Design and Implementation of Static Analyses for Tezos Smart Contracts

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Once deployed in blockchain, smart contracts become immutable: attackers can exploit bugs and vulnerabilities in their code, that cannot be replaced with a bug-free version. For this reason, the verification of smart contracts *before* they are deployed in blockchain is important. However, the development of verification tools is not easy, especially if one wants to obtain guarantees by using formal methods. This paper describes the development, from scratch, of a static analyzer based on abstract interpretation for the verification of real-world Tezos smart contracts. The analyzer is generic with respect to the property under analysis. This paper shows taint analysis as a concrete instantiation of the analyzer, at different levels of precision, to detect untrusted cross-contract invocations.

Additional Key Words and Phrases: Blockchain, Smart contracts, Program verification, Formal methods, Abstract interpretation, Tezos, Michelson, Low-level programming language, Untrusted calls

ACM Reference Format:
Luca Olivieri, Luca Negrini, Vincenzo Arceri, Thomas Jensen, and Fausto Spoto. XXXX. Design and Implementation of Static Analyses for Tezos Smart Contracts. *J. ACM* 37, 4, Article 111 (August XXXX), 24 pages.
https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

In recent years, blockchain-based technologies have seen a growing interest in both academia and industry. Blockchains are abstract shared data structures where data is *immutable*, *distributed*, and *decentralized*. In this context, smart contracts are programs stored as data, that can be executed within the blockchain. They were conceived as a set of promises, specified in digital form, namely contracts [2]. However, their purpose is now blurred, given the generality of the software that can run within modern blockchains, especially after the introduction of Turing-complete languages for smart contract implementation. Once a smart contract is deployed in blockchain, it becomes *immutable*, exactly like any other data, and it is impossible to modify its code. For this reason, contract implementations must be secure against attacks and bug-free, *before* their deployment in blockchain to avoid unexpected execution behaviors. In this context, formal verification techniques allow one to analyze software with mathematical theories and ensure the presence or absence of certain code properties, bugs, and vulnerabilities. However, according to Ferrara et al. [20],

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0004-5411/XXXX/8-ART111 $15.00
https://doi.org/XXXXXXX.XXXXXXX

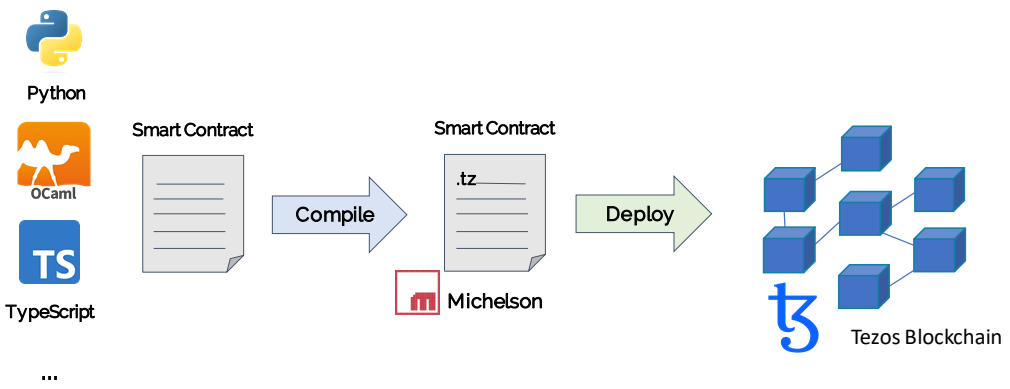


Fig. 1. Development pipeline of Tezos smart contracts.

tools based on formal methods require a significant theoretical background as well as consolidated programming skills for designing and implementing a new analysis.

This paper presents an experience report on the design and implementation from scratch of MichelsonLiSA[1], a static analyzer based on abstract interpretation for the verification of smart contracts executing on the Tezos blockchain, henceforth just referred to as Tezos smart contracts. It shows how LiSA [20, 33, 34] (Library for Static Analysis) facilitates this task, also for low-level languages such as Michelson [38], and how the peculiarities of smart contracts enable analyses that typically could not be applied to traditional software.

Contributions. This paper is an extended version of [40]. Compared to [40], it expands and clarifies all contents, providing detailed information about the design and implementation choices underlying MichelsonLiSA. Moreover, it instantiates MichelsonLiSA with taint analysis, to spot untrusted inter-contract invocations (UCCIs). Lastly, it reports experiments that demonstrate the applicability of techniques that typically do not scale for traditional software, while they do work instead on smart contracts, thanks to their conciseness.

Paper structure. Section 2 and Section 3 provide preliminary notions on Tezos smart contracts and blockchain software verification, respectively. Section 4 highlights design and implementation choices related to the development of MichelsonLiSA. Section 5 describes the development process of MichelsonLiSA. Section 6 uses taint analysis to detect untrusted cross-contract invocations and introduces a three levels version to improve the analysis results. Section 7 reports related work. Section 8 concludes the paper.

2 TEZOS SMART CONTRACTS

Tezos [23] is a public *permissionless* blockchain based on the proof-of-stake consensus, that supports Turing-complete smart contracts. In the Tezos ecosystem, there are several frameworks for the development of smart contracts, such as Archetype [3], LIGO [27], and SmartPy [53]. Most of them exploit *meta-programming* to develop smart contracts. Meta-programming is already widely used in many blockchains [2, 10, 18, 36, 45, 55], since it allows one to develop smart contracts in different high-level languages, that all compile to a single, normally low-level target language. In this way, it

[1] https://github.com/lisa-analyzer/michelson-lisa

Instruction	*Description*
ADDRESS	pop a contract value and push the address of that contract
AMOUNT	push the amount of the current transaction
BALANCE	push the current amount of mutez of the executing contract
CHAIN_ID	push the chain identifier
CONTRACT	replace the top of the stack after cast to a contract type
CREATE_CONTRACT	push a contract creation operation
IMPLICIT_ACCOUNT	push the address of a new implicit account
LEVEL	push the current block level
NOW	push the block timestamp
SELF	push the current contract
SELF_ADDRESS	push the address of the current contract
SENDER	push the contract that started the current internal transaction
SET_DELEGATE	push a delegation operation
SOURCE	push the contract that initiated the current transaction
TOTAL_VOTING_POWER	push the total voting power of all contracts
TRANSFER_TOKENS	push a transaction operation
VOTING_POWER	push the voting power of a contract

Table 1. Domain-specific operations of Michelson.

is possible to switch between popular high-level languages based on the programmer's preference and project requirements, keeping the low-level code compatible. Development frameworks for Tezos support popular high-level programming languages (e.g., Python, OCaml, and TypeScript), all compiled to the Michelson low-level language [38]. This is the only target language of the Tezos blockchain (see Figure 1).

Michelson is a statically-typed domain-specific bytecode language, expressive enough to implement Turing-complete smart contracts. The memory model is stack-based and data are manipulated in a last-in-first-out (LIFO) order. Currently, Michelson consists of around 100 bytecode instructions[2]: for stack manipulation (PUSH, DROP, SWAP, ...), for creation and management of high-level data structures (MAP, UPDATE, SIZE, ...), for arithmetic operations (SUM, SUB, AND, ...), for control flow (IF, LOOP, ...) and blockchain-specific ones (see Table 1).

Figure 2 shows a Tezos smart contract written in SmartPy (Figure 2a), a subset of Python, and its translation into Michelson (Figure 2b) obtained with the SmartPy [53] compiler. Figure 2a shows

[2]https://tezos.gitlab.io/michelson-reference

```python
import smartpy

# smart contract definition
class MyAdd(smartpy.Contract):
  def __init__(self):
    self.init(value = 0)

  @smartpy.entry_point
  def add(self, x, y):
    self.data.value = x + y
```

(a) Python code

```
parameter (pair %add (int %x) (int %y));
storage   int;
code
{
  CAR;         # @parameter
  # == add ==
  # self.data.value = params.x + params.y
  # @parameter
  UNPAIR;      # int : int
  ADD;         # int
  NIL operation; # list operation : int
  PAIR;        # pair (list operation) int
};
```

(b) Michelson code

Fig. 2. Meta-programming development: from Python to Michelson.

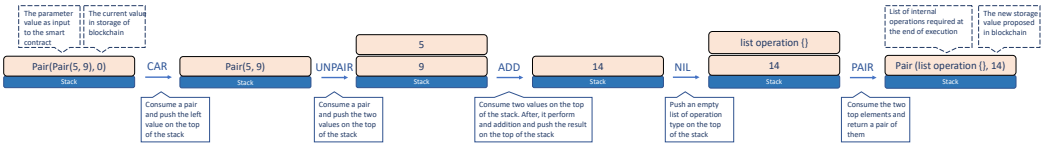


Fig. 3. An example of execution of the smart contract in Figure 2b.

that SmartPy contracts are defined as a class that inherits from `smartpy.Contract` (line 4). A contract has a state and one or more entry points, annotated with `@smartpy.entry_point` (line 8). The constructor `__init__` (line 5) calls `self.init` (an alias of `self.init_storage(arg = None, **kwargs)`) and initializes the fields that make up the contract state (the storage of the smart contract). In particular, the behavior of the program in Figure 2a is to initialize the storage with the value `0` (line 6), after which blockchain users can call, through a transaction, the method `add(self, x, y)` (line 9) to perform an addition operation between two numerical values and replace the storage value with the result of the operation (line 10). Figure 2b shows the translation in Michelson resulting from the SmartPy compiler. The structure of the Michelson smart contract has three components: (i) an explicitly-typed *parameter declaration* for the input, (ii) an explicitly-typed *storage declaration* for blockchain store locations, and (iii) a *code declaration* that defines the sequence of bytecode instructions. Technically, the input is a single value that specifies the data required for running the code. However, aggregate types, such as `pair` and `or`, allow one to provide more than a single input value to the contract (see line 1).

As already mentioned, the execution of a Michelson contract is stack-based: instructions pop and/or push values on a stack. In the Tezos blockchain, a smart contract execution request (*invocation*) specifies the address of the smart contract in the blockchain and its input.[3] The execution starts from a stack whose only element is the pair of the input and of the current value of the storage of the contract.

Figure 3 shows an execution of `add` from Figure 2b, with input `Pair(5,9)`, assuming that the current value of the contract storage is `0`: the initial stack contains only one element, that is, `Pair(Pair(5,9),0)`. Note that the user provides the input, while the blockchain protocol retrieves the storage value from the blockchain state. The first instruction in this example, `CAR`, splits the pair and projects it on its first component `Pair(5,9)` (the input), which gets pushed on the stack instead: the current storage value is discarded. The subsequent `UNPAIR` instruction decomposes `Pair(5,9)` into its two components `5` and `9`, that pushes on the stack instead. The `ADD` instruction computes their sum (`14`), that gets pushed on the stack instead. The `NIL` instruction pushes an empty list of operations to perform at the end of the execution and the final `PAIR` instruction boxes the list and the result into a pair. That pair is the result of the execution. The blockchain protocol will take its second component (`14`) and store it in the storage of the contract, for future use.

3 BLOCKCHAIN SOFTWARE VERIFICATION

Code verification can be applied from the very beginning of the implementation of the code. For blockchain software, it is particularly important to apply it *before* code deployment in blockchain, that is, before the code becomes immutable and difficult to patch. According to Chess et al. [9], the most used approach for finding bugs is *dynamic testing*, that executes the software and compares its output with the expected result. However, dynamic testing has drawbacks. The creation of test cases is not trivial and can require a lot of effort, as developers need to compute the expected results on each input case. Namely, *unit testing* verifies small portions of code (its *units*) over

[3] https://tezos.gitlab.io/michelson-reference/#execution

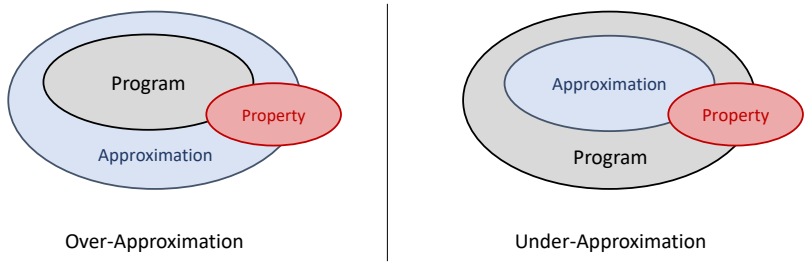


Fig. 4. Approximation schema.

normal input or cornercases that could generate errors. Testing can observe only a finite set of finite program executions [51, Chapt. 1.4.1]. Hence, dynamic testing can only show the presence of bugs, never their absence [15, Part I, Chapt. 3]. In addition, dynamic testing can only be applied from an advanced stage of development as it needs to be executed, increasing the cost of bug fixing in case of multiple bugs.

A complementary approach to dynamic testing is *static analysis*, that automatically verifies the properties of computer programs before their execution [51]. This reduces the cost, for developers, of bug fixing, giving them the chance to fix bugs and code smells at an early stage [9]. Therefore, for full code coverage and to prove or refute a code property, such as in the case of untrusted token transfers that will be consider in this article, it is necessary to use formal methods based on mathematical frameworks, such as abstract interpretation [12].

According to Cousot [11, Chapt. 1.2], abstract interpretation [12, 13] is a unifying theory of formal methods that proposes a general methodology for proving the correctness of computing systems. In static program analysis, abstract interpretation is used to approximate the concrete behavior of programs (their *concrete semantics*) with an abstract behavior (their *abstract semantics*). It also formalizes the intuition that semantics are more or less precise depending on the abstraction level. The idea behind abstract interpretation is that reasoning on the abstract properties implies some reasoning on the concrete ones. The abstraction is a necessary step to perform analyses that detect otherwise undecidable properties [50], that is, abstractions trade precision for decidability.

Abstract interpretation allows one to formalize a notion of *soundness*. A static analyzer is *sound* with respect to a program and a property of interest when it considers all possible program executions and is thus able to give definite guarantees on the property. Thus, if it does not issue any alarm, the property is guaranteed to hold for every possible execution. In other words, sound analyzers have no *false negatives* (situations when the property holds in at least one concrete execution, but the analyzer does not detect it and no alarm is issued). In particular, *soundness* is achieved by using over-approximations (Figure 4), that can however create *false positives* (situations when the property does not hold in any concrete execution but the analyzer conservatively assumes that it might hold because it considers *more* executions than the concrete ones). According to Meyer [29], it is generally better to use *sound* techniques, since false negatives can lead to critical issues whose mitigation might be impracticable in some contexts, such as blockchain.

4 FROM SCRATCH TO MICHELSONLISA

Static analysis based on formal methods requires a non-trivial theoretical background and development skills. In order to be able to design and implement a new analysis, it is necessary to construct an infrastructure providing its basic building blocks (parser, control flow graph (CFG) representation [1], fixpoint algorithms, etc.). Therefore, the development of even a toy static analyzer from

scratch is a big effort, unless a generic analysis infrastructure is already available, that can be used to reduce to development effort.

This section reports our successful experience with the design and implementation of MichelsonLiSA [40], a static analyzer for the Michelson language. In particular, it describes the challenges faced in analyzing that domain-specific language, the technologies involved for quick implementation, and the development timelines.

4.1 Challenges of Tezos Smart Contract Verification

As reported in Section 2, the development of smart contracts for the Tezos blockchain involves different programming languages, both high and low-level. Switching from high to low-level languages can imply a loss of information, making it difficult to understand, reverse engineer, analyze, and verify blockchain software. High-level languages typically feature compact instructions, types and annotations. Instead, low-level languages have a restricted instruction set and make all operations performed during the execution explicit, losing expressiveness and increasing code verbosity. In addition, compilation problems occur when the semantics of some high-level instruction may not be easily expressed in terms of low-level instructions.

In this scenario, an interesting case study for Tezos is SmartPy [53]. It is a framework that allows one to program smart contracts at high-level, in Python. However, Python is a general-purpose language with thousands of APIs: many of them cannot be compiled into Michelson, due to its domain restrictions. To overcome this problem, these functions are resolved at compile-time [54] and the results are hardcoded in the compiled code. Nevertheless, this leads to other two problems. The first and more immediate is that, while analyzing the Michelson bytecode, the usage of Python APIs is not visible. The second is that this resolution is correct only if the API call actually returns a constant, and the developer should check that. Let us explain this by means of the SmartPy smart contract in Figure 5a, that gets initialized with a numerical parameter `myPar1` through function `__init__` at line 6. This value can later be changed through function `myEntryPoint` at line 11. The `myEntryPoint` function uses `random.randint` at line 13, a standard Python API that has no transation into Michelson, since the latter has no instruction for generating random values, to ensure deterministic execution [41, 42, 57]. But the SmartPy compiler compiles that code without a single warning. Figure 5a shows the result: `random.randint` has been evaluated at compile-time and its random return value (7) has been hardcoded in the bytecode, at line 8. When running the Michelson code, it will not add a random value, as the Python programmer might naively expect, but will add 7, for all executions. Moreover, the constant 7 will likely change at next compilation, making the process non-deterministic.

In this case, code analysis at the high-level source code is not a viable choice. More generally, according to Logozzo et al. [28], the analysis of low-level code provides different advantages: (i) it is more faithful, as it analyzes the code that is actually executed (or closer to), (ii) it enables the analysis of code when source code is not available (for instance, for smart contracts already deployed in blockchain), (iii) it avoids redundant work that the compiler has already performed, such as name resolution, type checking, template/generics instantiation, and (iv) the semantics of high-level constructs is expanded by the compiler in the low-level code.

For these reasons, this paper focuses on the analysis of Michelson only.

4.2 Goals, Requirements and Technologies

A static analyzer such as MichelsonLiSA is composed of at least three main components (see Figure 6):

(1) a *parsing component* that reads and interprets the code to analyze;

```python
import smartpy as sp
import random

# A class of contracts
class MyContract(sp.Contract):
  def __init__(self, myPar1):
    self.init(myPar1=myPar1)
  # An entry point, i.e., a message receiver
  # (contracts react to messages)
  @sp.entry_point
  def myEntryPoint(self):
    self.data.myPar1 += random.randint(0,10)
```

(a) Python code

```
parameter (unit %myEntryPoint);
storage int;
code
{
  CDR;         # @storage
  # == myEntryPoint ==
  # self.data.myPar1 += 7 # @storage
  PUSH int 7; # int : @storage
  ADD;         # int
  NIL operation; # list operation : int
  PAIR;        # pair (list operation) int
};
```

(b) Michelson code

Fig. 5. An issue related to meta-programming from SmartPy.

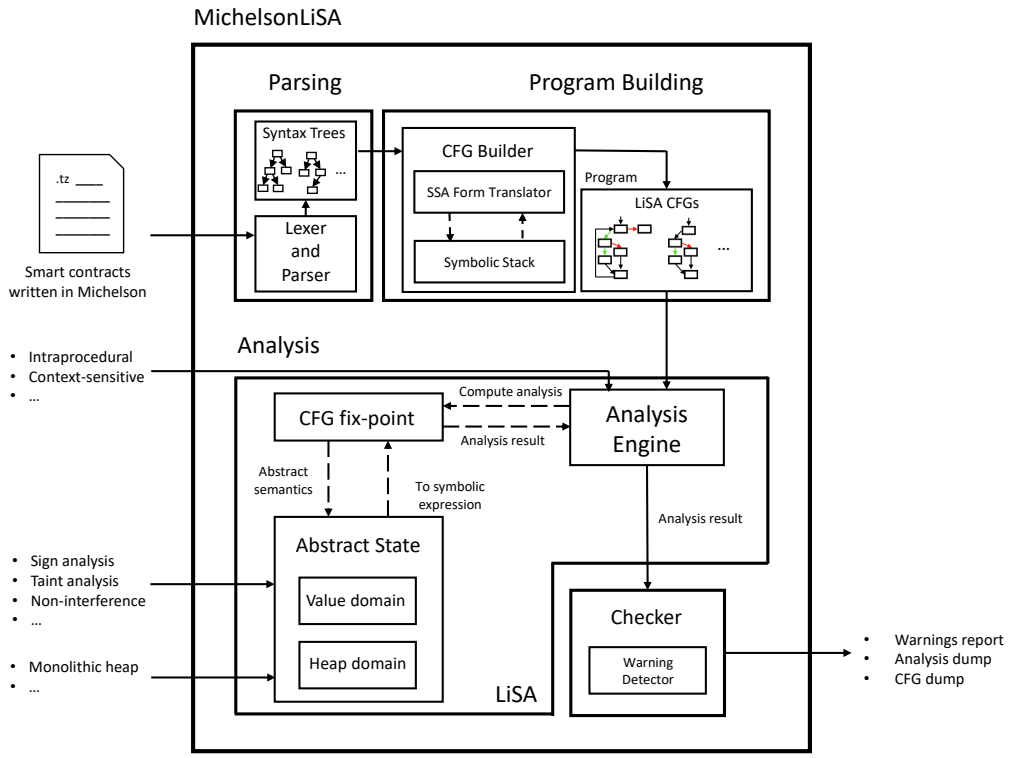


Fig. 6. MichelsonLiSA overall architecture.

(2) a *program builder* that creates a model of the program to analyze;
(3) an *analysis engine*, that analyzes and checks the program model.

Among these, the most complex is certainly the *analysis engine*, which requires non-trivial theoretical background and development skills. This paper relies on the analysis engine of LiSA [20, 33, 34], a framework that provides a general infrastructure for static analysis and standard components for

abstract interpretation. It is written in Java, a popular, platform-independent, enterprise language, that supports a wide range of tools for software development (IDEs, test frameworks, monitoring software, debugging environments). LiSA has been successfully applied to educational [20] as well as industrial solutions [42].

LiSA facilitates the development of analyses based on formal methods, but places some constraints, since its program model uses a representation of extensible control flow graphs where every instruction's semantics is the composition of atomic operations, agnostic w.r.t. the syntax of the source code. Moreover, LiSA is primarily designed for imperative and object-oriented languages and its application to other languages must be investigated case by case. Next sections discuss the three main components cited above and the impacts of adopting LiSA during the development of the MichelsonLiSA analyzer.

4.3 Code Parsing

A parser reads the input code, checks if it complies to the language syntax, and returns a structured representation of the parsed code, to be processed in a subsequent phase. The full grammar of Michelson specifies its syntax.[4] However, it currently lacks some syntactic sugar (such as annotations, use of brackets, smart contract structure or macros) widely used in real-world Tezos contracts. LiSA leaves the parsing logic to the user [33, Section 1.6]. Hence, we enriched that grammar and implemented it[5] in the ANTLR v4 format. ANTLR [46] is a popular tool that, starting from a grammar, builds a *lexer* and a *parser*. The lexer reads the input code and produces a sequence of strings called *lexemes*; the parser uses an $LL(*)$ algorithm [47], with lexemes as input. If the code complies with the grammar, the parser builds a structured *abstract syntax tree* (AST); otherwise, it rejects the input code with a syntax error [11, Chapter 5] and stops. Our ANTLR grammar is agnostic w.r.t. the implementation language of the lexer and parser (Java in our case): it can therefore be reused in future projects written in other languages.

4.4 Program Builder

After parsing, a program model must be built. LiSA models code as a collection of CFGs (representing the syntax of the input program) and provides rewriting rules of each CFG node into *symbolic expressions*. These are an internal extensible language representing atomic semantic operations (thus modeling the semantics of each instruction of the input program) [33, Section 1.6]. The ASTs produced by the parser can be used as the base for building CFGs. However, according to [16], the use of a stack makes it difficult to apply standard static analysis techniques. Moreover, LiSA is designed for traditional high-level languages that are typically variable-based, while Michelson is low-level and stack-based. Therefore, preliminary manipulations are necessary to provide a program intermediate representation (IR) that matches the analysis engine.

4.4.1 Intermediate Representation.

MichelsonLiSA implements an IR based on static single-assignment (SSA), constructed by using a symbolic stack to translate Michelson code into variable-based code. The algorithm is inspired by BC2BIR [16] and Tezla [49]. The translation maps each Michelson instruction[6] into a list of MichelsonLiSA instructions (LiSA's statements expressing the syntax and semantics of the corresponding Michelson instruction), by using new fresh variables. It tracks, abstractly, the

[4] https://tezos.gitlab.io/active/michelson.html#full-grammar
[5] https://github.com/lisa-analyzer/michelson-lisa/tree/master/michelson-lisa/src/main/antlr
[6] https://tezos.gitlab.io/active/michelson.html#core-instructions

```
parameter (pair int int);
storage int;
code {
  CAR;
  DUP;
  UNPAIR;
  COMPARE;
  GT;
  IF
  {  # True branch
    UNPAIR;
    ADD;
  }
  { # False branch
    UNPAIR;
    SUB;
  }

  NIL operation;
  PAIR;
}
```

(a) Michelson code

```
v0 = parameter_storage();
v1 = CAR(v0);
v2 = DUP(v1);
v3 = get_left(v2);
v4 = get_right(v2);
v5 = COMPARE(v3, v4);
v6 = GT(v5);
IF(v6)
{ # True branch
  v7 = get_left(v1);
  v8 = get_right(v1);
  v9 = ADD(v7, v8);
}
{ # False branch
  v10 = get_left(v1);
  v11 = get_right(v1);
  v12 = SUB(v10, v11);
}
v13 = phi(v9, v12);

v14 = NIL(operation);
v15 = PAIR(v14, v13);
```

(b) SSA form

Fig. 7. A Michelson smart contract and its translation into SSA form. The contract performs an addition if the first component of the input pair is larger than the second one; otherwise, it performs a subtraction. The result is encapsulated in a pair, consisting of an empty list of operations and of the new storage data value.

propagation of stack values through a symbolic stack of such variables.[7] That is, stack elements hold symbolic names, not their exact values. Figure 7 shows the translation of a Michelson contract into SSA.

Instructions that push values on the stack are translated into variable assignments, with fresh variables standing for stack elements, each assigned exactly once. Instructions that pop from the stack take as parameter the variables corresponding to the elements they pop. Some instructions can be both producers and consumers. Figure 8 shows an example of translation in SSA for some common instructions. `PUSH <type> <data>` pushes a constant of the declared type: it is translated with a fresh new variable that gets assigned to a constant of a declared type. `SUB` consumes its two operands from the stack and pushes their difference instead: it is translated as a function that receives the operands as arguments and yields their difference. `DROP` pops and discards the top of the stack: it is translated with a function with no return value. `PAIR` consumes the two topmost stack elements, and packs them into a pair that pushes on the stack instead: it is translated as a function with two arguments, that yields the pair. `UNPAIR` pops a pair, splits it, and pushes its two components instead: it is translated with two functions, that select the two components and store them into fresh new variables.

Some Michelson stack-modifying instructions perform relatively complex stack operations. Namely, `SWAP` exchanges the topmost two elements of the stack; `DIG n` shifts the stack element at depth `n` into the top of the stack, while `DUG n` does the converse. These instructions can be translated into SSA. Figure 9 shows an example for `DIG 2` (the position of the elements starts at 0, which is the topmost element).

[7] https://github.com/lisa-analyzer/michelson-lisa/tree/master/michelson-lisa/src/main/java/it/unive/michelsonlisa/frontend/visitors/MichelsonStack.java

```
0: PUSH int 23;
1: PUSH int 13;
2: SUB;
3: DROP;
4: PUSH int 23;
5: PUSH int 13;
6: PAIR;
7: UNPAIR;
8:
```

(a) Source code

```
0: []
1: [23]
2: [23,13]
3: [-10]
4: []
5: [23]
6: [23,13]
7: [Pair(13,23)]
8: [23, 13]
```

(b) Value stack

```
0: []
1: [v1]
2: [v1,v2]
3: [v3]
4: []
5: [v4]
6: [v4,v5]
7: [v6]
8: [v7, v8]
```

(c) Symbolic stack

```
0: v1 = PUSH(int, 23);
1: v2 = PUSH(int, 13);
2: v3 = SUB(v1,v2);
3: DROP(v3);
4: v4 = PUSH(int, 23);
5: v5 = PUSH(int, 13);
6: v6 = PAIR(v4,v5);
7: v7 = get_left(v6);
   v8 = get_right(v6);
8:
```

(d) SSA form

Fig. 8. Example of transformation into SSA form.

```
0: PUSH nat 5;
1: PUSH nat 3;
2: PUSH nat 2;
3: DIG 2;
4: DROP;
5:
```

(a) Source code

```
0: []
1: [5]
2: [5, 3]
3: [5, 3, 2]
4: [3, 2, 5]
5: [3, 2]
```

(b) Value stack

```
0: []
1: [v1]
2: [v1, v2]
3: [v1, v2, v3]
4: [v2, v3, v1]
5: [v2, v3]
```

(c) Symbolic stack

```
0: v1 = PUSH(nat, 5);
1: v2 = PUSH(nat, 3);
2: v3 = PUSH(nat, 2);
3: DIG(2);
4: DROP(v1)
5:
```

(d) SSA form

Fig. 9. Michelson code using a `DIG n` instruction and its SSA form representation.

```
0: IF
1: { # True branch
2:   PUSH int -1;
3: }
4: { # False branch
5:   PUSH int 7;
6: }
7:
```

(a) Source code

```
0: [0 || 1]
1: []
2: []
3: [-1]
4: [-1]
5: []
6: [7],
7: [-1 || 7]
```

(b) Value stack

```
0: [v0]
1: []
2: []
3: [v1]
4: [v1]
5: []
6: [v1],
   [v2]
7: [v3]
```

(c) Symbolic stack

```
0: IF(v0)
1: { # True branch
2: v1 = PUSH(int, -1);
3: }
4: { # False branch
5:   v2 = PUSH(int, 7);
6: } v3 = phi(v1, v2) #
     Junction point
7:
```

(d) SSA form

Fig. 10. Example of transformation of a conditional into SSA form, with a junction point. The ϕ-function is written as `phi`.

Michelson includes instructions for conditionals, such as `IF`, and for iteration, such as `LOOP`, both leading to branches and junction points. For junctions, SSA reconciles distinct values of the same variable, arising along different paths, through ϕ-functions [14]. The idea is to translate instructions separately along each path, using disjoint sets of variables, and then merge the variables that stand for the same stack element along different paths at the junction point. Figure 10 shows an example.

Michelson has *stack-protecting* instructions, such as `DIP n`, that temporarily freeze the topmost `n` elements of the stack, keeping them unaffected during the execution of a specified group of subsequent instructions. Figure 11(a) shows a snippet of code that uses `DIP 2` at line 3. There, the stack holds `[5, 3, 4]` (from bottom to top), as reported in Figure 11(b). `DIP 2` freezes its topmost two elements (3 and 4) during the execution of the instructions specified inside curly braces. Namely, `PUSH nat 1` pushes 1 immediately below the frozen elements, instead of on top of the stack, leading to the stack `[5, 1, 3, 4]`. Similarly, `ADD` pops the two topmost, unprotected stack elements 5 and 1 and pushes their sum immediately below the frozen elements. This behavior is reflected in the

```
0: PUSH nat 5;
1: PUSH nat 3;
2: PUSH nat 4;
3: DIP 2 {
4:  PUSH nat 1;
5:  ADD;
6: }
7:
```

(a) Source code

```
0: []
1: [5]
2: [5, 3]
3: [5, 3, 4]
4: [5, (3, 4)]
5: [5, 1, (3, 4)]
6: [6, (3, 4)]
7: [6, 3, 4]
```

(b) Value stack

```
0: []
1: [v1]
2: [v1, v2]
3: [v1, v2, v3]
4: [v1, (v2, v3)]
5: [v1, v4, (v2, v3)]
6: [v5, (v2, v3)]
7: [v5, v2, v3]
```

(c) Symbolic stack

```
0: v1 = PUSH(nat, 5);
1: v2 = PUSH(nat, 3);
2: v3 = PUSH(nat, 4);
3: DIP(2) {
4:   v4 = PUSH(nat, 1);
5:   v5 = ADD(v1, v4);
6: }
7:
```

(d) SSA form

Fig. 11. Michelson code that uses a `DIP n` instruction and its corresponding stack execution. Round brackets highlight the protected area of the stack.

SSA translation (Figure 11(d)): `PUSH nat 1` becomes `v1 = PUSH(nat, 5)`, with `v1` pushed on top of the symbolic stack (Figure 11(c)). Similarly for the two subsequent `PUSH` instructions. At line 3, the symbolic stack will be `[v1, v2, v3]` and `v2` and `v3` will become protected. Consequently, at line 4, the `PUSH` instruction is translated into `v4 = PUSH(nat, 1)`, with `v4` placed below the protected area of the symbolic stack, which becomes now `[v1, v4, v2, v3]`. The subsequent `ADD` instruction operates on the unprotected elements `v1` and `v4` and gets translated into `v5 = ADD(v1, v4)`, with `v5` pushed immediately below the protected values.

Michelson smart contracts interact with the context of Tezos where they execute. For instance, at the beginning of their execution, the stack holds a pair of the input value and of the current storage value. This must be made explicit in the SSA translation, as in Figure 7, with `v0 = parameter_storage()`. Instrumentation is needed for data structures as well. Namely, Michelson supports high-level data structures (sets, lists, maps, optionals) and has specific instructions to operate on them, such as `ITER`, `LOOP_LEFT` and `IF_CONST`. These typically push additional elements on the stack. For instance, `ITER` consumes a collection from the stack and applies a set of instructions to each of its elements. These get simulated in SSA by using assignments to additional variables.

4.4.2 *CFG Builder.*

At this point, a CFG builder can visit the IR and convert the elements into a CFG representation. Thanks to this IR, the CFG needn't be specific for a low-level language. Each node corresponds to a statement implementation that expresses the semantics of Michelson through *symbolic expressions* [33, Section 3.2.2], in order to be understandable by subsequent LiSA's analyses. Symbolic expressions can be considered as an internal language of LiSA to make the semantics of a node generic. The connections between one statement and another are indicated as edges. Intuitively, CFGs express the syntax of the program of interest, while symbolic expressions are used to construct the semantics of CFGs by specifying the meaning of the statements in each CFG node. In addition to the operations above, the builder expands the macros to analyze and handles each single component separately. For instance, `FAIL` is a sequence of `UNIT; FAILWITH` to trigger a smart contract failure: this is translated into two statements `v = UNIT` and `FAILWITH(v)`, connected by an edge. The first pushes a `unit` value[8] on the stack and the second explicitly aborts the current smart contract execution and exposes the top element of the stack as the exit value of the smart contract execution.

The output of this phase is a collection of CFGs that represent, in SSA form, the Michelson source program.

[8] https://tezos.gitlab.io/michelson-reference/#type-unit

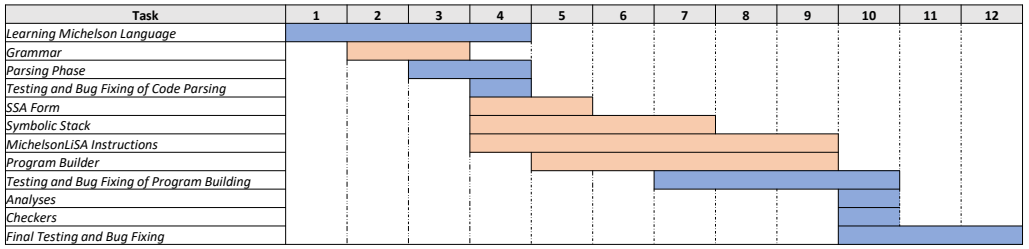


Fig. 12. Gantt chart of the MichelsonLiSA development. The timeline is divided into twelve working weeks. Critical activities are shown in red, while non-critical activities are shown in blue.

4.4.3 *Semantics of Domain Specific Operations.*

Table 1 contains the current list of domain-specific operations of Michelson. Although they are domain-specific, almost all of them, with the exception of `CONTRACT` (that can be seen as a cast), push a value on the stack that depends on the run-time environment (current amount of cryptocurrency in the transaction, current balance of a contract, current blockchain height, current address). In static analysis, their semantics will express overapproximations of the potential run-time values, that cannot be inferred statically. In general, MichelsonLiSA represents such operations as methods, potentially with input parameters, that return a constant value with the return type of the operation. The exact abstraction of that value will be handled at analysis time, since it has different abstractions, depending on the kind of analysis. For instance, for numerical analysis, some operations could return a specific numerical constant. Instead, for the UCCIs detection in Section 6.2, taintedness levels will abstract the returned values, as for that of `BALANCE`, that gets abstracted as *clean*.

4.5 Analysis Engine

The resulting CFGs are a program model that complies with the LiSA engine, ready to be analyzed. Given the program model and additional user settings, LiSA produces an entry and an exit state for each node (that is, statement) in the CFGs, containing the information inferred by the analysis. These can be subsequently sent to a checker. MichelsonLiSA allows the implementation of *syntactic* and *semantic* checkers. A syntactic checker performs checks that are only based on syntax (for instance, check if a variable is declared). A semantic checker exploits instead both the syntactic structure of the program and the semantic information produced by LiSA's analysis. In any case, it is possible to save the information contained in the nodes, and generate alerts and warnings.

5 DEVELOPMENT ROADMAP

The development of a static analyzer based on abstract interpretation is an expensive task, with respect to the time required and to the cost of the human resources needed to perform such complex activity. An analyzer for a general-purpose language such as Java can require many years of work and study to apply analyses at low-level (bytecode), supporting all language features and runtimes [56]. In comparison, Michelson has a manageable number of instructions (around 100), its memory model is simple and the language lacks advanced features (such as inheritance, interfaces, pointers, objects, variable scoping, shadowing, concurrency). Furthermore, the use of LiSA has considerably reduced the complexity of implementing MichelsonLiSA.

Figure 12 shows a Gantt chart of the tasks and timeline for the implementation of the first working prototype of MichelsonLiSA, supporting an information flow analysis (*taint* analysis [19, 60]) and a simple numerical analysis (*sign* analysis [12]). The activities were performed in a twelve weeks

window (60 person-days). The implementation was carried out by a single senior Java developer with prior knowledge of static analysis and abstract interpretation but not of the LiSA framework.

After a preliminary study of Michelson, the implementation started with the definition of the language grammar, using ANTLR. This activity has been marked as critical, as it is the first brick of the analyzer. Moreover, it has required several refinements, given the fragmented official documentation. Subsequently, lexer and parser have been implemented and tested on real-world smart contracts, checking the absence of any parse error. The activities related to program building have been critical because they allowed us to produce the program model on which the analyses are performed. The translator into SSA form required knowledge on symbolic stack computations, that in turn rely on the push/pop behavior of each individual instruction. This resulted in the definition and implementation of the semantics of each instruction and, when needed, in the design of additional instrumentations (such as ϕ-functions and multiple pushes of values on the stack). This phase required the biggest effort, in terms of time. The architecture has been developed so that it can be easily expanded in the future with new instructions. For instance, the logic of the symbolic stack and of the translation into SSA has been separated from the implementation of the semantics of the operations, defined in terms of symbolic expressions, by using two interfaces that model, abstractly, the behavior of an instruction when it pushes[9] or pops[10] stack values. Regarding the semantics of the symbolic expressions, LiSA natively provides some extensible classes for the most common instructions (such as numerical addition and subtraction). Moreover, across the LiSA's repositories, it was possible to find several examples of the implementation of the instructions semantics from which it has been possible to take inspiration, such as those from GoLiSA[11] and PyLiSA[12]. This simplified the implementation task, by focusing on domain-specific issues. Analyses and checks have been developed by exploiting classes, interfaces and the engine already provided by LiSA. Therefore, this part was the least problematic. It was only necessary to define abstract domains and checks that issue the warnings. The work terminated with testing and bug fixing on several examples of real-world code.

6 INFORMATION FLOW FOR UCCI DETECTION

Low-level code, such as that of Michelson, make blockchain software hard to understand, reverse engineer, and manually investigate. This section builds on the analysis in [40] for the detection of untrusted token transfers in Tezos smart contracts, discussing issues related to over-approximation and detection of untrusted cross-contract invocations (UCCIs). It proposes a novel version of that analysis, at different degrees of abstraction, to obtain different levels of over-approximation and consequently present warnings by priority, thus facilitating manual investigation.

6.1 Untrusted Cross-Contract Invocation Problem

In the blockchain context, one of the first applications of smart contracts has been the exchange of fungible and non-fungible tokens (crypto-currencies, tickets, documents, ...). *Permissionless* blockchains such as Tezos are trustless environments composed of untrusted peers, secured by economic incentive. For this reason, a common functional requirement for smart contracts is to avoid unexpected transfers of tokens, that might happen through UCCIs, to arbitrary and potentially

[9] https://github.com/lisa-analyzer/michelson-lisa/blob/master/michelson-lisa/src/main/java/it/unive/michelsonlisa/cfg/statement/interfaces/StackProducer.java
[10] https://github.com/lisa-analyzer/michelson-lisa/blob/master/michelson-lisa/src/main/java/it/unive/michelsonlisa/cfg/statement/interfaces/StackConsumer.java
[11] https://github.com/lisa-analyzer/go-lisa/tree/master/go-lisa/src/main/java/it/unive/golisa/cfg/expression
[12] https://github.com/lisa-analyzer/pylisa/tree/master/pylisa/src/main/java/it/unive/pylisa/cfg/expression

Typing

$\Gamma \vdash$ TRANSFER_TOKENS :: ty : mutez : contract ty : $A \Rightarrow$ operation : A

Semantics

TRANSFER_TOKENS / d : z : c : $S \Rightarrow$ transfer_tokens d z c : S

Fig. 13. Rules of TRANSFER_TOKENS [25, 26].

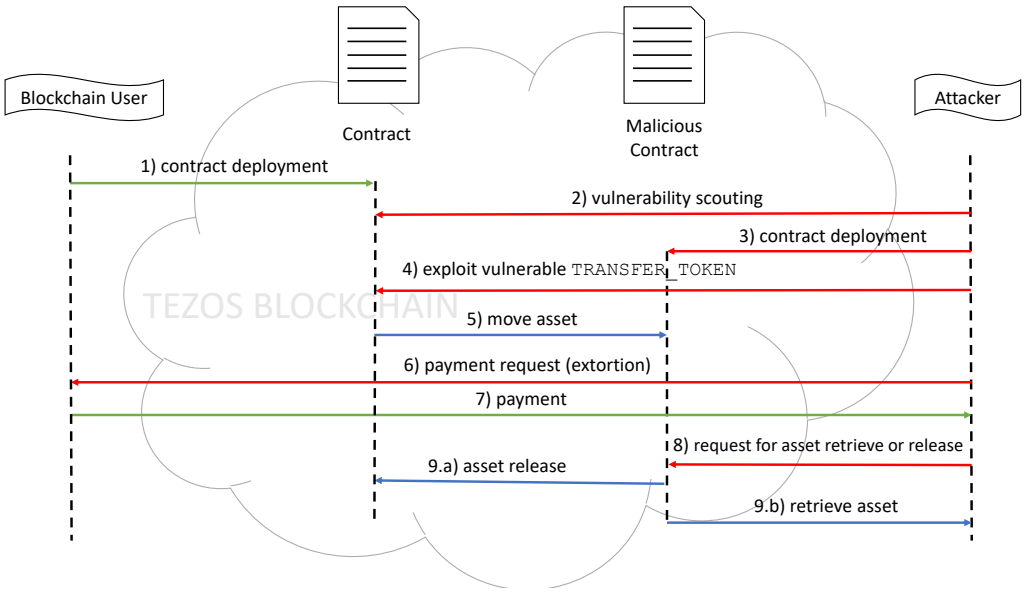


Fig. 14. Extortionware attack model exploiting UCCIs [7, 8].

untrusted peers. In terms of the Smart contract Weakness Classification (SWC) registry, these issues can be classified as *delegatecall to untrusted callee* (SWC-112) [32].

Namely, cross-contract invocations (CCIs) are delegate calls to external contracts, thus allowing smart contracts to execute the code of other contracts in blockchain. An example is for the exchange of fungible and non-fungible tokens. In this regard, Michelson provides the TRANSFER_TOKENS instruction (Figure 13) to withdraw tokens from the current contract balance and send them to a peer's account or to another contract. TRANSFER_TOKENS requires three parameters:

- the target contract c to transfer tokens to, typed as contract ty, where ty is the type of the contract parameter;
- the tokens z to transfer, typed as mutez, which is a specific type for manipulating tokens;
- the value parameter d of the contract c, that must have type ty.

CCIs are useful, but their naive use might introduce UCCIs that a malicious agent can exploit to inject arbitrary target values, that will be executed in blockchain, leading for instance to extortionware attacks [7, 8]. UCCIs occur when the contract to call is parameterized with untrusted input (that is, data from outside the blockchain). Users can provide any input, also anonymously. In Michelson, input and current storage value are implicitly pushed onto the stack at the beginning of each smart contract execution. Hence, an UCCI may happen whenever one of them is used as target contract of a TRANSFER_TOKENS.

```python
import smartpy as sp

@sp.module
def main():
  class Proxy(sp.Contract):
    def __init__(self, owner):
      self.data.owner = owner

    @sp.entrypoint
    def forward(self, callee):
      sp.transfer((), sp.balance, callee)
```

(a) Python code

```
parameter (contract unit);
storage   address;
code
{
  UNPAIR;
  NIL operation;
  SWAP;
  BALANCE;
  UNIT;
  TRANSFER_TOKENS;
  CONS;
  PAIR;
}
```

(b) Michelson code

Fig. 15. Tezos contract containing an UCCI.

Consider for instance the attack schema in Figure 14. A blockchain user might naively deploy a contract containing a vulnerable TRANSFER_TOKENS instruction and use it to handle assets. After contract deployment, its source code will remain immutable and exposed in the blockchain. An attacker could discover the vulnerability of the contract and exploit it to steal the contract's assets. Specifically, the attacker could redirect the target contract of the TRANSFER_TOKENS instruction to his own malicious contract, and subsequently demand a ransom or permanently take possession of the stolen assets.

Figure 15 shows a concrete example of UCCI, actually exploitable by an attacker. The contract is a proof of concept of a proxy implementation, inspired by the SWC-112 samples in the SWC registry [32]. In general, proxy contracts such as those using proxy upgrade patterns [43], are managed by special users called *contract admin* or *contract owner*. In Figure 15, the proxy contract allows one to set up a contract owner at initialization time (line 7 of Figure 15a) and to transfer the cryptocurrency in the smart contract through function `forward` (line 11). Every user can call `forward`, not just the owner, hence every user can provide the `callee` and transfer the crypto to it, leading to an UCCI. A fix requires a conditional statement to guarantee that only the `owner` may call `forward` (see [32]).

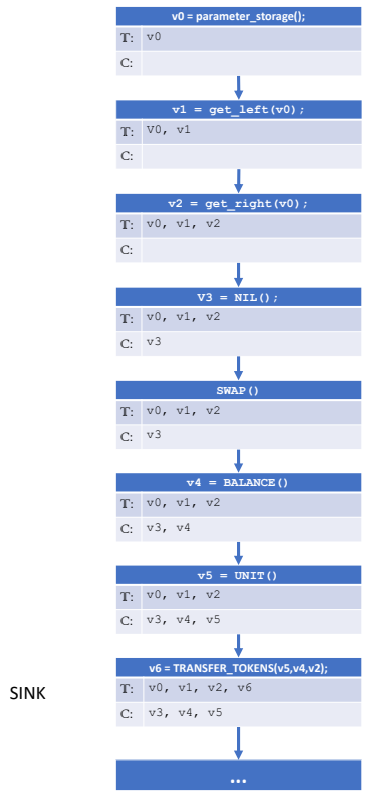
6.2 Taint Analysis for UCCIs Detection

Previous work [40] expressed the detection of UCCIs as a *taintedness* problem. Taint analysis is an instance of information flow analysis [17, 52], that allows one to detect if untrusted information flows, explicitly, from some *sources* into critical program points, called *sinks*. In this context, program variables (denoted by $\mathbb{V}$) are partitioned into *tainted* (denoted by $\mathbb{T}$) and *clean* (denoted by $\mathbb{C}$), where $\mathbb{V} = \mathbb{T} \cup \mathbb{C}$ and $\mathbb{T} \cap \mathbb{C} = \emptyset$. The variables in $\mathbb{T}$ are those that *may* contain untrusted information, while those in $\mathbb{C}$ do not contain tainted values across all possible program executions. The analysis identifies flows of information (in the form of value propagations) from variables in $\mathbb{T}$ to variables in $\mathbb{C}$.

For UCCIs detection, sources are statements providing untrusted user input. For the speicific case of Michelson, the untrusted input is on the stack at the beginning of the smart contract execution, as a pair of the input value and of the current storage value. Since there is no real function or instruction that pushes the input on the stack, MichelsonLiSA models the presence of such a pair by always prefixing the code with a call to function `parameter_storage()`. To consider the result of such function as tainted, `parameter_storage()` is considered as a source for the UCCI

```
1  v0 = parameter_storage();
2  v1 = get_left(v0);
3  v2 = get_right(v0);
4  v3 = NIL();
5  SWAP();
6  v4 = BALANCE();
7  v5 = UNIT();
8  v6 = TRANSFER_TOKENS(v5, v4, v2);
9  v7 = CONS(v6, v3);
10 v8 = PAIR(v7, v1);
```

(a) Michelson IR in SSA form



(b) CFG containing information of taint analysis

Fig. 16. Tezos contract containing an UCCI.

analysis. Instead, sinks are statements performing CCIs. For Michelson, they are the parameters of TRANSFER_TOKENS instructions.

6.2.1 *Running Example.*

During the analysis of the code in Figure 15b, MichelsonLiSA detects the explicit flow leading to an UCCI and issues a true positive warning on the TRANSFER_TOKENS instruction. Figure 16a shows the flow, whose source is highlighted with a blue box and whose sink is highlighted with a red box. Tainted information is propagated in gray. Namely, the analysis begins after the computation of the SSA form. It identifies sources and sinks at line 1 and line 8, respectively: Tainted data is propagated from `v0 = parameter_storage()` to `v2 = get_right(v0)` at line 3. Then, at line 8 it reaches TRANSFER_TOKENS through `v2`. The program has assigned `nil`, the current balance of the contract, and a unit value to `v3`, `v4` and `v5`, respectively. These variables are clean since such values are not related to the user input: they are constants or, in the case of BALANCE, they are a value that is not controlled by the user.

At the end of taint analysis, MichelsonLiSA issues a warning at line 8 because the sink, that is, the third parameter of TRANSFER_TOKENS, is tainted. Therefore, the user will be able to directly identify the critical point of the program highlighted by the warning, inspect the CFG with the

Analysis	Exec. time	Avg. time per file	# Warnings
Taint UCCI	2h 32m 8s	9.12s	2834

Table 2. Taint analysis for UCCI detection in Michelson smart contracts.

analysis information produced by MichelsonLiSA (a simplified view is in Figure 16b), understand the data propagation path and conclude that it is a true positive.

6.2.2 *Experimental Results.*

The goal of this experimental evaluation is to test applicability and performance of MichelsonLiSA, for the detection of UCCIs on Tezos smart contracts. The chosen artifact set is the same used in [40], i.e. 1000 Michelson smart contracts (770060 lines of code) containing the instruction `TRANSFER_TOKENS`. They have been randomly retrieved from [48], a repository containing 6983 Michelson contracts coming from a Tezos testnet. This set has been chosen for its code diversity, in terms of size and complexity, and for its many CCIs. The same would be difficult to retrieve from the Tezos blockchain through its public APIs.

Experiments have been executed on a HP EliteBook 850 G4 equipped with an Intel Core i7-7500U at 2,70/2,90 GHz and 16 GB of RAM memory, running Windows 10 Pro 64bit, with Oracle JDK version 13 to run the analyzer.

Table 2 reports the results of the experimental evaluation. In terms of time, the analysis requires less than nine seconds per smart contract, on average. The analysis issues warnings about 2834 cross-contract invocations distributed in 781 smart contracts.

6.2.3 *Discussion.*

In general, the precision of an analysis depends on its abstraction level, which is often inversely related to its computational cost. In particular, traditional taint analysis only tracks binary information (*taint*/*clean*) across program variables. This makes the analysis scalable to software of industrial size (between 100KLOCs and 1MLOCs) [22, 58]. Our taint analysis implementation applies over-approximations to guarantee *soundness*. This means that *clean* variables definitely hold trusted values, while *tainted* variables *might* contain untrusted values, being sound entiles false positives, that must be disambiguated by manual investigation. However, manual investigation is challenging. As Section 4.1 reports, Michelson is a low-level language and it is rather difficult to reverse-engineer its code, where high-level information is lost after compilation. At the end of the analysis, MichelsonLiSA provides an additional report containing the analyzed CFGs in various formats (such as html and dot), with details about the computed abstractions. This allows one to check, for each program point, which variables the analysis infers as tainted or clean. However, in order to spot over-approximations and false positives by manual investigation, one should manually recompute the entire execution stack for every single instruction and check if its execution might lead to a tainted value or not, exploiting MichelsonLiSA's report. This activity is time-consuming, given the complexity of some contracts.

Consider for instance the code in Figure 17. Its untrusted input is used to index a map containing hardcoded addresses. The analysis starts by propagating the parameter and storage inputs in `v0 = parameter_storage()`. The untrusted information of `v0` flows into `v1 = CAR(v0)` and then into `v3 = GET(v1,v2)`. Given a key and a map, the instruction `GET` retrieves a value from the map. Therefore, the input parameter is used to select a hardcoded address from a map. However, our analysis propagates the untrusted information to `v3` because at least one of the two variables in `GET(v1,v2)` is untrusted. Going forward, that untrusted information propagates to `v4 = extract_value(v3)`, `v6 = CONTRACT(v4)`, and `v7 = extract_value(v6)`. From there, it flows into `TRANSFER_TOKENS(v10,v9,v7)`, where the analysis issues a warning since `v7` is

```
1  parameter int ;
2  storage unit ;
3  code {
4    CAR ;
5    PUSH (map int address) {
6      Elt 0 "tz1KqT...b7QbPE" ;
7      Elt 1 "tz2VGB...S6rna5"
8    } ;
9    SWAP;
10   GET ;
11   IF_NONE { PUSH string "key not found" ;
12         FAILWITH }
13   {
14     CONTRACT unit ;
15     IF_NONE { PUSH string "invalid contract" ;
16           FAILWITH }{};
17     AMOUNT ;
18     UNIT ;
19     TRANSFER_TOKENS ;
20     NIL operation ;
21     SWAP;
22     CONS ;
23     UNIT ;
24     SWAP;
25     PAIR
   }
}
```

(a) Michelson smart contract

```
v0 = parameter_storage();
v1 = CAR(v0);
v2 = PUSH( map { 0 : "tz1KqT...b7QbPE", "1
     " : "tz2VGB...S6rna5" });
v3 = GET(v1,v2);
IF v4 = extract_value(v3) is None {
  v5 = PUSH ("key not found");
  FAILWITH();
}
v6 = CONTRACT(v4)
IF v7 = extract_value (v6) is None {
  v8 = PUSH ("invalid contract");
}
v9 = AMOUNT();
v10 = UNIT();
v11 = TRANSFER_TOKENS(v10,v9,v7);
v12 = NIL();
SWAP();
v13= CONS(v11,v12);
v14= UNIT();
SWAP();
v15=PAIR(v13,v14);
```

(b) Michelson IR in SSA form

Fig. 17. Smart contract that allows one to transfer an amount of tokens to an address that can be selected by the input parameter among those contained in a hard-coded map.

untrusted. However, it is not very intuitive to label this as a false positive and spot the over-approximation, given the reduced readability of low-level languages. Untrusted information originating from `parameter_storage()` at line 1 does not determine, explicitly, the target contract of `TRANSFER_TOKENS(v10,v9,v7)` at line 17, that comes instead from a read-only map (declared at line 5) containing two hardcoded contract addresses. Hence, the CCI transfers tokens to known contracts, always, and is not untrusted.

Given the complexity of the low-level code under analysis, we could not manually investigate all files and compute true positive and false positive rates. However, next section considers more precise abstractions, to spot possible over-approximations and prioritize warnings, hence easing manual investigation.

6.3 Taint Analysis with Three Levels

Taint analysis allows the analyzer to scale to software of industrial size. However, as shown by the benchmark of [40] and as also empirically evident for popular blockchains such as Ethereum [39], smart contracts are typically small (few hundreds/thousands of lines of code). Therefere, it becomes possible to collect more than binary information during taintness propagation without incurring into scalability issues. For instance, it is possible to design a taint analysis based on three sets of variables: $\mathbb{T}$, $\mathbb{C}$ and $\mathbb{P}$, where $\mathbb{V} = \mathbb{T} \cup \mathbb{C} \cup \mathbb{P}$ and $\mathbb{T} \cap \mathbb{C} = \emptyset$, $\mathbb{T} \cap \mathbb{P} = \emptyset$ and $\mathbb{C} \cap \mathbb{P} = \emptyset$. The variables in $\mathbb{T}$ are definitely tainted; those in $\mathbb{C}$ are definitely clean; those in $\mathbb{P}$ are *possibly tainted* (due to over-approximation). In this way, the analyzer can issue warnings of different priority, when the information that flows in a sink is tainted or possibly tainted.

Analysis	Exec. time	Avg. time per file	#T Warnings	#PT Warnings
Taint 3-level UCCI	2h 49m 18s	10.16s	2045	789

Table 3. Taint analysis with three levels for UCCIs detection of Michelson smart contracts.

6.3.1 *Experimental Results.*

Table 3 reports the results of executing our three-levels taint analysis on the same benchmark used in Section 6.2.2: **#T Warnings** is the number of warnings triggered in sinks where the information was marked as *tainted*; **#PT Warnings** is the number of warnings triggered in sinks where the information was marked as *possibly tainted*. The execution time is around ten seconds per smart contract, on average. The analysis issues warnings about 2834 cross-contract invocations: 2045 are related to tainted information, while 789 are related to possibly tainted information. They are distributed into 680 and 219 smart contracts, respectively (there are smart contracts that contains both kinds of warnings).

6.3.2 *Discussion.*

The proposed analysis distinguishes when an explicit flow from an untrusted input to a transfer token invocation *definitely* happens (when the parameter is *tainted*) or *might* happen (when the parameter is *possibly tainted*). The former are situations when there is a direct non-overapproximating flow of information from source to sink. The latter, instead, models situations when either there might be multiple execution paths leading to the sink with different taintedness, or when over-approximation has been applied. This helps the user investigate the warnings, giving priority to those that represent definite vulnerabilities.

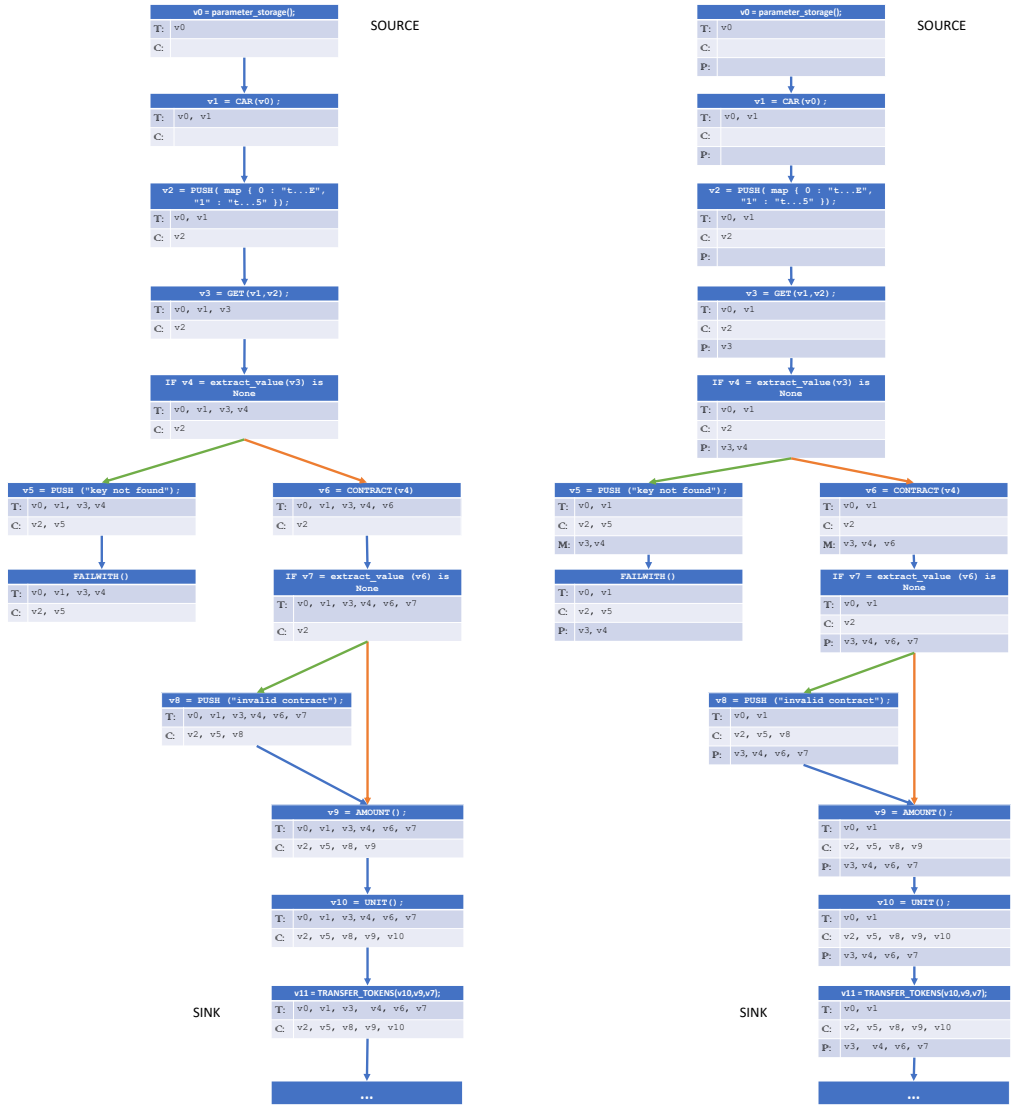
Figure 18 shows simplified CFGs with analysis information produced by MichelsonLiSA for the code in Figure 17. In general, the result of taint analysis is a set of warnings for potentially vulnerable program points, with the indication of the sink parameter that is reached by tainted data. Hence, manual investigation starts from the sinks. In Figure 18a, the only way for checking the correctness of the warning is to reconstruct the flow, backwards from the sinks, because there is no indication of possible overapproximations. In Figure 18b, instead, it is apparent where variables are added to the set $\mathbb{P}$: the user can check whether that is an overapproximation or not, without investigating all flows backwards.

Comparing the experimental results of the two approaches to taint analysis, the three-levels one detects around 27% of the total warnings as overapproximations. The analysis requires slightly more time than traditional taint analysis, a second more, on average. This might seem negligible, but is actually a 10% increase, on average. In industrial code analysis, this is a big difference in terms of time, assuming that there are enough resources to handle the information collected by the analysis. Instead, in the blockchain context, it is possible to design analyses that typically would not apply to traditional software, hence opening new development scenarios.

6.3.3 *Other limitations of Taint Analysis.*

Information flow analysis understands how information flows inside a program during its execution. Information flows can be of three different categories (see Figure 19):

- *explicit flows* are those when the information in variable x is explicitly transferred to y;
- *implicit flows* are those when the information in variable y implicitly depends on the information in variable x; (for instance, an assignment guarded by x)
- *side channels* are observable properties of the execution that depend on the information in variable x (for instance, the amount of computational resources consumed).



(a) CFG containing traditional taint analysis information.

(b) CFG containing taint analysis information with three levels.

Fig. 18. Simplified CFGs, as reported by MichelsonLiSA.

Taint analysis can only detect explicit flows. Nevertheless, it is a good compromise between performance and quality of the results. Historically, static information flow analysis for security focused on explicit flows in order to be cheaper and have fewer false positives. Implicit flows are harder to explain and understand, and their use by attackers remains a theoretical possibility only. Side channels are outside the scope of this paper, as information disclosure cannot introduce UCCIs.

```
var x,y
y = x
```

(a)

```
var x,y
if x == true:
  y = 3
else:
  y = 42
```

(b)

```
var x,y
if x == 1:
  (* time-consuming work *)
  y = 0
```

(c)

Fig. 19. Example of (a) explicit, (b) implicit, and (c) side channel flows, where h and l represent secret and public variables, respectively.

7 RELATED WORK

This section is divided in two parts. The first part presents related work about other analyzers and frameworks for the design and implementation of new static analyses for smart contracts. This first comparison does not consider the specific analyses that have been implemented for each analyzer and framework, but the structure and domain of application of such tools only. Fistly, the specific analyses are not relevant in this comparison; secondly, the implemented analyses for each framework are often not clarified in the description of the framework or tools.

The second part of this section instead reports other analyses that are somehow related to the use of information flow for UCCIs detection, which is the new analysis introduced here.

Many smart contract verification tools have emerged since the dawn of blockchain technology [59]. Most of them apply to Ethereum [2] since, historically, it was the first successful blockchain to introduce a Turing-complete language for smart contracts. Regarding Tezos, it is a relatively new blockchain, hence it does not boast a large coverage of verification tools. Mi-Cho-Coq [6], ConCert [30], and WhylSon [4] allow one to verify the functional correctness of Michelson contracts through proof assistants. They all rely on theorem proving, which requires formal specifications of the expected behavior of the code, such as pre- or post-conditions. Therefore, unlike MichelsonLiSA, their use is not fully automatic. The same holds for Helmholtz [37], that type-checks Michelson smart contracts against a user-provided specification based on a type system, by using the Z3 solver. Reis et al. [49] propose SoftCheck for data-flow analyses of Michelson code providing an IR called Tezla that linearizes the stack into a store of variables. The approach is similar to ours, especially regarding the IR form, but we followed the abstract interpretation approach instead. Bau et al. [5] extends MOPSA [31] to perform static analyses for Michelson. MOPSA is an abstract interpretation framework and the major alternative to LiSA. It is designed to compute fixpoints by induction on a program's syntax and considers a program as an extensible AST that initially contains the original source code, but that can be syntactically and semantically rewritten during the analysis.

Regarding UCCIs detection, several techniques are applied for other blockchains. ContractFuzzer [24] generates fuzzing inputs and defines test oracles to detect security vulnerabilities, including problems related to UCCIs in Solidity. Mythril [44] bases the analysis on symbolic execution and concrete execution techniques to discover vulnerabilities, including UCCIs. It combines static execution with dynamic execution to improve path coverage and accuracy. SMARTSHIELD [62] dynamically highlights state changes and alterations after CCIs. Wang et al. [61] propose a general platform for defect detection in smart contracts, including UCCI issues. The platform analyzes smart contracts and obtains the semantic description of corresponding functions and variables. Hence, it generates assertions to detect the defects of smart contracts. However, as the authors acknowledge, there are still some problems that need further research and improvement, especially related to the construction of assertions, where human intervention is required.

8 CONCLUSION

Smart contract verification is challenging. Every day new blockchains are born with new programming languages that require formal verification tools to avoid bugs and critical vulnerabilities. This paper describes how to implement and design from scratch an abstract interpretation-based static analyzer for Tezos smart contracts, relying on LiSA. This is a useful resource that supports developers, providing standard components for software verification and allowing one to reduce the implementation time. Furthermore, this paper investigated the use of taint analysis with different levels of abstraction for the detection of UCCIs. The results show, empirically, that it is possible to use abstractions not normally applicable to traditional code, opening new opportunities for the verification of smart contracts. Future work will develop other analyses and investigate other ways to improve taint analysis results, such as the introduction of backflow reconstruction on taint graphs [21]. Moreover, given the multi-language nature of LiSA [34], we will investigate blockchain interoperability to design a cross-blockchain taint analysis, involving other LiSA analyzers such as GoLiSA [41, 42] and PyLiSA [35].

Although this paper applies LiSA to Michelson smart contracts, the same technique can be used, in principle, on other programming languages for smart contracts. For instance, the idea of using information flow to identify UCCIs is not bound to Tezos in any way. However, the specific technicalities will change from language to language. For instance, the preliminary SSA transformation of Michelson code might not be useful for other programming languages. LiSA reduces the overhead of implementing new static analyses, but taking care of such distinguishing technical details still requires some effort and expertise.

ACKNOWLEDGMENTS

Work partially supported by SERICS (PE00000014), iNEST (ECS 00000043) projects funded by PNRR NextGeneration EU, and Bando di Ateneo per la Ricerca 2022, funded by University of Parma, (MUR_DM737_2022_FIL_PROGETTI_B_ARCERI_COFIN, CUP: D91B21005370003), “Formal verification of GPLs blockchain smart contracts”.

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