

Title of the Thesis

Master's Thesis by

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I hereby declare that the work presented in this thesis is entirely my own. I confirm that I specified all employed auxiliary resources and clearly acknowledged anything taken verbatim or with changes from other sources. I further declare that I prepared this thesis in accordance with the rules for safeguarding good scientific practice at Karlsruhe Institute of Technology (KIT).

Karlsruhe, xx MONTH 20XX

.....
(Michele Massetti)

Abstract

English abstract.

Zusammenfassung

Deutsche Zusammenfassung

Contents

List of Figures	xi
List of Tables	xiii
1 Introduction	1
1.1 Style and Typography	1
1.1.1 Sections	1
1.1.2 Spacing and Indentation	1
1.1.3 Bibliography and References	2
1.1.4 Floats (Figures, Tables, ...)	2
1.1.5 Example: Mathematics	3
2 Preliminary Knowledge	5
3 Vulnerabilities and Real-world exploits in Solidity Smart Contracts	7
3.1 Most common Vulnerabilities	7
3.1.1 Denial Of Services	7
3.2 Real world Exploits	8
3.2.1 XSURGE on BSC Chain	8
4 Analysis Tools	11
4.1 Typologies of Tools	11
4.2 Tools for analysing properties specified by user	11
4.2.1 Celestial	11
4.2.2 SmartPulse	11
4.2.3 VeriSol	11
4.2.4 Echidna	11
4.2.5 Solc-Verify	13
4.3 Tools without specification	14
4.3.1 SmartTest	14
4.3.2 Slither	15
4.3.3 Mythril	15
4.3.4 Maian	16
4.3.5 Securify	16
4.3.6 ContractLarva	16
5 First Content Chapter	17
5.1 First Section	17
5.1.1 A Subsection	17

5.2	Second Section	17
6	Second Content Chapter	19
6.1	First Section	19
6.2	Second Section	19
7	Evaluation	21
7.1	First Section	21
7.2	Second Section	21
7.3	Third Section	21
8	Conclusion	23
	Bibliography	25
A	Appendix	27
A.1	First Appendix Section	27

List of Figures

1.1	KIT logo	2
4.1	Echidna architecture	12
A.1	A figure	27

List of Tables

1.1 A table 3

1 Introduction

This is the thesis template of the *Application-oriented Formal Verification* research group at the Institute of Information Security and Dependability (KASTEL) at KIT. It was adapted from the thesis template of the SDQ research group. Hence, for more information on the formatting of theses, you can still refer to <https://sdqweb.ipd.kit.edu/wiki/Ausarbeitungshinweise> as well as your advisor.

In the following, we present some general recommendations. These are non-binding, however, and should be harmonized with your advisor.

1.1 Style and Typography

It is advisable to choose and stick to a specific style guide for your thesis' language. Especially for the English language, there are some commonly agreed style guides. At times, the recommendations of one guide contradict the ones from another. Therefore, be consistent in your choice! The following two style guides are the most common ones:

- *New Oxford Style Manual* for British English
- *The Chicago Manual of Style* for US-American English

If you are also interested in (some of the) choices considering the typography, you may consult *The Elements of Typographic Style* which comes with a plethora of explanations, many of them already baked into \TeX and \LaTeX .

1.1.1 Sections

- Avoid single sections. If you have, e.g., a section “1.1” then you should also have at least a section “1.2”.
- Avoid having too small chapters or sections. Rather use `\paragraph` to divide text into smaller chunks.

1.1.2 Spacing and Indentation

For separating parts of text in \LaTeX , please use two line breaks. They will then be set with correct indentation. Do *not* use:

- `\\`
- `\parskip`
- `\vskip`

or other commands to manually insert spaces, since they break the layout of this template.



Figure 1.1: KIT logo

1.1.3 Bibliography and References

The bibliography in this template is already configured. This template is based on `biblatex` and `biber`, which is preferred over the outdated `BBTeX` software. `Biber` is a bibliography processor, and thus reads both the `aux`- and `bib`-files to produce the bibliography. `Biber` should come with your `TeX` distribution. Please adjust your build environment if necessary (see <https://sdqweb.ipd.kit.edu/wiki/BibTeX-Literaturlisten#biblatex.2Fbiber>)

For referencing literature in your bibliography, you should use the following commands:

- `\citet{KeyBook2016}`: Ahrendt et al. (2016)
Use this when you want to explicitly talk about a publication within a sentence. This is especially sensible for publications that are of high relevance for your thesis.
- `\citep{KeyBook2016}`: (Ahrendt et al., 2016)
Use this for (implicit) references to indicate that what you wrote is based on the cited reference. The command can also be used for multiple references within one citation, separated by a comma (directly inside the command).

1.1.4 Floats (Figures, Tables, ...)

- Do not inline float environments such as tables, figures, listings, algorithms etc. Floats are elements that are automatically placed and optimized when compiling the document.
- Avoid using the options `H` or `h` for positioning floats.
- A reference: The KIT logo is displayed in Figure 1.1. (Use `\autoref{label}` for easy referencing.)
- **For tables:** The `booktabs` package offers nicely typeset tables, as in Table 1.1.
- For algorithms: Algorithms can be nicely set by a variety of packages, e.g., `algorithm2e`, `algorithmicx`, etc.
- For source code: The `lstlistings` or `minted` package offer nicely typeset and colored listings for your source code.

abc	def
ghi	jkl
123	456
789	0AB

Table 1.1: A table

1.1.5 Example: Mathematics

One of the nice things about the Linux Libertine font is that it comes with a math mode package.

$$f(x) = \Omega(g(x)) \ (x \rightarrow \infty) \Leftrightarrow \limsup_{x \rightarrow \infty} \left| \frac{f(x)}{g(x)} \right| > 0$$

For *definitions*, *theorems*, *proofs*, etc., please use the respective environments.

Theorem 1 (Pythagoras's theorem). *In a right-angled triangle, the following holds:*

$$a^2 + b^2 = c^2 \ .$$

2 Preliminary Knowledge

3 Vulnerabilities and Real-world exploits in Solidity Smart Contracts

3.1 Most common Vulnerabilities

3.1.1 Denial Of Services

The article *What is a denial-of-service attack* (2022) of CloudFare, proposes a definition of denial-of-service (DoS) attack. It is a type of cyber attack in which an attacker aims to render a computer or a informatic service (logical or phisical) unavailable to its intended users by interrupting the device's normal functioning.

In Solidity contetext, DoS consists of attacks where users can leave the contract inoperable for a small period of time, or in some cases, permanently. It represents a cathegory of attacks, consequently it is not possible to classify a specifc vulnerability or methodology for exploiting a thread.

As an example of this class of attack, I selected the smart contract presented by Arends (2022). It allows the user to place a bid to the contract. If it is the highest bid, it sends the previous leader the current bid and set the leader to the sender with the new highest bid. The vulnerability relies on line 12 (Referenceslst:DosContract1): the require condition is respected if the transaction which refunds the old leader doesn not revert. An attacker can exploit this vulnerability, creating a smart contract which cannot receive ether. Then it intacts with the vulnerable contract, becoming the leader. When the vulnerable tries to refund the attacker one, it will always revert because it cannot receive ether and no one could become the new leader.

```
1  pragma solidity ^0.8.0;
2
3  /**
4   * @title VulnerableContract
5   * @dev This contract is vulnerable to a denial of service (DoS) attack
6   */
7  contract VulnerableContract {
8      address payable leader;
9      uint256 public highestBid;
10
11     function bid() external payable {
12         require(msg.value > highestBid);
13
14         // Refund the old leader, if it fails then revert
15         require(leader.send(highestBid));
16
17         leader = payable(msg.sender);
```

```
18     highestBid = msg.value;
19 }
20
21 /// Helper function to check leader
22 function getLeader() external view returns (address) {
23     return leader;
24 }
25 }
```

Listing 3.1: Dos Vulnerable Contract.

Another example is

3.2 Real world Exploits

Real-world exploits that have happened in the recent years.

3.2.1 XSURGE on BSC Chain

The *xSurge Assets* (2021)'s whitepaper provides a presentation of the ecosystem. It is described as a great DeFi investing idea based on proprietary pricing algorithms embedded in the Surge Token Variants' contracts. Surge Token Variants each have their own Market Maker, allowing them to trade continuously and outlast both centralised and decentralised exchanges. The strategy is to reward long-term holding by increasing a holder's claim of the backing asset. Each Surge Token utilizes a built-in contract exchange system that renounces the need for a traditional liquidity pool. Both assets are stored within the contract itself, rather than a liquidity pool pair of the backing asset to the token using a traditional market maker method for exchange and price calculation.

One of the Surge Token is SurgeBNB, the one which is my focus of analysis. *XSURGE on the BSC Chain was Attacked by Lightning Loans — A Full Analysis* (2021) explains in depth how the attack to this contract occurred. The Official claimed that the attacker had stolen \$5 million in SurgeBNB through a backdoor vulnerability. XSURGE stated that a potential security vulnerability in the SurgeBNB contract was discovered on August 16th.

The attack is made by 4 main steps:

1. the attacker borrow 10,000BNB through flash loans.
2. Use all the BNB to buy SURGE. According to the current price, the attacker can buy 1,896,594,328,449,690 SURGE
3. He calls the "sell" function, for selling the obtained SURGE.
4. The sale function alters the data after the transfer, and the transfer code has a reentrance vulnerability. When the attack contract acquires BNB, the period before the SURGE contract's state changes (References1st:SellSURGE line 15), the attack contract can use the reentrance vulnerability to purchase SURGE again.

```

1  function sell(uint256 tokenAmount) public nonReentrant returns (bool) {
2
3      address seller = msg.sender;
4
5      // make sure seller has this balance
6      require(_balances[seller] >= tokenAmount, 'cannot sell above token amount');
7
8      // calculate the sell fee from this transaction
9      uint256 tokensToSwap = tokenAmount.mul(sellFee).div(10**2);
10
11     // how much BNB are these tokens worth?
12     uint256 amountBNB = tokensToSwap.mul(calculatePrice());
13
14     // send BNB to Seller
15     (bool successful,) = payable(seller).call{value: amountBNB, gas: 40000}("");
16     if (successful) {
17         // subtract full amount from sender
18         _balances[seller] = _balances[seller].sub(tokenAmount, 'sender does not have
this amount to sell');
19         // if successful, remove tokens from supply
20         _totalSupply = _totalSupply.sub(tokenAmount);
21     } else {
22         revert();
23     }
24     emit Transfer(seller, address(this), tokenAmount);
25     return true;
26 }

```

Listing 3.2: Sell function of Surge (SURGE) token.

The bnb Amount of the contract stays intact, and the total amount of SURGE tokens `totalSupply` has not been updated, because the attack contract spends all of the BNB balance to acquire SURGE each time (still remains the quantity before the sell). As a result, the price of token falls, allowing the attacker to purchase additional SURGE.

```

1  function purchase(address buyer, uint256 bnbAmount) internal returns (bool) {
2      // make sure we don't buy more than the bnb in this contract
3      require(bnbAmount <= address(this).balance, 'purchase not included in balance');
4      // previous amount of BNB before we received any
5      uint256 prevBNBAmount = (address(this).balance).sub(bnbAmount);
6      // if this is the first purchase, use current balance
7      prevBNBAmount = prevBNBAmount == 0 ? address(this).balance : prevBNBAmount;
8      // find the number of tokens we should mint to keep up with the current price
9      uint256 nShouldPurchase = hyperInflatePrice ? _totalSupply.mul(bnbAmount).div(
address(this).balance) : _totalSupply.mul(bnbAmount).div(prevBNBAmount);
10     // apply our spread to tokens to inflate price relative to total supply
11     uint256 tokensToSend = nShouldPurchase.mul(spreadDivisor).div(10**2);
12     // revert if under 1
13     if (tokensToSend < 1) {
14         revert('Must Buy More Than One Surge');
15     }
16
17     // mint the tokens we need to the buyer
18     mint(buyer, tokensToSend);
19     emit Transfer(address(this), buyer, tokensToSend);

```

```
20     return true;  
21 }
```

Listing 3.3: Purchase function of Surge (SURGE) token.

Repeating three times of Round 2 and Round 3 , the attacker accumulates a large amount of SURGE through reentry, and then sells all the SURGE to make a profit.

At the end of this transaction, the attack contract sold 1,864,120,345,279,610,000 SURGE, obtained 10327 BNB, and finally the profitable 297 BNB was sent to the attacker's address.

The following are the modifications suggested by the Beosin technical team for this attack:

- any transfer operation should be place after the state changes to avoid reentry assaults.
- Instead of using "call. value," use transfer or send to transfer.

4 Analysis Tools

In this chapter I describe the tools and their capabilities, how they perform the Analysis.

4.1 Typologies of Tools

I explain the different types of analysis existing in general, as Symbolic execution, formal specification, scanner, Symbolic execution.

4.2 Tools for analysing properties specified by user

Description of tools, I would say like an overview of their paper

4.2.1 Celestial

4.2.2 SmartPulse

4.2.3 VeriSol

4.2.4 Echidna

Echidna is an open-source smart contract fuzzer, developed by Grieco et al. (2020), which makes it easy to automatically generate tests to detect violations in assertions and custom properties. Rather than relying on a fixed set of pre-defined bug oracles to detect vulnerabilities during fuzzing campaigns, Echidna supports three types of properties:

- user-defined properties (for property-based testing;
- assertion checking;
- gas use estimation.

Figure 4.1 depicts the Echidna architecture as a two-step process: pre-processing and fuzzing. The tool starts with a collection of contracts that have been supplied, as well as attributes that have been integrated into one of the contracts. Echidna uses Slither, smart contract static analysis framework presented in 4.3.2, to build and analyse the contracts in order to find relevant constants and functions that directly handle Ether (ETH). The fuzzing effort begins in the second stage. Using the application binary interface (ABI) given by the contract, significant constants stated in the contract, and any previously gathered sets of transactions from the corpus, this iterative procedure creates random transactions.

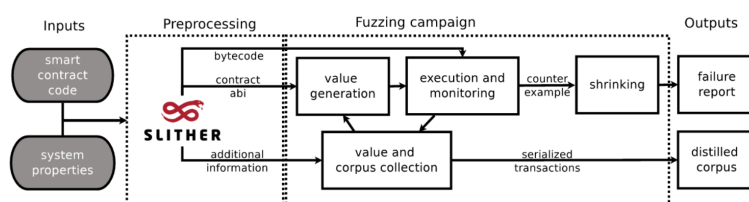


Figure 4.1: Echidna architecture

When a property violation is detected, a counterexample is created to indicate the smallest and most basic sequence of operations that caused the failure.

The code 4.1 provides an example of invariant in Echidna context. The Solidity contract contains a vulnerability a the backdoor function. The output of the terminal is presented in Listing 4.2: the attacker. For breaking the property, can call in order the functions `airdrop()` and `backdoor()`

```

1 contract Token{
2     mapping(address => uint) public balances;
3     function airdrop() public{
4         balances[msg.sender] = 1000;
5     }
6     function consume() public{
7         require(balances[msg.sender]>0);
8         balances[msg.sender] -= 1;
9     }
10    function backdoor() public{
11        balances[msg.sender] += 1;
12    }
13    function echidna_balance_under_1000() public view returns(bool){
14        return balances[msg.sender] <= 1000;
15    }
16 }

```

Listing 4.1: Solidity smart contract implementing a vulnerable Token and an Echidna invariant function.

```

1 $ echidna-test testtoken.sol --contract TestToken
2 ...
3 echidna_balance_under_1000: failed!
4 Call sequence, shrinking (1205/5000):
5 airdrop()
6 backdoor()
7
8 ...

```

Listing 4.2: Tool's result after the execution of the precious code.

The tool can be even used to test assertions. The aim is equivalent of the invariant testing methodology, but in this case properties are expressed using the Solidity annotation of assertion.

4.2.5 Solc-Verify

Ákos Hajdu and Jovanović (2020) present solc-verify, a source-level verification tool for Ethereum smart contracts. It takes smart contracts written in Solidity and discharges verification conditions using modular program analysis. It is built on top of the Solidity compiler, so it reasons at the level of the contract source code. Because of that, Solc-verify is able to reason about high-level contract attributes while accurately modeling low-level language semantics.

Solc-verify is implemented as an extension to the Solidity compiler. It accepts a collection of Solidity contracts, including specification annotations, and uses the Boogie verifier and SMT solvers to discharge verification conditions.

As Ákos Hajdu, Jovanović, and Ciocarlie (2020) explain, Solc-verify translates the annotated contracts to the Boogie Intermediate Verification Language (IVL). The key idea of the translation is to encode state variables as global heaps and functions as procedures. Solc-verify relies on the Boogie verifier to perform modular verification by discharging verification conditions to SMT solvers. The verification conditions encode the function body while assuming the preconditions, and then check if postconditions hold. In this process, function calls are replaced by their specification and loops by their invariants (modularity). Finally, the results are back-annotated to the Solidity source.

4.3 present an example of annotation, which states that the contract will ensure that the sum of individual balances is equal to the total balance in the bank.

```

1 pragma solidity >=0.7.0;
2
3 /**
4  * @notice invariant __verifier_sum_uint(balances) <= address(this).balance
5  */
6 contract SimpleBank {
7     mapping(address=>uint) balances;
8
9     function deposit() public payable {
10         balances[msg.sender] += msg.value;
11     }
12
13     function withdraw(uint256 amount) public {
14         require(balances[msg.sender] > amount);
15         bool ok;
16         (ok, ) = msg.sender.call{value: amount}(""); // Reentrancy attack
17         if (!ok) revert();
18         balances[msg.sender] -= amount;
19     }
20 }

```

Listing 4.3: An example Solidity smart contract implementing a simple bank with SolcVerify annotations.

Ákos Hajdu and Jovanović (2021) on GitHub repository, present the specification annotations. Those must be included in special documentation comments (`///` or `/** */`) and must start with the special doctag `@notice`. They must be side-effect free Solidity expressions (with some verifier specific extensions) and can refer to variables within the

scope of the annotated element. Functions cannot be called in the annotations, except for getters. The currently available annotations are listed below.

- Function pre/postconditions can be attached to functions. Preconditions are assumed before executing the function and postconditions are checked (asserted) in the end. The expression can refer to variables in the scope of the function. The postcondition can also refer to the return value if it is named.
- Contract level invariants can be attached to contracts. They are included as both a pre- and a postcondition for each public function. The expression can refer to state variables in the contract (and its balance).
- Loop invariants can be attached to for and while loops. The expression can refer to variables in scope of the loop, including the loop counter.
- Modification specifiers can be attached to functions. The target can be a (1) state variable, including index and member accesses or (2) a balance of an address in scope. Note however, that balance changes due to gas cost or miner rewards are currently not modeled.
- Event data specification can be attached to events that should be emitted when certain data changes. Events can declare the state variable(s) they track for changes, or in other words, the variables for which the event should be emitted on a change.

4.3 Tools without specification

4.3.1 SmartTest

SmartTest is a safety analyzer for Ethereum smart contracts developed by So, Hong, and Oh (2021). It adopts a symbolic execution technique for effectively detecting vulnerable transaction sequences. The main challenge of the project involves the tool to find transaction sequences, revealing the vulnerabilities of the analysed smart contract. Therefore, bugs are discovered as the cause of the interaction of multiple transactions. The purpose of SmartTest is to automatically deliver vulnerable transaction sequences, which demonstrate the weaknesses of the smart contract. The main idea is to build a statistical model using known vulnerable transaction sequences and use it to direct symbolic execution toward more successfully detecting unknown vulnerabilities. Symbolic execution is guided by statistical language models, so it can prioritize transaction sequences which are likely to reveal vulnerabilities. This strategy involves firstly to run unguided symbolic execution on existing vulnerable contracts, then to learn a probability distribution over vulnerable transaction sequences.

The tool is implemented as an extension of VeriSol, a verifier for Solidity Contracts. SmartTest is build on top of that, adding its own functionalities:

- symbolic execution with a language model.
- symbolic executor for transaction sequences.

- constraint solving optimization.

4.3.2 Slither

Slither is described by Feist, Grieco, and Groce (2019) as an open-source static analysis framework. It uses its own intermediate representation, SlithIR, which was created to simplify static analysis of Solidity code. Concolic analysis, taint analysis, and control flow checking are involved for detecting a variety of security vulnerabilities. It is designed to provide granular information about smart contract code and the flexibility necessary to support many applications.

It is mainly used for:

- Automated vulnerability detection: a large variety of smart contract bugs can be detected without user intervention.
- Automated optimization detection: Slither detects code optimizations that the compiler misses.
- Code understanding: printers summarize and display contracts' information to aid in the study of the codebase.
- Assisted code review: through its API, a user can interact with Slither.

Slither implements more than twenty bug detectors, regarding reentrancy, Uninitialized variables, Shadowing and many other. The tool allows the developers to integrate more detectors, therefore it extends Slither's capabilities to detect more advanced bugs.

Slither (2019) is written in python 3 and it is published on GitHub. During the installation, I did not find any particular issues.

4.3.3 Mythril

Mythril is a security analysis tool for Ethereum smart contracts. It was introduced by Mueller (2018).

The tool relies on concolic analysis, taint analysis and control flow checking of the EVM bytecode to prune the search space and to look for values that allow exploiting vulnerabilities in the smart contract. It is targeted at finding common vulnerabilities, and is not able to discover issues in the business logic of an application. *SmartContractSecurity. SWC Registry* (2020)'s taxonomy of vulnerabilities is used by Mythril for classify them. Listig 4.4 illustrates an example of output of Mythril analysis. At the second line, there is the reference to the vulnerability classified by SWC Registry with the ID of 110 (Assert Violation).

```

1 ===== Exception State =====
2 SWC ID: 110
3 Severity: Medium
4 Contract: Token
5 Function name: transferArray(address[],uint256[])
6 PC address: 4385

```

```
7 Estimated Gas Usage: 944 - 6585
8 An assertion violation was triggered.
9 It is possible to trigger an assertion violation. Note that Solidity assert() statements
  should only be used to check invariants. Review the transaction trace generated for this
  issue and either make sure your program logic is correct, or use require() instead of
  assert() if your goal is to constrain user inputs or enforce preconditions. Remember to
  validate inputs from both callers (for instance, via passed arguments) and callees (for
  instance, via return values).
10 -----
11 In file: test.sol:309
12
13 function transferArray(address[] tos, uint256[] values) public returns (bool) {
14     for (uint8 i = 0; i < tos.length; i++) {
15         require(transfer(tos[i], values[i]));
16     }
17
18     return true;
19 }
20
21 -----
```

Listing 4.4: Example of the output of Mythril Analysis.

4.3.4 Maian

4.3.5 Securify

4.3.6 ContractLarva

contractLarva is a runtime verification tool for Solidity contracts.

5 First Content Chapter

The content chapters of your thesis should of course be renamed. How many chapters you need to write depends on your thesis and cannot be said in general.

Check out the examples theses in the SDQWiki:

https://sdqweb.ipd.kit.edu/wiki/Hinweise_zu_Abschlussarbeiten#Beispiele_3

Of course, you can split this .tex file into several files if you prefer.

5.1 First Section

...

5.1.1 A Subsection

...

5.1.1.1 A Subsubsection

5.2 Second Section

...

6 Second Content Chapter

...

6.1 First Section

...

6.2 Second Section

...

Add additional content chapters if required by adding new .tex files in the sections/ directory and adding an appropriate `\input` statement in `thesis.tex`.

7 Evaluation

...

7.1 First Section

...

7.2 Second Section

...

7.3 Third Section

...

8 Conclusion

...

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A Appendix

A.1 First Appendix Section

Figure A.1: A figure

...