than 10 ETH in Figure 16b. This shows that, as long as the top contracts cannot be exploited, the total amount of Ether that is actually at stake will be nowhere close to the upper bound of "vulnerable" Ether.

To make sure this fact generalizes to the whole Ethereum blockchain and not only our dataset, we fetch the balances for all existing contracts. This gives a total of 15,459,193 contracts. Out of these, we find that only 463,538 contracts have a non-zero balance, which is merely 3% of all the contracts. Out of the contracts with a non-zero balance, the top 10 contracts account for 54% of the total amount of Ether, the top 100 for 92% and the top 1000 for 99%. This shows that our dataset follows the same trend as the Ethereum blockchain in general: a very small amount of contracts hold most of the wealth.

Manual inspection of high value contracts in our dataset. We decide to manually inspect the top 6 contracts — i.e contracts with the highest balances at the time of writing — marked as vulnerable by any of the tools in our dataset. We focused on the top 6 because it happened to be the number of contracts which currently hold more than 100,000 ETH. These contracts hold a total of 1,695,240 ETH, or 83% of the total of 2,037,521 ETH currently held by all the contracts in our dataset. We give an overview of the findings here and a more in-depth version in Appendix A.

Investigation of the contract at 0xde0b295669a9fd93d5f28d9ec85e40f4cb697bae:

The source code for this contract is not directly available. However, we discovered that this is the multi-signature wallet of the Ethereum foundation [1] and that its source code is available on GitHub [3]. We inspect the code and find that the only calls taking place require the sender of the message to be an owner. This by itself is enough to prevent any re-entrant call, as the malicious contract would have

Address	Ether balance	Deployment date	Flagged vulnerabilities
0xde0b295669a9fd93d5f28d9ec85e40f4cb697bae	649,493	2015-08-08	Oyente: RE
0x7da82c7ab4771ff031b66538d2fb9b0b047f6cf9	369,023	2016-11-10	MadMax: LE, Zeus: IO
0x851b7f3ab81bd8df354f0d7640efcd7288553419	189,232	2017-04-18	MadMax: LE
0x07ee55aa48bb72dcc6e9d78256648910de513eca	182,524	2016-08-08	Securify: RE
0xcafe1a77e84698c83ca8931f54a755176ef75f2c	180,300	2017-06-04	MadMax: LE
0xbf4ed7b27f1d666546e30d74d50d173d20bca754	124,668	2016-07-16	Securify: TO, UE; Zeus: LE, IO

Figure 17: Top six most valuable contracts flagged as vulnerable by at least one tool.

to be an owner, which does not make sense. Furthermore, although the version of Oyente used in the paper reported the re-entrancy, more recent versions of the tool did not report this vulnerability anymore. Therefore, we safely conclude that the re-entrancy issue was a false alert.

We were able to inspect 4 of the 5 remaining contracts. The contract at address <code>0x07ee55aa48bb72dcc6e9d78256648910de513eca</code> is the only one for which we were unable to find any information. The second, third and fifth contracts in the list were also multi-signature wallets and exploitation would require a majority owner to be malicious. For example, for Ether to get locked, the owners would have to agree on adding enough extra owners so that all the loops over the owners result in an out-of-gas exception. The contract at address <code>0xbf4ed7b27f1d666546e30d74d50d173d20bca754</code> is a contract known as <code>WithDrawDAO[4]</code>. We did not find any particular issue, but it does use a delegate pattern which explains the locked Ether vulnerability marked by Zeus.

We present a thorough investigation of the high-value contracts in Appendix A. Overall, all the contracts from Figure 17 that we could analyze seemed quite secure and the vulnerabilities flagged were definitely not exploitable. Although there are some very rare cases that we present in Section 7 where contracts with high Ether balances are being stolen, these remain exceptions. The facts we presented up to now help us confirm that the amount of Ether at risk on the Ethereum blockchain is nowhere as close as what is claimed [27, 34].

7 RELATED WORK

Some major smart contracts exploits have been observed on Ethereum in recent years [46]. These attacks have been analyzed and classified [13] and many tools and techniques have emerged to prevent such attacks [25, 29]. In this section, we will first provide details about two of the most prominent historic exploits and then present existing work aimed at increasing smart contract security.

7.1 Motivating Large-scale Exploits

TheDAO exploit. TheDAO exploit [46] is one of the most infamous bugs on the Ethereum blockchain. Attackers exploited a re-entrancy vulnerability [13] of the contract which allowed for the draining of the contract's funds. The attacker contract could call the function to withdraw funds in a re-entrant manner before its balance on TheDAO was reduced, making it indeed possible to freely drain funds. A total of more than 3.5 million Ether were

drained. Given the severity of the attack, the Ethereum community finally agreed on hard-forking.

Parity wallet bug. The Parity Wallet bug [16] is another prominent vulnerability on the Ethereum blockchain which caused 280 million USD worth of Ethereum to be frozen on the Parity wallet account. It was due to a very simple vulnerability: a library contract used by the parity wallet was not initialized correctly and could be destructed by anyone. Once the library was destructed, any call to the Parity wallet would then fail, effectively locking all funds.

7.2 Analyzing and Verifying Smart Contracts

There has been a lot of efforts in order to prevent such attacks and to make smart contracts more secure in general. We will here present some of the tools and techniques which have been presented in the literature.

Oyente. Oyente [38] is one of the first tools which has been developed to analyze smart contracts. It uses symbolic execution to check for the following vulnerabilities: transaction ordering dependency, re-entrancy and unhandled exceptions. The tool takes as input the bytecode of a smart contract and a state of the Ethereum blockchain. It emulates the EVM and explores the different paths of the contracts. It then uses the Z3 SMT solver [24] to decide the satisfiability of conditions which would make the program vulnerable in the current path.

ZEUS. ZEUS [34] is a static analysis tool which can check for a vast range of vulnerabilities such as re-entrancy, unhandled exceptions, integer overflows, transaction order dependency and others. Unlike Oyente, it operates on the high-level representation of the smart contract written in Solidity and not on the bytecode. It first generates a XACML-styled [47] policy from the Solidity abstract syntax tree (AST) which can be further customized by the user. A policy could for example enforce that the amount to send to a user is always smaller or equal to his balance. It then transpiles the policy and the Solidity contract code to LLVM bitcode [36] and finally uses constrained Horn clauses [15, 39] over the LLVM bitcode to check that the policy is respected.

Maian. Maian [43] is also a tool to analyze contracts but instead of using static analysis to find bugs in the contract, it tries to find vulnerabilities across long sequences of invocations of a contract. It focuses mainly on finding three types of vulnerabilities: contracts that can be removed from the blockchain by anyone, contracts which can lock funds by being unable to send Ether, and contracts which can "leak" Ether to a user they have never interacted with. The tool performs symbolic analysis across multiple executions

of the contract in order to find traces that violate the security properties being checked.

SmartCheck.[51] is a tool which, as ZEUS, analyzes the high-level solidity source code of the smart contract to find vulnerabilities. It is also able to find a wide range of vulnerabilities such as re-entrancy, unhandled exceptions, locked Ether, integer overflows and many more. Not unlike ZEUS, SmartCheck transforms the solidity contract in an intermediate representation (IR) but uses an XML-based. It then uses XPaths patterns to check for security properties in the contract IR. This simple approach makes the system efficient but loses precision for vulnerabilities which cannot naturally be expressed as XPaths, such as re-entrancy.

Securify. Securify [52] is a static analysis tool which checks security properties of the EVM bytecode of smart contracts. The security properties are encoded as patterns written in a domain-specific language, and checked either for compliance or violation. To analyze the contract, Securify first transforms the EVM bytecode into a stackless static-single assignment form. It then infers semantic facts from the contract such as data and control-flow dependencies which it encodes in stratified Datalog [53]. It finally interprets the security patterns to check for their violation or compliance by querying the inferred facts.

ContactFuzzer. Unlike the previous tools, ContractFuzzer [33] uses dynamic analysis and more particularly fuzzing to find vulnerabilities in smart contracts. It is capable of detecting a wide range of vulnerabilities such as re-entrancy, locked Ether or unhandled exceptions. To operate, ContractFuzzer generates inputs for the contracts by looking at their Application Binary Interface (ABI). It uses an instrumented EVM to run the fuzzed contracts and records the executed instructions during fuzzing and, analyzes them later on to find vulnerabilities in the contract. Due to the dynamic analysis nature of the detection, this tool has a substantially higher true positive rate than the static analysis tools previously presented.

Vandal. Vandal [17] is a static analysis tool which is in many ways similar to Securify [52]. Vandal also analyzes the EVM bytecode by decompiling it and encodes properties of the smart contract into Datalog. The tool is able to detect vulnerabilities, such as reentrancy and unhandled exceptions, and can easily be extended by writing queries to check for other types of vulnerabilities in Datalog.

MadMax. MadMax [27] also statically analyzes smart contracts but focuses mainly on vulnerabilities related to gas. It is the first tool to detect so-called unbounded mass operations where a loop is bounded by a dynamic property such as the number of users, causing the contract to always run out of gas passed a certain number of users. MadMax is built on top of the decompiler implemented by Vandal and also encodes properties of the smart contract into Datalog. It is performant enough to analyze all the contracts of the Ethereum blockchain in only 10 hours.

Gasper. Gasper [19] is also a static analysis tool focused on gas but instead of looking for vulnerabilities it searches for patterns which might be costly to the contract owner in terms of gas. Gasper builds a control flow graph from the EVM bytecode and uses symbolic execution backed by an SMT solver to explore the different paths that might be taken. Gasper looks for patterns such as dead code or

expensive operations in loops to help contract developers reduce gas cost.

Sereum. Sereum [44] focuses on detecting and preventing exploitation at runtime rather than trying to detect vulnerabilities beforehand. It proposes a modification to the Go Ethereum client which is able to detect and reject re-entrancy exploits and could also handle other exploits. It first performs taint analysis to infer properties about variables in the contract and then checks that tainted variables are not used in a way which would violate security properties. For re-entrancy, it uses this technique to check that no variable accessing the contract storage is used in a reentrant call.

Formal verification. There has also been some efforts to formally verify smart contracts. [31] is one of the first efforts in this direction and defines the EVM using Lem [42], which allows to generate definitions for theorem provers such as Coq [14]. [28] presents a complete small-step semantics of EVM bytecode and formalizes it using the F^* proof assistant [50]. A similar effort is made in [30] to give an executable formal specification of the EVM using the K Framework [45].

teEther. teEther [35] is different from the previous works presented, as it does not try to protect contracts but rather to actively find an exploit for them. It first analyzes the contract bytecode to look for critical execution paths. Critical paths are execution paths which may result in the contract sending money to an arbitrary address, the contract being self-destructed or the contract delegating control to an arbitrary address. To find these paths, it uses an approach close to Oyente [38], first using symbolic execution and then the Z3 SMT solver [24] to solve path constraints.

8 CONCLUSION

In this paper, we surveyed the 21,270 vulnerable contracts reported by six recent academic projects. We proposed a Datalog-based formulation for performing analysis over EVM execution traces and used it to analyze a total of more than 16 million transactions executed by these contracts. We found that at most 504 out of 21,270 contracts have been subjected to exploits. This corresponds to at most 9,066 ETH (1.8 million USD), or only 0.29% of the 3 million ETH (600 million USD) claimed to be at risk. From what we can infer by analyzing the blockchain, a majority of Ether is held by only a small number of contracts. Further, the vulnerabilities reported on these contracts are either false positives or not applicable in practice, making exploitation significantly less attractive.

Our results suggest that the impact of vulnerable smart contracts on the Etherium blockchain had been exaggerated. We hypothesize that the reasons for the significant gap between vulnerable and exploited are multi-fold: lack of appetite for exploitation, the sheer difficulty of executing some exploits, fear of attribution, other more attractive exploitation options, etc.

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A INVESTIGATIONS

In this appendix, we will give a more in-depth security analysis of the top value contracts we presented in Section 6. In particular, we will focus on the vulnerabilities detected by the different tools and show how it could, or not, affect the contract.

0xde0b295669a9fd93d5f28d9ec85e40f4cb697bae

This contract has been flagged as being vulnerable to re-entrancy by Oyente. For a contract to be victim of a re-entrancy attack, it must CALL another contract, sending it enough gas to be able to perform the re-entrant call. In Solidity terms, this is means that the contract has to invoke address.call and not explicitly set the gas limit. By looking at the source code [3], we find 2 such instances: one at line 352 in the execute function and another at line 369 in the confirm function. The execute is protected by the onlyowner modifier, which requires the caller to be an owner of the wallet. This means that for a re-entrant call to work, the malicious contract would need to be an owner of the wallet in order to work. The confirm function is protected by the onlymanyowners modifier, which requires at least n owners to agree on confirming a particular transaction before it is executed, where n is agreed upon at contract creation time. Furthermore, confirm will only invoke address.call on a transaction previously created in the execute function.

0x7da82c7ab4771ff031b66538d2fb9b0b047f6cf9

This is the contract for multi-signature wallet of the Golem project [9] and uses a well-known multi-signature implementation. We use the source code available on Etherscan to perform the audit. This contract is marked with two vulnerabilities, locked Ether by MadMax and integer overflow by Zeus.

We first focus on the locked Ether, which is due to an unbounded mass operation [27]. An unbounded mass operation is flagged when a loop is bounded by a variable which value could increase, for example the length of an array. This is because if the number of iteration becomes too large the contract would run out of gas every time, which could indeed result in locked funds. Therefore, we check all the loops in the contract. There are 8 loops in the code, at lines 43, 109, 184, 215, 234, 246, 257 and 265. All the loops except the ones at lines 257 and 265 are bound by the total number of owners. As owner can only be added if enough existing owners agree, running out-of-gas when looping on the number of owners cannot happen unless the owners agree. The loops at lines 257 and 265 are in a function called filterTransactions and are bounded by the number of transactions. The function filterTransactions is only used by two external getters, getPendingTransactions and getExecutedTransactions and could therefore not result the Ether getting lock. However, as the number of transactions is ever increasing, if the owner submit enough transactions, the filterTransactions function could indeed need to loop over too many transactions and end up running out-of-gas on every execution. We estimate the amount of gas used in the loop to be around 50 gas, which means that if the number of transactions reaches 100,000, it would required more than 5,000,000 gas to list the transactions, which would probably make all calls run out of gas. The contract has only received a total of 281 transactions in more

than 3 years so it is very unlikely that the number of transactions increase this much. Nevertheless, this is indeed an issue which should be fixed, most likely by limiting the maximum numbers of transactions that can be retrieved by getPendingTransactions and getExecutedTransactions.

Next, we look for possible integer overflows. All loops discussed above use an uint as a loop index. In Solidity, uint is a uint256 which makes it impossible to overflow here, given than neither the number of owners or transactions could ever reach such a number. The only other arithmetic operation performed is owners.length - 1 in the function removeOwner at line 103. This function checks that the owner exists, which means that owners.length will always be at least 1 and owners.length can therefore never underflow.

0x851b7f3ab81bd8df354f0d7640efcd7288553419

This contract is also a multi-sig wallet, this time owned by Gnosis Ltd.² We use the source code available on Etherscan to perform the audit. The contract looks very similar of the one used by 0x7da82c7ab4771ff031b66538d2fb9b0b047f6cf9 and has also been marked by MadMax as being vulnerable to locked Ether because of unbounded mass operations. Again, we look at all the loops in the contract and find that as the previous contract, it loops exclusively on owners and transactions. As in the previous contract, we assume looping on the owners is safe and look at the loops over the transactions. This contract has two functions looping over transactions, getTransactionCount at line 303 and getTransactionIds at line 351. Both functions are getters which are never called from within the contract. Therefore, no Ether could ever be locked because of this. Unlike the previous contract, getTransactionIds allows to set the range of transactions to return, therefore making the function safe to unbounded mass operations. However, getTransactionCount does loop over all the transactions, and as before, could therefore become unusable at some point, although it is highly unlikely.

0xcafe1a77e84698c83ca8931f54a755176ef75f2c

This contract is again a multi-sig wallet, this time owned by the Aragon project³. We also use the contract published on Etherscan for the audit. It appears that the source code for this contract is exactly the same as the one of 0x851b7f3ab81bd8df354f0d7640efcd7288553419 except that it is missing a contract called MultiSigWalletWithDailyLimit. This contract was also flagged as being at risk of unbounded mass operations by MadMax, the conclusions are therefore exactly the same as for the previous contract.

0xbf4ed7b27f1d666546e30d74d50d173d20bca754

This contract is the only one which is very different from the previous ones. It is the WithdrawDAO contract, which has been created for users to get their funds back after The DAO incident [46]. We use the source code from Etherscan to audit the contract. This contract has been flagged with several vulnerabilities: Securify

²https://gnosis.io/

³https://aragon.org/

flagged it with transaction order dependency and unhandled exception, while Zeus flagged it with locked ether and integer overflow. The contract has two very short functions: withdraw which allows users to convert their The DAO tokens back to Ether, and the trusteeWithdraw which allows to send funds which cannot be withdrawn by regular users to a trusted address. We first look at the transaction order dependency. As any user will only ever be able to receive the amount of tokens he possesses, the order of the transaction should not be an issue in this contract. We then look at unhandled exceptions. There is indeed a call to send in the trusteeWithdraw which is not checked. Although it is not particularly an issue here, as this does not modify any other state, an error should probably be thrown if the call fails. We then look at locked ether. The contract is flagged with locked ether because of what Zeus classifies as "failed send". This issue was flagged because if the call to mainDAO. transferFrom always raised, then the call to msg.sender.send would never be reached, indeed preventing from reclaiming funds. However, in this context, mainDAO is a trusted contract and it is therefore safe to assume that mainDAO. transferFrom will not always fail. Finally, we look at the integer overflow issue. The only place where an overflow could occur is in trusteeWithdraw at line 23. This could indeed overflow without some assumptions on the different values. For this particular contract, the following assumptions are made.

```
\label{eq:this.balance} this.balance + mainDAO.balanceOf(this) \geq mainDAO.totalSupply() \\ \\ mainDAO.totalSupply() > mainDAO.balanceOf(this) \\
```

As long as these assumptions hold, which was the case when the contract was deployed, this expression will never overflow. Indeed, if we note t the time before the first call to trusteeWithdraw and t+1 the time after the first call, we will have

```
\begin{split} \text{this.balance}_{t+1} &= \text{this.balance}_{t} - \big( \text{this.balance}_{t} + \\ &\quad \text{mainDAO.balanceOf(this)} - \text{mainDAO.totalSupply()} \big) \\ &= -\text{mainDAO.balanceOf(this)} + \text{mainDAO.totalSupply()} \end{split}
```

which means that every subsequent call will compute the following.

```
\label{eq:this.balance} \begin{split} & \text{this.balance}_{t+1} + \text{mainDAO.balanceOf(this)} - \text{mainDAO.totalSupply()} \\ & = -\text{mainDAO.balanceOf(this)} + \text{mainDAO.totalSupply()} + \\ & \text{mainDAO.balanceOf(this)} - \text{mainDAO.totalSupply()} \\ & = 0 \end{split}
```

This will always result in sending 0 and will therefore not cause any overflow. If some money is newly received by the contract, the amount received will be transferred the next time trusteeWithdraw is called.