TEZLA, an intermediate representation for static analysis of MICHELSON smart contracts

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Abstract

This paper introduces TEZLA, an intermediate representation of MICHELSON smart contracts that eases the design of static smart contract analysers. This intermediate representation uses a store and preserves the semantics, flow and resource usage of the original smart contract. This enables properties like gas consumption to be statically verified. We provide an automated decompiler of MICHELSON smart contracts to TEZLA. In order to support our claim about the adequacy of TEZLA, we develop a static analyser that takes advantage of the TEZLA representation of MICHELSON smart contracts to prove simple but non-trivial properties.

1 Introduction

The term “smart contract” was proposed by Nick Szabo as a way to formalize and secure relationships over public networks [22]. In a blockchain, a smart contract is an application written in some specific language that is embedded in a transaction (hence the program code is immutable once it is out in the network). Some examples of smart contracts applications are the management of agreements between parties without resorting to a third party (escrow) and to function as a multi-signature account spending requirement. Smart contracts have the ability to transfer/receive funds to/from users or from other smart contracts and can interact with other smart contracts.

There has been recent reports of bugs and consequently attacks in smart contracts that have led to losses of millions of dollars worth of assets. One of the most famous and most costly of these attacks was on the Distributed Autonomous Organization (DAO), on the Ethereum blockchain. The attacker managed to withdraw approximately 3.6 million ether from the contract.

Given the fact that a smart contract in a blockchain can’t be updated or patched, there is an increasing interest in providing tools and mechanisms that guarantee or potentiate the correctness of smart contracts and to verify certain properties.

However, current tools and algorithms for program verification, based for example on deductive verification and static analysis, are usually designed for classical store-based languages in contrast with MICHELSON, the smart contract language for the Tezos Blockchain [12, 2], which is stack based.

To facilitate the usage of such tools to verify MICHELSON smart contracts, we present TEZLA, a store based intermediate representation language for MICHELSON, and its respective tooling. We provide an automated decompiler of MICHELSON smart contracts to TEZLA. The

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The Tezla decompiler preserves the semantics, flow and resource usage of the original smart contract, so that properties like gas consumption can be faithfully verified at the Tezla representation level. To support our work, we present a case-study of a demo platform for the static analysis of Tezos smart contracts using the Tezla intermediate representation alongside with an example analysis.

The paper is structured as follows. In section 2 we introduce the syntax and semantics of Tezla. The decompiler mechanism is described in section 3. Section 4 addresses the static analysis platform case-study that targets Tezla-represented smart contracts. Finally section 5 concludes with a general overview of this contribution and future lines of work.

2 Tezla

Tezla aims to facilitate the adoption of existing static analysis tools and algorithms. As such, Tezla is an intermediate representation of Michelson code that uses a store instead of a stack, enforces the Static Assignment Form (SSA) and preserves information about gas consumption. We will see in the next section how such characteristics ease the translation of Tezla program into their Control Flow Graph (CFG) forms and the construction of data-flow equations.

Compiled languages (like Albert, LIGO, SmartPy, Lorentz, etc.) also provide a higher-level abstraction over Michelson. However, as it happens with most compiled languages, the produced code may not be as concise or compact as expected which, in the case of smart contracts, may result in undesired costs. Tezla was designed to have a tight integration with the Michelson code to be executed, not as a language that compiles to it nor a higher level language that ease the writing of Michelson smart contracts.

In the Tezla representation, push-like instructions are translated into variable assignments, whereas instructions that consume stack values are transformed to expressions that use as arguments the variables that match the values from the stack. Furthermore, lists, sets and maps deconstruct and lifting of option and or types that happen implicitly are represented through explicit expressions added to Tezla.

Since the operational effect of stack manipulation is transposed into variable assignments, we also expose in a Tezla represented contract the stack manipulation as instructions that act as no-op instructions in the case of a semantics that do not take resource consumption into account\(^1\). In the case of a resource aware semantics, these instructions will semantically encode this consumption.

The following section describes in detail the process of transforming a Michelson smart contract to a Tezla representation.

2.1 Push-like instructions and stack values consumption

Instructions that push \(N\) values to the stack are translated to \(N\) variable assignments of those values. The translation process maintains a Michelson program stack that associates each stack position to the variable to which that position value was assigned to. When a stack element is consumed, the corresponding variable is used to represent the value. A very simple example is provided in fig. 1.

The block on figure 1a is translated to the Tezla representation shown in figure 1b.

From the previous example, we can also observe that Michelson instructions that consume \(N\) stack variables are translated to an expression that consumes those \(N\) values. Concretely,

\(^1\)This is the case of the semantics presented in this paper.
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PUSH nat 5;
PUSH nat 6;
ADD;

(a) Michelson code.

v1 := PUSH nat 5;
v2 := PUSH nat 6;
v3 := ADD v1 v2;

(b) Tezla code.

Figure 1: Stack manipulation example.

the instruction ADD that consumes two values (say, a and b), from the stack is translated to ADD a b.

2.2 Branching

Michelson provides developers with branching structures that act on different conditions. As Tezla aims at being used as an intermediate representation for static analysis, there are some properties we would like to maintain. One such property is static single assignment form (SSA-form) [18]. This is guaranteed as Tezla-represented smart contracts are, by construction, in SSA-form, since each assignment uses new variables.

In order to deal with branching, the Tezla representation makes use of \( \phi \)-functions (see [18]) that select between two values depending on the branch. As an illustration consider the Michelson example in figure 2a.

parameter int;
storage (list int);

(a) Michelson code.

code { UNPAIR;
        SWAP;
        IF_CONS
          { DUP ; DIP { CONS ; SWAP } ;
            ADD ; CONS }
        { NIL int ; SWAP ; CONS };
        NIL operation ;
        PAIR }

v0 := CAR parameter_storage;
v1 := CDR parameter_storage;
SWAP;
IF_CONS v1
  { v2 := hd v1;
v3 := tl v1;
v4 := DUP v2;
v5 := CONS v2 v3;
SWAP;
v6 := ADD v4 v0;
v7 := CONS v6 v5 }
  { v8 := NIL int;
SWAP;
v9 := CONS v0 v8
};
v10 := \phi(v7, v9);
v11 := NIL operation;
v12 := PAIR v11 v10;

(b) Tezla code.

Figure 2: Branching example.

This contract takes an int as parameter and a list of ints as storage and inserts the sum of the parameter with the head of the list at the list’s head. If the list is empty, it inserts the parameter into the empty list. Here, each branch of the IF_CONS instruction will result in a stack with a list of integers, whose values depends on which branch was executed.

This translates to the Tezla representation presented figure 2b.
The variable \( v_{10} \) will receive its value through a \( \phi \)-function that returns the value of \( v_7 \) if the true branch is executed, or the value of \( v_9 \) otherwise.

The \texttt{IF\_CONS} instruction deconstructs a list in the true branch, putting the head and the tail of the list on top of the stack. From this example, it is possible to observe that the deconstruction of a list is explicit through two variable assignments. This is also the behaviour of \texttt{IF\_NONE} and \texttt{IF\_LEFT} instructions, where the unlifting of \texttt{option} and \texttt{or} types happens explicitly through an assignment.

### 2.3 Loops, maps and iterations

\texttt{Michelson} also provides language constructs for looping and iteration over the elements of lists, sets and maps. These are treated using the same \( \phi \)-functions mechanism in order to preserve SSA-form. We can observe this on the example fig. 3.

\begin{verbatim}
PUSH nat 0 ; v0 := PUSH nat 0;
LEFT nat ; v1 := LEFT nat v0;
LOOP_LEFT LOOP_LEFT v2 := \( \phi (v1, v12) \)
{ DUP ; v3 := unlift_or v2;
  PUSH nat 100 ; v4 := DUP v3;
  COMPARE ; v5 := PUSH nat 100;
  GE ; v6 := COMPARE v5 v4;
  IF v7 { PUSH nat 1; v8 := PUSH nat 1;
    ADD ; v9 := ADD v8 v3;
    LEFT nat } v10 := LEFT nat v9;
  } { RIGHT nat } v11 := RIGHT nat v3;
  } v12 := \( \phi (v10, v11) \);
  } unlift_or v2;
  INT v13 := INT v13;

(a) \texttt{Michelson} code. (b) \texttt{Tezla} code.

Figure 3: Loop example.
\end{verbatim}

This example uses a \texttt{LOOP\_LEFT} (loop with an accumulator) to sum 1 to a \texttt{nat} (starting with the value 0) until that value becomes greater than 100 and casts the result to an \texttt{int}. This example translates to the code presented in fig 3b.

Note that the \texttt{LOOP\_LEFT} variable is assigned to the value of \( v_1 \) if it is the first time that the loop condition is checked, or \( v_{12} \) if the program flow comes from the loop body. Also notice that the same explicit deconstruction of an \texttt{or} variable is applied here, where \( v_5 \) gets assigned the value of the unlifting of the loop variable in the beginning of the loop body and at the end of the loop. Similar behaviour applies to the other looping and iteration instructions.

### 2.4 Full example

We now present a full example of a complete \texttt{Michelson} smart contract (figure 4a).
The contract takes a list of bools as parameter and iterates over that list. It performs a boolean AND between an element of the list and the previous AND (the initial value of this accumulator is the bool on the storage). Depending on the result it either adds 1 or -1 to the int on the storage. The values to be stored are the last AND result, the nat that was previously on the storage (notice that this value isn’t changed nor it is used anywhere else in the program) and the resulting int from the sums on the iteration. This contract translates to the Tezla code of fig. 4b.

In this complete example we can observe that a Michelson contract has a parameter and storage. The initial stack of any Michelson smart contract is a stack that contains a single pair whose first element is the input parameter and second element is the contract storage. As such, we introduce a variable called parameter_storage that contains the value of that pair.

The final stack of any Michelson smart contract is also a stack that contains a single pair whose first element is a list of internal operations that it wants to emit and whose second element is the resulting storage of the smart contract. We identify the variable containing this pair through the addition of a return instruction.
3 Building statics analyses for Tezla smart contracts

In this section, we present the experiments conducted in order to test and demonstrate the applicability of the Tezla intermediate representation to perform static analysis.

3.1 SoftCheck

We build and organise these static analyses upon a generic data-flow analysis platform called SoftCheck [16]. SoftCheck provides an internal and intermediate program representation, called SCIL, rich enough to express high-level as well as low-level imperative programming constructs and simple enough to be adequately translated into CFGs.

SoftCheck is organised upon a generic monotone framework [13] that is able to extract a set of data-flow equations from (1) a suitable representation of programs and; (2) a set of monotone functions; and then to solve them. SoftCheck is written in OCAML and makes use of functor interfaces to leverage its genericity (see fig 5).

By generic we mean that, given a translation from a programming language to SCIL. SoftCheck gives the ability to instantiate its underlying monotone framework by means of a functor interface. Then all defined static analyses are automatically available for the given programming language.

On the other hand, once written as a set of properties and monotone functions, a particular static analysis can be incorporated (again, through instantiating a functor) as an available static analysis for all interfaced programming languages.

SoftCheck offers several standard data-flow analysis such as very busy expressions, available expressions, tainted analysis etc.

We propose in the next sections to detail how we have interfaced Tezla with SCIL, how we have designed a simple but useful data-flow analysis within SoftCheck and how we have tested this analysis on the Michelson smart contracts running in the Tezos blockchain.

Figure 5: SoftCheck in a picture
3.2 Constructing a Tezla Representation of a Contract

To obtain the Tezla representation of a smart contract, we first developed a parser to obtain an abstract syntax representation of a Michelson smart contract. This parser was implemented in OCaml and Menhir and respects the syntax described in the Tezos documentation [2]. It allows us to obtain a data type that fully abstracts the syntax (with the exception of annotations). To improve the integration between these two forms, Tezla data types were built upon the data types of Michelson.

Control-flow graphs are a common representation among static analysis tools. We provide a library for automatic extraction of such representation from any Tezla-represented smart contract. This library is based upon the control-flow generation template present on SoftCheck. As such, control-flow graphs generated with this library can be used with SoftCheck without further work. To instantiate the control-flow graph generation template, we simply provided the library with a module with functions that describe how control flows between each node.

3.3 Sign detection: an example analysis

Here we devise an example of a static analysis for sign detection. The abstract domain consists of the following abstract sign values: 0 (zero), 1 (one), 0+ (zero or positive), 0- (zero or negative), \(\top\) (don’t know) and \(\bot\) (not a number). These values are organised according to the lattice on figure 6.

![Sign lattice](image)

Figure 6: Sign lattice.

Using SoftCheck, we implemented a simple sign detection analysis of numerical values. By definition, nat's have a lowest precision value of 0+, while int's can have any value. Every other data type has a sign value of \(\bot\).

This implementation does not propagate information to non-simple types (pair, or, etc.), but it does perform some precision refinements on branching.

To implement such an analysis, we provided SoftCheck, in addition to the previously defined Tezla control-flow graph library, a module that defines how each instruction impacts the sign value of a variable. Then, using the integrated solver mechanism based on the monotone framework, we are able to run this analysis on any Tezla represented smart contract.

We now present an example. Figure 7 shows the code of a smart contract and its Tezla representation. This contract multiplies its parameter by \(-5\) if the parameter is equal to 0, or by \(-2\) otherwise, and stores the result in the storage. Figure 8 shows the control-flow graph of representation of that contract.

Running this analysis on the previously mentioned contract produced the results available in Figure 9. In these results we can observe the known sign value of each variable at the exit of each
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\texttt{parameter nat ;}
\texttt{storage int ;}
\texttt{code \{ CAR ;}
  \texttt{DUP ;}
  \texttt{PUSH nat 0 ;}
  \texttt{COMPARE ;}
  \texttt{EQ ;}
  \texttt{IF \{ PUSH int -5 ; MUL \}}
  \texttt{\{ PUSH int -2 ; MUL \} ;}
  \texttt{NIL operation ;}
\texttt{PAIR \}}

(a) Michelson code.

\texttt{v0 := CAR parameter_storage;}
\texttt{v1 := DUP v0;}
\texttt{v2 := PUSH nat 0;}
\texttt{v3 := COMPARE v2 v1;}
\texttt{v4 := EQ v3;}
\texttt{IF v4}
\texttt{\{ v5 := PUSH int -5;}
\texttt{v6 := MUL v5 v0}
\texttt{\} ;}
\texttt{v7 := PUSH int -2;}
\texttt{v8 := MUL v7 v0 ;}
\texttt{v9 := phi(v6, v8);}
\texttt{v10 := NIL operation;}

(b) Tezla code.

Figure 7: Example contract for sign analysis.

block of the control-flow graph in Figure 8. For brevity purposes, we omitted non-numerical variables from the result.

It it possible to observe from the results that the analysis takes into account several details. For instance, the sign of values of type nat are, by definition, always zero or positive. The analysis also refines the sign values on conditional branches according to the test. In this case, we can notice that in blocks 6 and 7 (true branch) the sign value of v1 must be 0, as the test corresponds to 0 == v1. Complementary to this, in blocks 8 and 9 the value of v1 assumes the sign value of +, given that being a nat value its value must be 0+ and we know that its values is not zero because the test 0 == v1 failed.

We can also conclude from the result of this analysis that the block 17 (true branch) will never be carried out, as the test of that conditional (0 < v11) will always be false because the sign of v11 is 0-, which means it will always be less than 0.

Due to the Tezla nature, we were able to take advantage of existing tooling, such as the SoftCheck platform, and effortlessly design the run a data-flow analysis. This enables and eases the development of static analysis that can be used to verify smart contracts but also to perform code optimisations, such as dead code elimination. Albeit simple, the sign analysis can be used to instrument such dead code elimination procedure.

3.4 Experimental Results and Benchmarking

Tezla and all the tooling are implemented in OCaml and are available under [1]. Tezla accepts Michelson contracts that are valid according to the Tezos protocol 006 Carthage. We conducted Experimental evaluations that consisted in transforming to Tezla and running the developed analyses on a batch of smart contracts.

In order to so, we implemented a tool that allows the extraction of smart contracts available in the Tezos blockchain. With that tool, we extracted 142 unique smart contracts. We tested these unique contracts alongside 21 smart contracts we have implemented ourselves.
We successfully converted all smart contracts with a coverage result of all Michelson instructions except for 9 instructions that were not used in any of these 163 contracts. On those, we ran the available analyses and obtained the benchmarks presented on Table 1. These experiments were performed on a machine with an Intel i7–8750H (2.2 GHz) with 6 cores and 32 GB of RAM.

In the absence of an optimisation tool that takes advantages of the information computed by the analysis, the reports produced by the analysis need to be manually inspected. These reports, the source code of contracts under evaluation, as well as the respective analysis result and other performed static analyses are available at [3, 17].

|                         |                  | Worst-case (number of instructions) |
|-------------------------|------------------|-------------------------------------|
| Average time            | 0.48 s           | 2231                                |
| Worst-case (time)       | 9.87 s (926 instructions) | (6.08 s)                            |
| Average time per instruccion | 0.0009             |                                     |

Table 1: Benchmark results.
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4 Related Work

Albert [8] is an intermediate language for the development of Michelson smart contracts. This language provides an high-level abstraction of the stack and some of the language datatypes. This language can be compiled to Michelson through a compiler written in Coq that targets Mi-Choc-Coq [7], a Coq specification of the Michelson language.

Several high-level languages [4, 5, 14, 9, 21] that target Michelson have been developed. Each one presents a different mechanism that abstracts the low-level stack usage. However, a program analysis tool that would target one of these languages should not be easily reusable to programs written in the other languages.

Scilla [19, 20] is an intermediate language that aims to be a translation target of high-level languages for smart contract development. It introduces a communicating automata-based computational model that separates the communication and programming aspects of a contract. The purpose of this language is to serve as a basis representation for program analysis and verification of smart contracts.

Slither [11], presented in 2019, is a static analysis framework for Ethereum smart contracts. It uses the Solidity smart contract compiler generated Abstract Syntax Tree to transform the contract into an intermediate representation called SlithIR. This representation also uses a SSA form and reduced instruction in order to facilitate the implementation of program analyses of smart contracts. However Slither has no formal semantics and also the representation is not able to accurately model some low level information like gas computations.

Solidifier [6] is a bounded model checker for Ethereum smart contracts that converts the original source code to Solid, a formalisation of Solidity that runs on its own execution environment. Solid is translated to Boogie, an intermediate verification language that is used by the
bounded model checker Corral, which it then used to look for semantic-property violations.

Durieux et. al [10] presented a review on static analysis tools for Ethereum smart contracts. This work presents an extensive list of 35 tools, of which 9 respected their inclusion criteria and were used to test several vulnerabilities on a sample set of 47,587 smart contracts.

5 Conclusion

To the best of our knowledge, this is the first work towards a static analysis framework for Tezos smart contracts. Tezla positions itself as an intermediate representation obtained from a Michelson smart contract, the low-level language of Tezos smart contracts. This representation abstracts the stack usage through the usage of a store, easing the adoption of mechanism and frameworks for program analysis that assume this characteristic, while maintaining the original semantics of the smart contract.

We have presented a case study on how this intermediate representation can be used to implement a static analysis by using Tezla along side the SoftCheck platform. This has shown how effortlessly one can perform static analysis on Michelson code without forcing developers to use a different language or implement ad-hoc static analysis tooling for a stack based language.

Michelson smart contracts have a mechanism of contract level polymorphism called entrypoints, where a contract can be called with an entrypoint name and an argument. This mechanism takes the form of a parameter composed as nesting of or types with entrypoint name annotations. This parameter is then checked at the top of contract in a nesting of IF_LEFT instructions, running the desired entrypoint this way. This mechanism is optional and transparent to smart contracts without entrypoints. As such, they are also transparent to Tezla. We therefore plan to extend Tezla in order to deal with entrypoints and generate isolated components for each entrypoint of a smart contract, which allow us to obtain clearer control-flow graphs and analysis results.

Future plans include a formal account of the Tezla resource analysis in order to formally verify that the semantics (including gas consumption) of a Tezla-represented contract are maintained in respect to the original Michelson code. This will also make way to the development of a platform for principled static analysis of Michelson smart contracts. We plan to study which properties are of interest so that we can integrate existing tools and algorithms for code optimization, resource usage analysis and security and correctness verification.

Another direction to tackle is the interfacing of Tezla with other static analysis platforms such as those provided by the MOPSA project [15] which, among other abilities, provides a means to integrate static analyses.

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