Safety Verification of Declarative Smart Contracts

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Abstract—Smart contracts manage a large number of digital assets nowadays. Bugs in these contracts have led to significant financial loss. Verifying the correctness of smart contracts is, therefore, an important task. This paper presents an automated safety verification tool, DCV, that targets declarative smart contracts written in DeCon, a logic-based domain-specific language for smart contract implementation and specification. DCV proves safety properties by mathematical induction and can automatically infer inductive invariants using heuristic patterns, without annotations from the developer. Our evaluation on 20 benchmark contracts shows that DCV is effective in verifying smart contracts adapted from public repositories, and can verify contracts not supported by other tools. Furthermore, DCV significantly outperforms baseline tools in verification time.

I. INTRODUCTION

Smart contracts are programs that process transactions on blockchains – a type of decentralized and distributed ledgers. The combination of smart contracts and blockchains has enabled a wide range of innovations in many fields including banking [12], trading [31], [13], and financing [37], etc.

Nowadays, smart contracts are managing a massive amount of digital assets [1] but they also suffer from security vulnerabilities [2], [3], [1], which have lead to significant financial loss. In addition, since smart contracts are stored and executed on blockchains, once they are deployed, it is hard to terminate execution and update the contracts when new vulnerabilities are discovered.

One way to reduce potential vulnerabilities, whose patterns are unknown during development, is safety verification: a smart contract that is always safe is less likely to suffer from undiscovered vulnerabilities [25], [32]. Thus, this work focuses on the problem of safety verification for smart contracts.

Most existing solutions directly verify the implementation of smart contracts [7], [23], [28], [25], [32]. These solutions have worked very well on verifying properties concerning one single transaction, e.g., integer overflow. However, when it comes to properties that needs to hold across an infinite sequence of transactions, these approaches suffer from low efficiency due to state explosion issues. Some solutions [21], [15] trade soundness for efficiency, verifying properties up to a certain number of transactions.

On the other hand, in model-based verification approaches, a formal model of the smart contract is specified separately from the implementation. Given such a formal model and the implementation, two kinds of verification problems are studied: (1) Does the formal model satisfy the desired properties [29], [16], (2) Is the implementation consistent with the formal model [18]? While this verification approach is generally more efficient, as the formal model abstracts away implementation details that are irrelevant to the verification task, it does require additional effort from the user since they need to specify the formal model in addition to the implementation. Additionally, the steep learning curves of formal specification languages may limit the adoption of such verification approach.

This paper proposes an alternative verification approach based on an executable specification of smart contracts. In particular, we target smart contracts written in DeCon [17], a domain-specific language for smart contract specification and implementation. A DeCon contract is a declarative specification for the smart contract by itself, making it more efficient to reason about than the low-level implementation in Solidity. It is also executable, in that it can be automatically compiled into a Solidity program which can be deployed and run on the Ethereum blockchain. Automatic code generation based on the verified specification can save developers the manual effort of implementing the contract. The high-level abstraction and executability of DeCon make it an ideal target for verifying contract-level properties.

We implement a prototype, DCV (DeCon Verifier), for verifying declarative smart contracts. Properties are specified as declarative queries for safety violations in the DeCon language. DCV verifies safety invariants using mathematical induction on the sequence of transactions. A typical challenge in induction is to infer inductive invariants that can help prove the target property. Our key insight for addressing this challenge is that the DeCon language exposes the exact logical predicates that are necessary for constructing inductive invariants, which makes inductive invariant inference tractable.

Another benefit of using DeCon is that it provides uniform interfaces for both contract implementation and property specification. Specifically, DeCon models the smart contract states as relational databases, and properties as violation queries against these databases. Thus, developers can specify both the contract logic and its properties in a declarative and succinct way, and finish the verification and implementation automatically.

This paper makes the following contributions.

- A verification method for smart contracts, targeting contract-level safety invariants based on a declarative specification language and the induction proof strategy (Sections IV, V).
- A domain-specific adaptation of the Houdini algorithm [26] to infer inductive invariants for automated
proof (Section V).
- An open-source verification tool for future study and comparison.
- Evaluation that compares DCV with state-of-the-art verification tools, on 20 representative benchmark smart contracts. Specifically, DCV successfully verifies all benchmarks, including the ones not supported by other tools. Furthermore, it is significantly more efficient than other tools in terms of verification time (Section VI).

II. ILLUSTRATIVE EXAMPLE

Figure 1 presents an overview of DCV. It takes a smart contract and a property specification (in the form of a violation query) as input, both of which are written in the DeCon language (Section III). The smart contract is then translated into a state transition system, and the property is translated into a safety invariant on the system states. DCV then verifies the transition system preserves the safety invariant by mathematical induction. In our prototype, the verification is performed by Z3 [11], an automated theorem prover.

If the verification succeeds, DCV guarantees that the smart contract is safe by ensuring that the violation query result is always empty, and returns an inductive invariant as a proof. However, if the verification fails, DCV returns "unknown", indicating that the smart contract may not satisfy the specified safety invariant.

In the rest of this section, we use a voting contract as an example to illustrate the workflow of DCV. This example is adapted from the voting example in Solidity [8], simplified for ease of exposition.

A. A Voting Contract

Listing 1 shows the implementation of this voting contract in DeCon [17], which consists of three major components:

1) Participants cast their votes by sending vote transactions, and these transaction records are stored in the "Vote Txs" table (on the left), with the voter address and proposal ID ("Prop.") listed as columns.
2) For each proposal p, the number of votes it receives can be counted by grouping the entries in the "Vote Txs" table by the "Prop." column, and then counting the number of entries within each group. The counting results are displayed in the "Vote counts" table (middle).
3) The proposal that first reaches a quorum is declared as the winner. Suppose in this example there are 5 participants and the quorum size is 3, proposal 2 is selected as the winner as it gets 3 votes.

B. Smart contract written in DeCon language

Listing 1 shows the implementation of this voting contract in DeCon [17], which consists of three major components:

1) Relation declaration and annotation. The relations shown in Figure 2 along with other auxiliary relations, are declared in lines 1 to 10 of Listing 1. These declarations define the table schema in relational databases, where each schema consists of the table name followed by column names and types in parentheses. Optionally, a square bracket annotates the index of the primary key columns, indicating that these
columns uniquely identify a row. For example, the relation votes(proposal: uint, c: uint)[0] on line 5 has the first column, proposal ID, as the primary key because votes are counted for each unique proposal. If no primary keys are annotated, all columns are interpreted as primary keys, meaning that the table is a set of tuples.

A special kind of relation is a singleton relation, annotated by ∗. Singleton relations only have one row, such as winningProposal in line 8.

By default all relational tables are initialized to be empty, except relations annotated by the init keyword (line 12). These relations are initialized by the constructor arguments passed during deployment.

(2) Relation definition in inference rules. Each relation is defined in the form of a rule, head :- body. Similar to the rules used in Datalog programs, the body consists of a list of relational literals, and is evaluated to true if and only if there exists a valuation of all variables such that each literal has the corresponding concrete entries in the table. If the body is true, the head is inserted into the corresponding table.

For instance, the rule in line 15 specifies that a vote transaction can be committed if there is no winner yet, the message sender is a registered voter, and the voter has not voted before. The literal recv_vote(p) represents a transaction handler that evaluates to true upon receiving a vote transaction request. Rules that contain such transaction handlers (literal with a recv_ prefix in the relation name) are referred to as transaction rules. Committing a transaction inserts a new entry into the transaction table (“Vote Txs” in Figure 2).

Inserting a new vote(v,p) literal also triggers updates to all its direct dependent rules. A rule is considered directly dependent on a relation R if and only if a literal of relation R is in its body. In this case, relation votes and voted are updated next. The chain of dependent rule updates continues until no further dependent rules can be triggered, and the transaction handling is finished. Using this mechanism, the votes for each proposal, as well as the winning proposal, are automatically updated when new votes are approved.

On the other hand, if the body of a transaction rule evaluates to false upon receiving a transaction request, the transaction request is rejected, and no updates are made to any of the affected relations.

(3) Properties as violation query. Line 32 specifies a safety property as another relation, which is further annotated as a violation query in line 33. This relation is defined by the rule in line 34. If the rule is evaluated to true, it means that there exists two different winning proposals, indicating a violation to the safety invariant that there is at most one winning proposal. Such violation query rule is expected to be always false during the execution of a correct smart contract.

C. Translating DeCon Contract to State Transition System

In order to perform formal verification, DeCon contracts are encoded as state transition systems. The state space comprises all possible valuations of the relational tables, and each successful transaction triggers an atomic state transition step (the transaction atomicity is guaranteed by the underlying Ethereum blockchain). Such encoding naturally captures the semantics of smart contracts: reactive programs that listen and respond to requests (transactions).

Figure 3 illustrates part of the transition system translated from the voting contract in Listing 1. The middle portion (labeled “States after i Txs”) shows a state that is reached after i transactions from one of the initial states. At this point in the execution, proposal p1 has received two votes, proposal p2 has one, and no winner has been declared yet. Two outgoing edges from this state are highlighted. The one on top represents a vote(p1) transaction, where p1 receives an additional vote, thereby achieving the quorum and becoming the winning proposal. This transaction can be executed only if certain conditions are met, which are annotated on the edge (only part of the conditions are shown due to space limit). The edge is derived from the transaction rule r in Listing 1, line 15 (recv_vote(p1) ∧ ¬hasWinner ∧ ...), and its dependent rules from line 19 to 26 (votes[p1] ≥ Q ∧ ...). This edge leads to a new state in which the number of votes for proposal p1 is incremented by one, and it becomes the winner, which is also translated from line 19 to 26.
Similarly, the bottom right shows another transaction where proposal $p_2$ gets a vote, but $\text{hasWinner}$ remains $\text{False}$ since no proposal has reached the quorum.

Section [\ref{sec:translation}] formally describes the algorithm to translate a DeCon smart contract into a state transition system. **Property.** The violation query rule (line 31) is translated into the following safety invariant:

\begin{equation}
\neg \exists p_1, p_2. \ \text{wins}(p_1) \land \text{wins}(p_2) \land p_1 \neq p_2 \tag{1}
\end{equation}

It states that there do not exist proposals $p_1$ and $p_2$ such that the violation query is true, which means there is at most one winning proposal.

\textbf{D. Proof by Induction}

To prove safety invariants of a smart contract against an infinite sequence of transactions, DCV adopts the mathematical induction approach. Given a state transition system, and a safety invariant, the proof consists of two steps:

1) Base case: all initial states satisfy the safety invariant.
2) Induction step: if the safety invariant holds for some state $s$, then it also holds for all possible next states $s'$.

One of the biggest challenges in automatic induction proof is finding inductive invariants. In some cases, a true safety invariant may not be inductive, which means that although the safety invariant is true for all possible states, it can still fail the induction proof step. To successfully complete the induction step, an inductive invariant $\text{inv}(s)$ needs to be found, such that $\text{inv}(s) \land \text{prop}(s)$ is inductive, where $s$ is the state variable.

For example, the safety invariant in Equation 1 cannot be proved inductively on its own. To make it inductive, it needs to be augmented by an inductive invariant, such as the following:

\begin{equation}
\forall u \in \text{Proposal}. \ \text{wins}[u] \implies \text{hasWinner} \tag{2}
\end{equation}

which asserts that if any proposal $u \in \text{Proposal}$ is marked as the winner, the predicate $\text{hasWinner}$ must also be true.

Inductive invariants are typically inferred in a guess-and-check manner [26], where a set of candidate invariants are enumerated until an inductive one is found. However, such approaches heavily rely on good heuristics to generate a set of candidate invariants. The insight of DCV is that, rules in DeCon contracts provide a concise and high-quality source of logical predicates for constructing inductive invariants. Since they only concern high-level logic and do not include implementation details, the extracted predicates are much smaller in size than those extracted from lower-level implementations, greatly speeding up the invariant search process. For instance, the predicates in Equation 2 ($\text{wins}[u]$, $\text{hasWinner}$), are presented in the DeCon transaction rules in Listing 1.

We describe the details of predicate extraction and inductive invariant generation in Section [\ref{sec:translation}].

\section{III. The DeCon Language}

A DeCon contract consists of three main blocks: (1) Relation declarations, (2) Relation annotations, and (3) Rules.

\begin{center}
\begin{tabular}{c}
(Contract) $P := \text{Decl} \mid \text{Annot} \mid \text{Rule}$
\end{tabular}
\end{center}

\textbf{Relation declarations.} As shown in Figure [\ref{fig:decon_language}], there are three kinds of relation declaration syntax:

- Simple relations ($\text{SR}$) have a string for a relation name, followed by a schema in parenthesis, and optional primary key indices in a square bracket. The schema consists of a list of column names and types. When inserting a new tuple to a table, if a row with the same primary keys exists, then the row is replaced by the new tuple.
- Singleton relations ($\text{SG}$) are relations annotated with a $*$ symbol. These relations have only one row. Row insertion is also an update for singleton relations.
- Transaction relations ($\text{TR}$) are relations with prefix $\text{recv}_\_\$, which are interpreted as an event trigger for incoming transaction requests. For example, in line 15 of listing 1, the literal $\text{recv\_vote}(p)$ is triggered to be true when the contract receives a vote transaction, with parameter $p$ being the proposal ID.

In addition to these user-declared relations, there are reserved relations for built-in smart contract constructs that do not need to be declared. For example, relation $\text{msgSender}(p: \text{address})$ is reserved for incoming message sender address. Similarly, there are reserved relations for message values, current block number, contract constructors, etc.

\textbf{Relation annotations.} Three kinds of relation annotations are supported:

- $\text{init}$ indicates that the relation is initialized by a constructor argument passed during deployment.
- $\text{violation}$ means that the relation represents a safety violation query.
- $\text{public}$ generates a public interface to read the contents of the corresponding relational table.

\textbf{Rules.} Figure [\ref{fig:decon_language}] shows the syntax of DeCon rules. A DeCon rule is of the form $\text{head}:-\text{body}$, which is interpreted from right to left: if the body is true, then it inserts the head tuple into the corresponding relational table.

A rule body is a conjunction of literals, and is evaluated to true if there exists a valuation of variables $\pi: V \rightarrow D$ such that all literals are true. $\pi$ maps a variable $v \in V$ to its concrete value in domain $D$. Given a variable valuation $\pi$, a relational literal is evaluated to true if and only if there exists a matching row in the corresponding relational table.
Other kinds of literals, including conditions, functions, and aggregations, are interpreted as constraints on the variables.

In particular, DeCon supports three kinds of rules. Their differences in syntax and semantics are described as follows:

- **Join rules** are rules that have a list of predicates in the rule body, and contain at least one relational literal. A predicate can be either a relational literal, a condition, or a function.

- **Transaction rules** are a special kind of join rules that have one special literal in the body: transaction handlers. A transaction handler literal has `recv_\_` prefix in its relation name, and is evaluated to true when the corresponding transaction request is received. The rest of the rule body specifies the approving condition for the transaction.

- **Aggregation rules** are rules that contain a relational literal `R(\bar{x})` and an aggregator `y = Agg n : R(\bar{y})`, where `Agg` can be either `max`, `min`, `count`, or `sum`. For each valid valuation of variables in `R(\bar{x})`, it computes the aggregate on the matching rows in `R(\bar{y})`. Take the following rule from the voting contract as an example.

For each unique value \( p \) in the second column of table `vote`, the aggregator `c = count: vote (_,p)`, counts the number of rows in table `vote` whose second column equals \( p \).

DeCon contracts are executable on the Ethereum blockchain [17]. To execute, they are first compiled into Solidity [9], which is further compiled to bytecode for the Ethereum blockchain.

**IV. Program Transformation**

**A. Declarative Smart Contracts as Transition Systems**

This section introduces the algorithm to translate a DeCon smart contract into a state transition system \( (S, I, E, Tr) \) where

- \( S \) is the state space: the set of all possible valuations of all relational tables in DeCon.
- \( I \subseteq S \) is the set of initial states that satisfy the initial constraints of the system. All relations are by default initialized to zero, or unconstrained if they are annotated to be initialized by constructor arguments.
- \( E \) is the set of transaction types. Each element in \( E \) corresponds to a type of transaction in DeCon (analogous to a transaction function definition in Solidity).
- \( Tr \subseteq S \times E \times S \) is the transition relation, generated from DeCon rules. \( Tr(s,e,s') \) means that state \( s \) can transit to state \( s' \) via transaction \( e \).

In the rest of this section, we introduce the algorithm to generate the transition relation from a DeCon smart contract.

**B. Transition Relation**

The transition relation \( Tr \) is defined by a formula \( tr : S \times E \times S \rightarrow Bool \). Given \( s,s' \in S, e \in E \), \( s \) can transition to \( s' \) in one step via transaction type \( e \) if and only if \( tr(s,e,s') \) is true. Equation (3) defines \( tr \) as a disjunction over the set of formulas encoding each transaction rule. \( R \) is the set of rules in the DeCon contract. \( TR \) is the set of transaction rules in \( R \), \( \Gamma \) is a map from relation to its modeling variable, e.g., the relation `vote(proposal:uint, count:uint) [0]` is mapped to `votes : uint \rightarrow uint`. Recall from Section III that transaction rules are rules that listen to the incoming transaction and is only triggered by the incoming transaction request. Therefore, \( r.tr \) is the literal with `recv_\_` prefix in \( r \)'s body.

\[
tr \triangleq \bigvee_{r \in TR} \left[ \text{EncodeRule}(r, R, \Gamma, r.tr) \land e = r.TxName \right] 
\]

**Algorithm 1 EncodeRule**

**Input:** (1) A DeCon rule \( r \), (2) the set of all DeCon rules \( R \), (3) a map from relation to its modeling variable \( \Gamma \), (4) a trigger \( \tau \), the newly inserted literal that triggers \( r \)'s update.

**Output:** A formula over \( S \times S \), encoding \( r \)'s body condition, and all state updates triggered by inserting \( r \)'s head literal.

1. **Body** \( \leftarrow \) EncodeRuleBody(\( \Gamma \), \( r \), \( \tau \))
2. **Dependent** \( \leftarrow \{ \text{EncodeRule}(dr, R, \Gamma, \tau') \mid (dr, \tau') \in \text{DependentRules}(r, R) \} \)
3. \( \langle H, H' \rangle \leftarrow \text{GetStateVariable}(\Gamma, r.head) \)
4. **Update** \( \leftarrow H' = \text{GetUpdate}(H, r, \tau) \)
5. **TrueBranch** \( \leftarrow \text{Body} \land \text{Update} \land (\bigwedge_{d \in \text{Dependent}} d) \)
6. **FalseBranch** \( \leftarrow \neg \text{Body} \land (H' = H) \)
7. **return** **TrueBranch** \( \oplus \) **FalseBranch**

The procedure EncodeRule is defined by Algorithm 1. We explain it using the voting contract in Listing 1 as an example.

It takes four inputs: (1) a DeCon rule \( r \), (2) the set of all DeCon rules \( R \), (3) a map from relation to its modeling variable \( \Gamma \), (4) and a trigger \( \tau \), the newly inserted literal that triggers \( r \)'s update. In particular, a trigger \( \tau \) takes the form `insert \{literal\}` or `delete \{literal\}`. It is used to inform the subroutine EncodeRuleBody how a relation is updated, and that the rest of the rule body in \( r \) needs to be encoded as a logical formula. For example, when a new `vote` transaction
is received, the trigger \( \tau \) is \text{insert recv\_vote}(p)\text{,} where \( p \) is the transaction parameter.

In step 1, \( r \)'s body is encoded as a boolean formula, \textit{BodyConstraint}, by calling a procedure \text{EncodeRuleBody} (Section IV-C). Take the rule for \textit{vote} transaction in line 15 of Listing 1 as an example. Its body is encoded as:

\[
\neg \text{hasWinner} \land \neg \text{hasVoted}[v] \land \text{isVoter}[v]
\]

Step 2 first selects direct dependent rules of \( r \) from the set of all DeCon rules \( R \), by calling a subroutine \text{DependentRules}(r, R)\text{. It returns a set of tuple } (dr, \tau')\text{.} dr \text{ is a direct dependent rule of } r \text{, and } \tau' \text{ is the corresponding trigger for } dr \text{.} A \text{ rule } dr \text{ is directly dependent on rule } r \text{ if and only if } r \text{ 's head relation appears in } dr \text{ 's body. For example, rules in line 19 and 26 of Listing 1 are directly dependent on the } \text{vote} \text{ transaction rule in line 15.} \text{ For the next trigger } \tau'\text{, literal insertion results from a new relational tuple being derived from one of the rules. For example, if the rule for transaction } \text{vote} \text{ is evaluated to true, the next trigger } \tau' \text{ is } \text{insert vote}(v, p)\text{.} \text{ Literal deletion happens when literals with primary keys are inserted: inserting such literals implicitly deletes the literals with the same primary keys, if exist. Next, for each direct dependent rule } dr \text{ of } r \text{ and trigger } \tau'\text{, it gets } dr\text{'s encoding by recursively calling itself on } dr \text{ and } \tau'\text{.}

Step 3 generates state variables for the head relation, where \( H \) is for the current step, and \( H' \) is for the next transition step. Step 4 generates the head relation update constraint: \( H' \) equals inserting or deleting \( r \) 's evaluation result from \( H \). \text{GetUpdate}(H, r, \tau) \) is defined as follows:

\[
\text{GetUpdate}(H, r, \tau) = \begin{cases} 
H.\text{insert}(r.\text{head}), \\
\text{if } r \text{ is agg. rule } \lor \tau = \text{insert -} \\
H.\text{delete}(r.\text{head}), \\
\text{if } r \text{ is join rule } \land \tau = \text{delete -} 
\end{cases}
\]

If \( r \) is an aggregation rule, the update is directly encoded as insertion since new aggregation results implicitly overwrite the old ones. If \( r \) is a join rule, and the trigger \( \tau \) is a tuple deletion, then \( r \) 's join result with the deleted tuple needs to be deleted as well. Otherwise, \( \tau \) is an insertion, and the update for relation \( r.\text{head} \) is also an insertion. Suppose we are in the recursion step for encoding the \textit{votes} rule in line 19, its update constraint is generated as: \( \text{votes}' = \text{Store}(\text{votes}, p, \text{votes}[p]+1) \), where the number of votes for proposal \( p \) is incremented by one.

Step 5 generates the constraint where \( r \) 's body is false, in conjunction with the update constraint and all dependent rules' constraints. Step 6, on the other hand, generates constraints where \( r \) 's body is false, no dependent rule is triggered, and the head relation remains the same. Step 7 returns the final formula as an exclusive-or of the true and false branches, which encodes \( r \) 's body and how its update affects other relations in the contract.

C. Encoding Rule Bodies

The procedure \text{EncodeRuleBody} is defined by two sets of inference rules:

- \( \Gamma, \tau \vdash r \leftrightarrow \phi \) states that a DeCon rule \( r \) is encoded by a boolean formula \( \phi \) under context \( \Gamma \) and \( \tau \).
- \( \Gamma, \tau \vdash \text{Pred} \leftrightarrow \phi \) states that a predicate \text{Pred} is encoded by a formula \( \phi \) under context \( \Gamma \) and \( \tau \).

The contexts (\( \Gamma \) and \( \tau \)) of both judgments are defined in the same way as the input of Algorithm 1.

Figure 6 shows the inference rules that define the first judgment \( \Gamma, \tau \vdash r \leftrightarrow \phi \). They are interpreted as follows.

- A \text{Join} rule is encoded as a conjunction of the predicates, each of which is encoded from a literal in the rule body. The encoding of individual literals is introduced later in this section.

- Unlike \text{Join} rules, aggregation rules (\text{Sum} and \text{Count}) have separate inference rules for tuple insertion (+) and deletion (−). Because the relation between new and old aggregation results needs to be encoded. In these reference rules, \( \bar{k} \) represents the primary keys of relation \( H \), extracted from the array \( \bar{y} \), and \( \Gamma(H)[\bar{k}].\text{value} \) reads the current aggregate result. Note that, unlike the \text{Join} rules, the literal \( R(\bar{x}) \) here does not join with the aggregation literal, because it is only introduced to obtain valid valuations for the rule variables (every row
in table $R$ is a valid valuation). For each valid valuation, the aggregator computes the aggregate summary for the matching rows in table $R$ (Section III).

For $Max$ and $Min$ aggregation rules, DCV only encodes the their update for tuple insertions, based on the assumption that they only apply to transaction relations (tables that stores the transaction records), which are append only and has no primary keys. In other words, they have no tuple deletion.

This assumption is made for two reasons. First, updating $Max$ and $Min$ for tuple deletion is complicated, because if the current maximum or minimum is deleted, the second largest or smallest element needs to be fetched and become the new aggregation result. Such update requires storing the whole table and even maintaining sorted table entries. Second, Ethereum has strict limits on the computation and storage of each smart contract and its transactions. Maintaining maximum and minimum for tables with delete operation is very expensive to be executed on Ethereum. We survey smart contracts in public repositories and find no contract with such logic. Therefore, DCV adds such assumption and greatly simplify the rule encoding.

**Encoding individual literals.** Following are the inference rules for judgment: $\Gamma, \tau \vdash Pred \models \phi$, which encodes individual literals.

\[
\begin{align*}
\Gamma, \tau \vdash R(\bar{x}) \models \tau &\equiv \tau (\bar{x}) \text{ (Lit1)} \\
\Gamma, \tau \vdash R(\bar{x}) \models \tau &\equiv \tau (\bar{x}) \text{ (Lit2)} \\
\end{align*}
\]

where $\bar{k}$ represents the primary keys in relational literal $R(\bar{x})$, extracted from $\bar{x}$, and $\bar{v}$ represents the remaining fields in $\bar{x}$.

\[
\Gamma, \tau \models C \equiv y = F(\bar{x}) \models y = F(\bar{x}) \text{ (Function)}
\]

Conditions and functions are directly encoded as they are, as shown in the above rules.

**Rule derivation and recursion.** DCV assumes that on every new incoming transaction request, there is at most one new tuple derived by each rule, and that there is no recursion in the rules.

Rule recursion means that a rule is dependent on itself. A rule $r_a$ is dependent to another rule $r_b$ (r_a \rightarrow r_b) if $r_b$’s head relation appears in $r_a$’s body. This dependency relation is transitive: $r_a \rightarrow r_b \land r_b \rightarrow r_c \implies r_a \rightarrow r_c$. Using this dependency annotation (→), rule recursion means $r_a \rightarrow \ldots \rightarrow r_a$.

This assumption keeps the size of the transition constraint linear to the number of rules in the DeCon contract, thus making the safety verification tractable. We find this assumption holds for most smart contracts in the financial domain, and is true for all of the ten benchmark contracts in our evaluation.

**Multi-contract Interactions.** Multi-contract interaction is specified implicitly by DeCon rules that join relations from different contracts. Such interactions are performed via message passing. Unlike prior work checking for message handling errors, DCV assumes that message delivery and handling are always successful, and instead focuses on the functional correctness. Note that such interactions are limited to functions without mutual recursions. Mutual recursions are not supported because it breaks the atomicity assumption of a transaction. To illustrate, suppose contract A’s transaction calls contract B’s transaction Foo, which in turn calls another transaction of contract A. In this case, the execution of two transactions of contract A overlap, breaking the atomicity of transactions.

**D. Safety Invariant Generation**

Each violation query rule $qr$ in a DeCon contract is first encoded as a formula $\phi$ such that $\Gamma, \tau \models qr \models \phi$. Note that the context $\Gamma$ is the same mapping used in the transition system encoding process. The second context, trigger $\tau$, is a reserved literal check($\cdot$), which triggers the violation query rule after every transaction.

Next, the safety invariant is generated from $\phi$ as follows:

\[
Prop \equiv \neg(\exists x \in X. \phi(s, x))
\]

where $X$ is the state space for the set of non-state variables in $\phi$. The property states that there exists no valuations of variables in $X$ such that the violation query is non-empty. In other words, the system is safe from such violation.

**V. Verification Method**

**A. Proof by Induction**

Given the state transition system translated from the DeCon smart contract, the target property $prop(s)$, which is translated from the violation query, is proven by mathematical induction. In particular, let $S$ be the set of states in the transition system, and $E$ be the set of transaction types ($vote$ is the only transaction type in the example in Listing 1). Given $s, s' \in S, e \in E$, let $init(s)$ indicate whether $s$ is in the initial state, and $tr(s, e, s')$ indicate whether $s$ can transition to $s'$ via transaction type $e$. The mathematical induction is as follows:

\[
\begin{align*}
PropInd(init, tr, prop) &\equiv Base(init, prop) \\
Base(init, prop) &\equiv \forall s \in S. init(s) \\
Induction(tr, prop) &\equiv \forall s, s' \in S, e \in E. \\
& \quad tr(s, e, s') \implies inv(s) \land prop(s) \\
\end{align*}
\]

where $inv(s) \land prop(s)$ is an inductive invariant inferred by DCV such that $prop(s)$ is proved to be an invariant of the transition system.

Algorithm 2 presents the procedure to infer inductive invariants. It first extracts a set of predicates $P$ from the set of transaction rules $R$ (Section V-B). Then it generates a set of candidate invariants using predicates in $P$, following two heuristic patterns (Section V-C). Finally, it invokes a recursive
Algorithm 2 Procedure to find inductive invariants.

Input: a transition system ts, a map from relation to its modeling variable Γ, and a set of DeCon transaction rules R.
Output: an inductive invariant of ts.
1: function FINDINDUCTIVEINVARIANT(C, ts)
2:   for inv in C do:
3:     if refuteInv(inv, C, ts) then
4:       return FindInductiveInvariant(C \ inv, ts)
5:   end if
6: end for
7: return \bigwedge_{ci \in C} c_i
8: end function
9: P ← \bigcup_{r \in R} ExtractPredicates(r, Γ)
10: C ← GenerateCandidateInvariants(P)
11: return FindInductiveInvariant(C, ts)

Algorithm 2 presents the predicate extraction procedure. It first transforms each literal in the transaction rule into a predicate, and puts them into a set P_0. Some predicates in P_0 do not contain enough information on their own, e.g., predicates that contain only free variables. Because the logic of a rule is established on the relation among its literals (e.g., two literals sharing the same variable τ means joining on the corresponding columns). On the contrary, predicates that contain constants, e.g. hasWinner == true, convey the matching of a column to a certain concrete value, and can thus be used directly in candidate invariant construction.

Therefore, in the next step, each predicate p in P_0 is augmented by one of its matching predicates in matchingPredicates(p, r), which is the set of predicates in rule r that share at least one variable with predicate p. This set of augmented predicates is P_1. Finally, the union of P_0 and P_1 is returned.

C. Candidate Invariant Generation

Given the set of predicates in P, DCV generates candidate invariants following two heuristic template patterns. Each pattern is a logical formula that consists of one or more placeholders. These placeholders are replaced by predicates extracted from transaction rules (P) during template instantiation. DCV unions all possible template instantiations as the set of candidate invariants.

The concrete forms of the two template patterns used in DCV are as follows:

\{∀x ∈ X. ¬init(s) ⇒ ¬p(s, x) | p ∈ P\}
\{∀x ∈ X. ¬init(s) ∧ q(s, x) ⇒ ¬p(s, x) | p, q ∈ P\}

where X is the set of non-state variables in the body of the formula. ¬init(s) is used as the implication premise so that the whole formula can be trivially implied by the transition system’s initial constraints.

Having ¬p as the implication conclusion is based on the observation that, in order to prove safety invariants, a lemma is needed to prevent the system from unsafe transitions. Recall from Section V-B that predicate p is one of the transaction conditions, thus having ¬p in the invariant can prevent relevant transactions from committing. In the second pattern, we add another predicate q ∈ P_0 in the implication premise to make the pattern more robust to different contracts and properties.

VI. Evaluation

| Benchmarks | Properties                        |
|------------|-----------------------------------|
| wallet     | No negative balance.              |
| crowFunding| No missing fund.                  |
| ERC20      | Account balances add up to totalSupply. |
| ERC721     | All existing tokens have an owner.|
| ERC777     | No default operator is approved for individual account. |
| ERC1155    | Each token’s account balances add up to that token’s totalSupply. |
| controllableToken | Account balances add up to totalSupply. |
| partitionToken | Account balances add up to totalSupply in each partition. |
| paymentSplitter | No overpayment. |
| vestingWallet | No early release. |
| voting     | At most one winning proposal.     |
| auction    | Each participant can withdraw at most once. |

Implementation. We implement the smart contract transformation and inductive invariant generation algorithms in
TABLE II: Verification efficiency measured in time (seconds). TO stands for time-out after 1 hour. Unknown (?) means the verifier cannot verify the contract property. Errors (×) from solc are caused by a known software issue [5]. Solc-verify also returns errors on some benchmarks because it fails to analyze part of the OpenZeppelin libraries used in those benchmarks.

| Group                        | Name            | #Rules | LOC | DCV reference | Solc reference | Solc-verify reference |
|------------------------------|-----------------|--------|-----|---------------|-----------------|-----------------------|
| **Open standards and examples** | wallet          | 12     | 67  | 1             | ?               | 17                    |
|                              | crowdfunding    | 14     | 85  | 2             | 1 ×             | ? 38                  |
|                              | ERC20           | 19     | 389 | 2             | 20 ×            | 50                    |
|                              | ERC721          | 13     | 520 | 2             | TO ×            | 50                    |
|                              | ERC777          | 31     | 562 | 2             | TO ?            | 74 ?                  |
|                              | ERC1155         | 18     | 645 | 2             | 12 TO           | 36 48                 |
|                              | paymentSplitter | 6      | 166 | 1             | TO 12           | 25 ?                  |
|                              | vestingWallet   | 7      | 113 | 1             | TO ?            | 55 14                 |
|                              | voting          | 6      | 36  | 2             | × TO            | ? ?                   |
|                              | auction         | 13     | 146 | 58            | × TO            | ? ?                   |
|                              | controllableToken | 23    | 55  | 2             | 29 2           | × 46                  |
|                              | partitionToken  | 16     | 70  | 2             | 1 1             | 14 30                 |
| **Top ERC20 Tokens**         | bnb             | 24     | 172 | 2             | 3 1             | 55                    |
|                              | link            | 20     | 308 | 2             | 1 2             | 36 46                 |
|                              | ltcSwapAsset    | 25     | 655 | 2             | TO ×            | 50                    |
|                              | matic           | 25     | 510 | 2             | 2 ×             | 74 60                 |
|                              | shib            | 22     | 508 | 2             | 1 ×             | 42 51                 |
|                              | tether          | 27     | 474 | 2             | 42 ×            | × 49                  |
|                              | theta           | 21     | 213 | 2             | 270 1           | 45 49                 |
|                              | wbtc            | 28     | 731 | 2             | TO ×            | × 67                  |

Scala and use Z3 [11] to check the satisfiability of generated formulas. Quantified formulas are handled by Z3’s default heuristics.

**Benchmarks.** We collect 20 benchmark contacts in two groups. The first group consists of 12 contracts from open libraries [6], [8] and examples from prior research [10]. Each selected contract either has contract-level safety specifications annotated, or has proper documentation from which we can come up with a contract-level safety specification. Table I shows the contract names in group one and their target properties. The second group consists of the most popular contracts: a list of top ERC20 contracts (based on circulating market cap) maintained by Etherscan [12]. Based on this list, we filter out the ones without source code or having unsupported features (e.g., cryptographic algorithms) and obtain another 8 benchmark contracts. Since all of these contracts follow the ERC20 standards, they are verified against the same property for the ERC20 token contract.

**Baselines.** We use solc [9] and solc-verify [23] as the comparison baselines. Solc is a Solidity compiler with a built-in checker to verify assertions in source programs. It has been actively maintained by the Ethereum community, and version 0.8.13 is used for this experiment. Solc-verify extends from solc 0.7.6 and performs automated formal verification using strategies of specification annotation and modular program verification. We have also considered Verx [32] and Zeus [25], but neither is publicly available.

**Experiment setup.** We modify certain functionalities and syntax of the benchmark contracts so that they are compatible with all comparison tools. In particular, the delegate vote function of the voting contract contains recursion, which is not yet supported by DeCon, and is thus dropped. In addition, solc and solc-verify do not support inline assembly analysis. Therefore, inline assembly in the Solidity contracts are replaced with native Solidity code. Minor syntax changes are also made to satisfy version requirements of the two baseline tools.

With these modifications, for each reference contract in Solidity, we implement its counterpart in DeCon. Then we conduct verification tasks on three versions of benchmark contracts: (1) DeCon contracts with DCV, (2) reference Solidity contracts with solc and solc-verify, and (3) Solidity contracts generated from DeCon with solc and solc-verify. For each set of verification tasks, we measure the verification time and set the time budget to be one hour. All experiments are performed on a 2.4GHz core (single-threaded) and 4GB memory.

**Results.** Table II shows the evaluation results. DCV verifies all but one contract in two seconds, with auction taking 58 seconds. In particular, the properties for the voting and auction contract are not inductive, and thus require inductive invariant generation. Auction takes more time because it contains more rules and has a more complicated inductive invariant.

On the other hand, solc only successfully verifies 12 reference contracts, with one of them taking 270 seconds to finish. It times out on six contracts, and reports SMT solver invocation error on another two. This error has been an open issue according to the GitHub repository issue tracker [5], which is sensitive to the operating system and the underlying library versions of Z3.

Similarly, solc-verify verifies 10 reference contracts, and reports unknown on four others. It also returns errors on...
six contracts because it cannot analyze certain parts of the included OpenZeppelin libraries, although the libraries are written in compatible Solidity version.

For Solidity contracts generated from DeCon, solc verifies six and solc-verify verifies 15. The performance difference between the reference version and the DeCon-generated version is potentially caused by the fact that DeCon generates stand-alone contracts that implement all functionalities without external libraries. On the other hand, DeCon implements contract states (relations) as mappings from primary keys to tuples, which may incur extra analysis complexity compared to the reference version.

In summary, DCV is highly efficient in verifying contract-level safety invariants, and can handle a wider range of smart contracts compared to other tools. By taking advantage of the high-level abstractions of the DeCon language, it achieves significant speedup over the baseline tools. In several instances, baseline tools timeout after an hour or report an error, while DeCon is able to complete verification successfully.

VI. RELATED WORK

**Smart contract verification.** Solc [28], Solc-verify [23], Zeus [25], Verisol [38], and Verx [32] perform safety verification for Solidity smart contracts. Similar to DCV, they infer inductive invariants to perform sound verification of safety properties. They also generate counter-examples as a sequence of transactions to disprove the safety properties. SmartACE [39] is a safety verification framework that incorporates a wide variety of verification techniques, including fuzzing, bounded model checking, symbolic execution, etc. In addition to safety properties, SmartPulse [35] supports liveness verification. It leverages the counterexample-guided abstraction refinement (CEGAR) paradigm to perform efficient model checking, and can generate attacks given an environment model.

DCV differs from these work in that it uses a high-level executable specification, DeCon, as the verification target. Such high-level modeling improves verification efficiency, but it also means that DCV can only apply to smart contracts written in DeCon, while the other tools can work on most existing smart contracts in Solidity or Move.

The Move Prover [20] (MVP) is a formal verifier for smart contracts written in the Move language [4]. Similar to DCV, MVP also verifies safety properties. However, they target different languages and blockchain platforms. DCV is based on DeCon, which is declarative and more abstract, while Move is imperative. In addition, Move contracts work on the Diem blockchain, while DeCon currently supports Ethereum and Solidity. Despite the differences, we believe DCV could also benefit Move. An interesting future direction would be to implement a Move compiler for DeCon, so that DeCon can serve as a declarative specification for smart contracts on the Diem blockchain, while Move as the implementation language can provide better support for other verification tasks.

**Formal semantics of smart contracts.** KEVM [18] introduces formal semantics for smart contracts, and can automatically verify that a Solidity program (its compiled EVM bytecode) implements the formal semantics specified in KEVM. This verification is also sound, but it focuses on the functional correctness of each Solidity function, instead of the state invariants across multiple transactions.

Formal semantics of EVM bytecode have also been formalized in F* [22] and Isabelle/HOL [14]. Scilla [33] is a type-safe intermediate language for smart contracts that also provides formal semantics. They offer precise models of the smart contract behaviors, and support deductive verification via proof assistants. However, working with a proof assistant requires non-trivial manual effort. On the contrary, DCV provides fully automatic verification.

**Vulnerability detection.** Security [36] encodes smart contract semantic information into relational facts, and uses Datalog solver to search for property compliance and violation patterns in these facts. Oyente [27] uses symbolic execution to check generic security vulnerabilities, including reentrancy attack, transaction order dependency, etc. Maian [30] detects vulnerabilities by analyzing transaction traces. Unlike the sound verification tools, which require some amount of formal specification from the users, these work require no formal specification and can be directly applied to any existing smart contracts without modification, offering a quick and lightweight alternative to sound verification, although may suffer from false positives or negatives.

**Fuzzing and testing.** Fuzzing and testing techniques have also been widely applied to smart contract verification. They complement deductive verification tools by presenting concrete counter-examples. ContractFuzzer [24] instruments EVM bytecodes to log run-time contract behaviors, and uncovers security vulnerabilities from these run-time logs. Smartisan [19] uses static analysis to predict effective transaction sequences, and uses this information to guide fuzzing process. SmartTest [34] introduces a language model for vulnerable transaction sequences, and uses this model to guide the search path in the fuzzing phase.

VIII. CONCLUSION

We present DCV, an automatic safety verification tool for declarative smart contracts written in the DeCon language. It leverages the high-level abstraction of DeCon to generate succinct models of the smart contracts, performs sound verification via mathematical induction, and applies domain-specific adaptations of the Houdini algorithm to infer inductive invariants. Evaluation shows that it is highly efficient, verifying all 20 benchmark smart contracts, with significant speedup over the baseline tools.

Our experience with DCV has also inspired interesting directions for future research. First, although DCV can verify a wide range of contracts in the financial domain, we find certain interesting applications that require non-trivial extensions to the modeling language, including contract inheritance, interaction between contracts, and functions that lie outside relational logic. Second, since DCV verifies on the contract logic-level, we would also like to verify translation correctness.
for the DeCon-to-Solidity compiler, to ensure the end-to-end soundness of DCV’s verification results.

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