# Smart contract design meets state machine synthesis: case studies

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Abstract—Modern blockchain systems support creation of smart contracts – stateful programs hosted and executed on a blockchain. Smart contracts hold and transfer significant amounts of digital currency which makes them an attractive target for security attacks. It has been shown that many contracts deployed to public ledgers contain security vulnerabilities. Moreover, the design of blockchain systems does not allow the code of the smart contract to be changed after it has been deployed to the system. Therefore, it is important to guarantee the correctness of smart contracts prior to their deployment.

Formal verification is widely used to check smart contracts for correctness with respect to given specification. In this work we consider program synthesis techniques in which the specification is used to generate correct-by-construction programs. We focus on one of the special cases of program synthesis where programs are modeled with finite state machines (FSMs). We show how FSM synthesis can be applied to the problem of automatic smart contract generation. Several case studies of smart contracts are outlined: crowdfunding platform, blinded auction and a license contract. For each case study we specify the corresponding smart contract with a set of formulas in linear temporal logic (LTL) and use this specification together with test scenarios to synthesize a FSM model for that contract. These models are later used to generate executable Solidity code which can be directly used in a blockchain system.

### 1. Introduction

Since the invention of a blockchain data structure in 2008 various cryptocurrencies have been emerging, evolving and gaining popularity. This popularity is explained by the fact that blockchain systems are fully operable without a trusted entity. Recent cryptocurrencies support creation of *smart contracts* – stateful programs executed on a blockchain that encode the rules governing transactions. The execution of smart contracts is enforced by the consensus algorithm in the underlying blockchain system.

Smart contracts are a powerful tool to encode arbitrary contractual agreements in a machine-readable form but as with any programs they are error-prone and hard to reason about. Furthermore, the blockchain systems design principles make impossible contract's code modification after

it has been deployed to blockchain. Also smart contracts hold and transfer significant amount of digital currency which makes them an attractive target of various attacks and drastically increases the cost of an error in smart contract code. It has been shown that many contracts deployed to public ledgers contain security vulnerabilities and these vulnerabilities have led to theft of millions of US dollars in cryptocurrency equivalent. Thus, it is of paramount importance to ensure that smart contracts are correct. Various methods based on formal verification have been proposed to achieve this goal [1], [2], [3].

Another method to build correct programs is program synthesis, which has a lot in common with formal verification. The problem of program synthesis is formulated as follows: given a specification in formal logic, construct a program conforming to that specification. This problem is known to be undecidable in general, however various methods were proposed for some special cases of programs. Unlike formal verification, automated synthesis of smart contracts has received very little attention, although program synthesis application for smart contracts looks promising given the fact that they are relatively small (less than 100 SLOC in average [4]).

Program synthesis is a very broad topic and in this work we only focus on the problem of FSM synthesis where programs are defined in terms of FSMs. The rationale behind this is that smart contract logic can often be expressed with an FSM. Moreover, modeling contracts as FSMs is a recommended design pattern for Solidity – a language of Ethereum [5] contracts [6]. In fact there is a tool Verisolid [7] that facilitates creating FSM smart contract models and generating Solidity code from these models. A user can specify temporal properties and verify that generated contracts conform to these properties.

In this work we employ techniques and tools (EFSM-TOOLS <sup>1</sup>) outlined in [8]. We have no intent to compare different FSM synthesis tools as for case studies in Section 3 synthesis solving terminates within seconds. In our approach input events of a FSM correspond to methods of a contract and output actions – to implementations of those methods. We synthesize smart contract FSM models based on formal specification in temporal logic and test

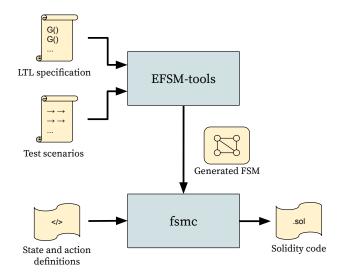


Figure 1. Data-flow diagram of the proposed approach.

scenarios. Afterwards, given the contract's state declaration and the implementation of its methods in a corresponding programming language, we can generate contract's code that is guaranteed to be correct with respect to the specification. Code generation is straightforward and similar to that in VERISOLID tool, however VERISOLID does not support multiple transitions labeled by the same event so we had to implement our own tool FSMC <sup>2</sup>. The high-level data-flow diagram for the proposed approach is shown in Figure 1.

**Contributions.** To the best of our knowledge, this work is the first attempt to employ specification-based program synthesis techniques to automatically generate smart contract source code. Specifically, we provide case studies to show that LTL synthesis can be successfully applied for some types of contracts to generate their FSM models and use these models to obtain source code that meets some formal properties.

### 2. Background and related work

In this section we introduce some basic concepts of blockchain systems and smart contracts necessary to understand the rest of the paper. Then we define FSMs that are used to model smart contracts and introduce formalism that are used to specify them. Finally we state the problem of specification-based FSM synthesis and provide some references to its efficient solutions.

#### 2.1. Smart contracts

A blockchain is a list of records, called blocks, containing some data. Blockchain can be used as a ledger that is maintained in a distributed network, for instance in cryptocurrencies this ledger stores a transaction list. Effectively, a ledger in cryptocurrencies stores the mapping from

2. https://github.com/d-suvorov/fsmc/

accounts to their balances in digital currency. We refer to this digital currency as *coins*. The nodes of a network called *miners* execute consensus algorithm and decide on which blocks will be added. It is assumed that the majority of nodes are honest as they are incentivized to add new valid blocks, and the integrity of the system is based on that assumption.

Modern blockchain systems support *smart contracts* – executable programs stored on a blockchain. A contract is executed by miners which agree on the outcome of the execution and update the blockchain accordingly. Hence arbitrary contractual agreements can be expressed in program code and enforced without relying on a trusted party. Most popular smart contract systems share the same concepts but for the rest of the paper we consider Ethereum-like smart contracts.

In Ethereum [5], smart contracts are a type of accounts associated with executable code and a storage file. Smart contracts can be created by sending a transaction of a special kind to a blockchain. A code of the contract consists of methods – entry points which are called when transactions are send to the address of that contract. Essentially, transactions act as method invocations. Contracts can receive coins with these transactions and send coins to other accounts via send instructions. Each instruction of a method consumes some amount of *gas* during execution. The user who sends a transaction must pay gas for its execution. If a transaction runs out of gas during its execution the control returns to sender. An example of a smart contract is shown in the next section.

The problem of creating correct smart contracts have been actively studied over the past years. One of the first work by Delmolino et al. outlines common pitfalls specific to smart contract development. Since then, a variety of techniques have been used to verify smart contracts. Different tools based on symbolic execution were created: OYENTE [2], MYTHRIL [9], MANTICORE [10], MAIAN [11]. An early work of Bhargavan et al. uses F\* programming language [1]. Lately modern theorem provers have been employed to formalize different aspects of smart contracts in blockchain systems [3], [12], [13] and used to mechanize reasoning about those aspects. Sergey et al. [14] design a new functional language, implement its embedding into Coq and mechanize proofs of safety and liveness properties of smart contracts. Flint [15] is a programming language that was designed specifically for writing robust smart contracts. Flint employs linear type theory to prevent unintentional loss of coins. An interesting example of contractoriented languages are Bamboo [16] and Obsidian [17] as they model smart contracts as state machines and make state transitions explicit. Model checking can also be used to verify smart contracts. Nehai et al. [18] use NUSMV model checker to create a blockchain application model (including a blockchain model itself) and check its temporal properties.

Idelberger *et al.* [19] propose to use defeasible deontic logic to create smart contracts, which is somewhat similar to our approach. However, the execution of such smart contracts relies on an external logic engine. This setup negatively affects the performance. We generate FSM models

which can be encoded in some programming language and executed directly.

# 2.2. Specification-based FSM synthesis

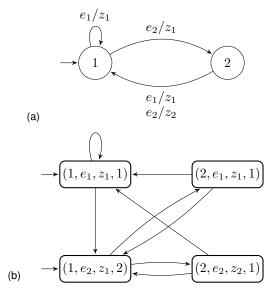


Figure 2. An example of an FSM (a) and its Kripke structure (b).

We are following [8] and define a finite state machine (FSM) as a tuple  $(S, s_{\text{init}}, E, Z, \delta, \lambda)$ , where

- S is a finite set of states,
- $s_{\text{init}} \in S$  is the *initial state*,
- E is a finite set of input events,
- Z is a finite set of output *actions*,
- $\delta: S \times E \to S$  is the transition function,
- $\lambda: S \times E \to Z^*$  is the output function (with  $Z^*$  we denote a set of strings over Z).

An FSM reads a sequence of input events one by one and transforms it into a sequence of output actions. With each input event it generates new output actions according to  $\lambda$ and changes its active state according to  $\delta$ .

Model checking. Model checking is a technique for automatically verifying finite-state systems with respect to a given specification [20]. It is common to formalize the specification as a formula in temporal logic. In linear temporal logic (LTL), formulas express some properties of execution paths [21]. To proceed with its definition we first define a Kripke structure. With P we denote a set of atomic propositions, which characterize execution states. Formally, a Kripke structure is a tuple  $(S_K, I, T, L)$ , where

- $S_K$  is a set of states,
- $I \subseteq S_K$  is a set of initial states,
- $T \subseteq S_K \times S_K$  is a transition relation, which must be left-total (that is, from each state there is a transition to at least one state),  $L: S_K \to 2^P$  is a labeling function.

An example of an FSM and a corresponding Kripke structure is shown in Figure 2. To label transitions we use this notation: input event / output action.

LTL formulas are defined over infinite paths in Kripke structures. The formulas are built up from temporal operators, atomic propositions and connectives familiar from propositional logic  $(\land, \lor, \neg, \rightarrow)$ . If f is a Boolean formula, then it simply states with which atomic propositions the first state of the path is marked. If f is an LTL formula, then saying that f holds for a state of an infinite path means that it holds for the infinite suffix of the path starting from this state. The following temporal operators can be used.

- The neXt operator: X f means that f has to hold at the next state of the path.
- The Globally operator: G f means that f has to hold on the entire suffix of the path.
- The  $\mathbf{F}uture$  operator:  $\mathbf{F} f$  means that f eventually has to hold (somewhere on the suffix of the path starting from this state).
- The Until operator:  $f \cup Q$  means that f has to hold at least until q becomes true, which must hold at this or some future state.
- The **R**elease operator:  $f \mathbf{R} g$  means that g has hold until and including the point where f first becomes true; if f never becomes true, g must remain true forever.

The formula f is true for some Kripke model M means that it is satisfied for all infinite paths of M.

FSM synthesis. The problem of FSM synthesis by the specification is well-known. In its different statements the specification may be given as temporal formula, a set of test scenarios or the combination of the two. A test scenario for FSM  $(S, s_{init}, E, Z, \delta, \lambda)$  is a sequence of pairs  $(e_1, A_1), \ldots, (e_n, A_n)$ , where each  $e_i \in E$  and  $A_i \in Z^*$ and, a FSM conforms to it if and only if it produces a sequence of actions  $A_1 \cdot A_2 \cdot \ldots \cdot A_n$  (with  $\cdot$  we denote sequence concatenation) given a sequence of events  $e_1, \ldots, e_n$ as its input. Exact synthesis methods are mostly based on transition to SAT [8], [22]. In [8] different approaches based on transition to SAT and QSAT were examined. In the most efficient approach scenarios are encoded in SAT and LTL formulas are incorporated with iterative counterexample prohibition. In BoSy tool [23], [24], encoding in QSAT instead of SAT is used and a transition system is generated only from a set of LTL formulas. The generated transition system is guaranteed to be minimum in terms of the number of states.

#### 3. Case studies

This section contains case studies that evolve from simple example for illustration purposes only to more realistic examples taken from the literature. For each case study we provide a formal LTL specification and a result model that was generated with this specification and test scenarios.

In this section we extend FSMs with guard conditions. A guard condition is a Boolean expression

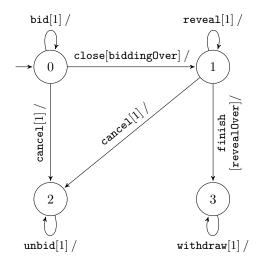


Figure 3. Blinded auction. FSM generated for size = 4 states.

that labels FSM transition. Guard conditions affect the semantics of FSMs in the following way: the transition can be executed only if its guard condition is satisfied. We use this notation to label transitions: input event [guard condition] / output action. A test scenario now is a sequence of triples  $\{(e_i, c_i, A_i)\}$ , where  $e_i$  is an input event,  $c_i$  is a guard condition and  $A_i$  is a sequence of output actions. If a sequence of output actions is omitted (as in input event [guard condition] / or  $(e_i, c_i, .)$ ) it is implicitly assumed that it consists of one action with the same name as the corresponding input event.

In our approach input events of an FSM correspond to methods of a contract and output actions – to implementations of those methods. We specify smart contracts with a set of LTL formulas in terms of these events and actions. Formal specification is then combined with test scenarios and provided as input to EFSM-TOOLS to generate an FSM that complies with given specification and test scenarios. Figure 3 shows an example of a generated FSM. Given the implementation of FSM output actions and the definitions of used predicates, FSM can be translated to executable code. Figure 4 shows an example of generated Solidity code, where lines 2–12 correspond to contract's state definition, lines 14–19 – to predicate definition and lines 40–44 – to bid action definition (other action definitions are omitted for brevity).

# 3.1. Crowdfunding

For illustrative purpose, let us first consider a simplistic example of a crowdfunding platform. In such a platform users can donate coins (denoted with event donate) during a predefined period of time which ends when variable donationOver becomes true. When the donation period is over, the owner of the campaign can request collected coins (event getFunds). After that donors can claim their donations back (event reclaim) and possibly get them back if not enough coins were collected during the campaign

(notFunded = True). Intuitively, one can model the logic of this contract using an FSM with two states. More formally, the logic of described contract is formulated as follows:

- 1) getFunds cannot happen more than once;
- donate cannot happen after getFunds has happened;
- 3) reclaim cannot happen before getFunds;
- 4) getFunds can happen only if donationOver = True:
- 5) reclaim can happen only if notFunded = True.

With a straightforward translation we can formalize these properties in LTL as follows.

$$G(getFunds \rightarrow X \neg FgetFunds)$$
 (1)

$$\mathbf{G}(\mathtt{getFunds} \to \neg \mathbf{Fdonate}) \tag{2}$$

$$getFunds \mathbf{R} \neg reclaim \tag{3}$$

$$\mathbf{G}(\mathtt{getFunds} \to \mathtt{donation0ver})$$
 (4)

$$\mathbf{G}(\mathtt{reclaim} \to \mathtt{notFunded}) \tag{5}$$

Figure 5 shows an FSM generated with EFSM-TOOLS from this specification the set of scenarios  $S=\{s_1,s_2,s_3\}$ , where

```
\begin{split} s_1 &= [(\texttt{donate}, \mathsf{True}, .), (\texttt{donate}, \mathsf{True}, .), \\ &(\texttt{donate}, \mathsf{True}, .)]; \\ s_2 &= [(\texttt{getFunds}, \texttt{donation0ver}, .), \\ &(\texttt{reclaim}, \texttt{notFunded}, .), \\ &(\texttt{reclaim}, \texttt{notFunded}, .)]; \\ s_3 &= [(\texttt{donate}, \mathsf{True}, .), (\texttt{getFunds}, \texttt{donation0ver}, .), \\ &(\texttt{reclaim}, \texttt{notFunded}, .), (\texttt{reclaim}, \texttt{notFunded}, .)]. \end{split}
```

Another advantage of using formal logic is that now we can reason about about the system. For instance, from properties 1 and 3 we can derive that getFunds cannot happen after reclaim.

### 3.2. Blinded auction

Now we consider a more realistic example of blinded auction taken from [7]. During a predefined period of time after contract creation, users can make hidden bids (denoted with event bid). When this period is over (biddingOver = True) the auction can be closed (event close), after which follows the next period when users are allowed to reveal their bids. When the second period is over (revealOver = True) the auction can be finished (event finish). At any time before finishing the auction can be canceled (cancel), after which users can claim back their bids (event unbid).

The logic of this blinded auction can be formulated as follows (we provide corresponding LTL formulas along-side).

 close, finish and cancel cannot happen more than once:

```
\begin{split} & G(\texttt{close} \to X \neg F \texttt{close}), \\ & G(\texttt{finish} \to X \neg F \texttt{finish}), \\ & G(\texttt{cancel} \to X \neg F \texttt{cancel}); \end{split}
```

```
_cancel_action(); state = ST_3;
    contract BlindedAuction {
      enum State { ST_0, ST_1, ST_2, ST_3 }
                                                          29
2
                                                                  }
                                                          30
3
      State private state = States.ST_0;
4
      struct Bid {
                                                          31
5
        bytes32 blindedBid;
                                                          32
                                                                function
                                                                               bid() public
                                                          33
6
        uint deposit;
                                                                 function
                                                                             close() public
7
                                                          34
                                                                 function withdraw()
                                                                                     public
8
      mapping(address => Bid[]) private bids;
                                                          35
                                                                            reveal() public
                                                                 function
9
                                                          36
      mapping(address => uint) private pendingReturns;
                                                                 function
                                                                            finish() public
10
      address private highestBidder;
                                                                 function
                                                                             unbid() public
11
      uint private highestBid;
                                                          38
      boolean private closed = false;
                                                          39
12
                                                                 function _bid_action() public {
13
                                                          40
                                                                   bids [msg.sender].push(Bid({
                                                          41
                                                                     blindedBid: blindedBid,
14
      function biddingOver() private returns (bool) {
                                                                     deposit: msg. value
15
        return now > creationTime + 5 days;
                                                          42
16
                                                          43
                                                                   }));
      function revealOver() private returns (bool) {
                                                          44
                                                                  pendingReturns[msg.sender] += msg.value;
17
        return now >= creationTime + 10 days;
                                                          45
18
19
                                                          46
20
                                                          47
                                                                             _close_action() public
                                                                 function
                                                                            _reveal_action() public
21
      function cancel() public {
                                                          48
                                                                 function
22
        require(state == States.ST_0
                                                          49
                                                                 function
                                                                            _finish_action() public
23
                 || state == States.ST_2)
                                                          50
                                                                 function _withdraw_action() public
24
        if (state == ST_0) {
                                                          51
                                                                 function
                                                                            _cancel_action() public
25
          _cancel_action(); state = ST_3;
                                                          52
                                                                             _unbid_action() public
                                                                 function
26
                                                          53
27
        if (state == ST_2) {
```

Figure 4. Blinded auction. Generated Solidity code.

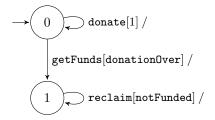


Figure 5. Crowdfunding. FSM generated for size = 2 states.

2) bid cannot happen after close has happened:

$$\mathbf{G}(\mathtt{close} \to \neg \mathbf{Fbid});$$

3) reveal and cancel cannot happen after finish has happened:

$$G(\texttt{finish} \rightarrow \neg F(\texttt{reveal} \lor \texttt{cancel}))$$

4) finish, close, bid and reveal cannot happen after cancel has happened:

$$G(\mathtt{cancel} o 
eg F(\mathtt{finish} \lor \mathtt{close} \lor \mathtt{bid} \lor \mathtt{reveal}))$$

5) finish and reveal cannot happen before close:

close 
$$\mathbf{R}$$
 (¬finish  $\land$  ¬reveal);

6) unbid cannot happen before cancel:

cancel 
$$\mathbf{R} \neg \mathtt{unbid}$$
;

7) withdraw cannot happen before finish:

```
finish R ¬withdraw;
```

8) close can happen only if biddingOver = True:

$$G(\texttt{close} \rightarrow \texttt{biddingOver});$$

9) finish can happen only if revealOver = True:

$$\mathbf{G}(\mathtt{finish} \to \mathtt{revealOver}).$$

This formal LTL specification and a set of test scenarios was used to generate a FSM depicted in Figure 3. Test scenarios for this and the next case study can be found online <sup>3</sup>. Given Solidity code associated with output actions labeling FSM transitions, the full smart contract code can be generated. The code generated from synthesized FSM is shown in Figure 4.

#### 3.3. License server

This is an example taken from [19]. Here we consider a smart contract that could be used to monitor the execution of the agreement between two parties, namely Licensor and Licensee. We assume that these parties perform as client agents connected to some blockchain network. The contract consists of the following clauses which were copied from [19] and annotated with event names that we are going to use in the rest of this section to model contract execution.

- The Licensor grants the Licensee a license to evaluate the Product (getLicense).
- 2) Licensee must not publish the results of the evaluation (use) of the Product without the approval (getApproval) of the Licensor; the approval must be obtained before the publication. If the Licensee

<sup>3.</sup> https://github.com/d-suvorov/sc-gen

publishes results of the evaluation of the Product without approval from the Licensor, the Licensee has 24 hours to remove the material.

- 3) The Licensee must not publish comments (comment) on the evaluation of the Product, unless the Licensee is permitted to publish the results of the evaluation.
- 4) If the Licensee is commissioned (getCommission) to perform an independent evaluation of the Product, then the Licensee has the obligation to publish the evaluation results.
- This license will terminate automatically if Licensee breaches this Agreement.

There is not a timer that can be used to trigger some transition in a blockchain system, that is why we introduce special events noRemove and noPublish. noRemove happens if the results of the evaluation of the Product were not removed in due time. noPublish happens if the Licensee was commissioned to perform an independent evaluation and did not published the results. Thus LTL specification is less abstract and at the first sight less intuitive than the informal description above. For instance to state that it is permitted to use and publish results after getting an approval we introduce the property  $\mathbf{G}(\mathtt{getApproval} \to \mathbf{G}(\neg \mathtt{noRemove}))$ : "noRemove cannot happen after getApproval has happened". Given that property, and the fact that getApproval can only happen after getLicense, we can derive that terminate cannot happen after getApproval. The latter property can be formalized and verified, which is an advantage of using formal logic system for specifying a contract.

We introduce LTL specification in two stages. The following formulas encode general principles of the system (e.g., "remove cannot happen if nothing has been published").

$$\begin{aligned} & \mathbf{G}(\texttt{getLicense} \to \mathbf{X} \neg \mathbf{F} \texttt{getLicense}) & (1) \\ & \mathbf{G}(\texttt{getApproval} \to \mathbf{X} \neg \mathbf{F} \texttt{getApproval}) & (2) \end{aligned}$$

$$\mathbf{G}(\mathsf{noRemove} \to \mathbf{X} \neg \mathbf{F} \mathsf{noRemove}) \tag{3}$$

$$\mathbf{G}(\mathtt{noPublish} \to \mathbf{X} \neg \mathbf{FnoPublish}) \tag{4}$$

$$publish \mathbf{R} \neg remove \tag{5}$$

$$G(remove \rightarrow X(publish R \neg remove))$$
 (6)

$$publish \mathbf{R} \neg noRemove \tag{7}$$

$$G(\texttt{remove} \to X(\texttt{publish} R \neg \texttt{noRemove}))$$
 (8)

$$getLicense \mathbf{R} \neg getApproval \tag{9}$$

getLicense 
$$\mathbf{R} \neg \text{getCommission}$$
 (10)

$$getCommission \mathbf{R} \neg noPublish \tag{11}$$

$$\mathbf{G}(\mathtt{publish} \to \mathbf{X}(\mathtt{getCommission} \; \mathbf{R} \; \neg \mathtt{noPublish})) \; \; (12)$$

$$\mathbf{G}(\texttt{terminate} \to \mathbf{X} \neg \mathbf{F} \texttt{noRemove}) \tag{13}$$

$$\mathbf{G}(\texttt{terminate} \to \mathbf{X} \neg \mathbf{FnoPublish}) \tag{14}$$

 $\mathbf{G}(\mathtt{terminate} o$ 

$$\neg \mathbf{F}(\mathtt{getLicense} \lor$$

The following formulas encode contractual clauses.

$$\begin{array}{l} (\texttt{getLicense} \lor \texttt{terminate}) \; \mathbf{R} \\ & ((\texttt{use} \lor \texttt{publish}) \to \texttt{terminate}) \\ & \mathbf{G}(\texttt{getLicense} \to \end{array} \tag{1}$$

$$\neg \mathbf{F}((\mathtt{use} \lor \mathtt{publish}) \land \mathtt{terminate})) \tag{2}$$

$$(\mathtt{getApproval} \lor \mathtt{getCommission} \lor \mathtt{terminate}) \ \mathbf{R}$$

$$(comment \to terminate) \tag{3}$$

$$\textbf{G}(\texttt{noRemove} \rightarrow \texttt{terminate}) \tag{4}$$

$$\textbf{G}(\texttt{noPublish} \rightarrow \texttt{terminate}) \tag{5}$$

$$\mathbf{G}(\mathtt{getApproval} \to \mathbf{G} \neg \mathtt{noRemove})$$
 (6)

(7)

 $G(\mathtt{getCommission} o G \neg \mathtt{noRemove})$ 

online (the link was provided in the previous section).

The original contract is formulated in terms of deontic modalities, i.e., in terms of permissions, obligations and related concepts. A shortcoming of specifying this smart contract in temporal logic (and using it to synthesize FSM model) is not tracking these modalities: given a sequence of actions there is no easy way to figure out permissions and obligations of contractual parties. On the other hand, the resulting representation is efficient, which is important in case of on-chain deployment, and could be used to

determine whether or not the given sequence of actions leads

### 4. Conclusion and discussion

to contract termination.

We argue that automated program synthesis could find more applications for smart contract generation as they often have simpler structure than general purpose programs and it is an open research question whether a Turing-complete language is necessary for smart contract programming. We would like to draw attention of the community to the problem of automatic synthesis of smart contracts. We provided several case studies to show that LTL synthesis can be applied to generate FSM models for smart contracts of some types. In these models input events correspond to smart contract methods and output actions correspond to these methods' implementation. Generated FSM models can further be used to obtain programs that are correct with respect to some formal temporal properties.

Our approach can be straightforwardly extended for systems of interacting smart contracts and used to specify, synthesize and verify them. Another interesting method to extend the supported class of verified properties is to incorporate source-level formal verification techniques. Output actions in synthesized FMSs correspond to smart contract methods, hence we can use other verification frameworks to prove source-level properties about these methods and combine them with temporal properties of FSM models itself.

In practice smart contracts receive, hold and send coins and transaction execution costs some amount of gas. It is

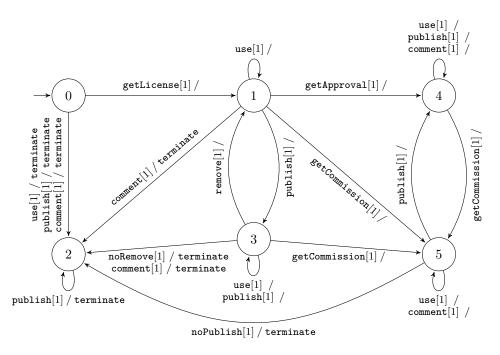


Figure 6. License. FSM generated for size = 6 states.

important to be able to use these concepts to formulate properties of interest about smart contracts. Hence, other possibilities for future work include using SAT or SMT to encode such concepts and extending specification language to incorporate these.

A drawback of using LTL synthesis is that LTL is not expressive enough to formulate properties of kind " $\phi$  can happen infinitely often (while  $\psi$  has not happened)". For example the formula **EG**  $\phi$  in CTL can be used to state that there is a path on which  $\phi$  always holds. However this problem can be easily mitigated by specifying test scenarios in which donate repeats N times, where N is greater than the number of transitions of FSM to be generated.

Despite the simple remedy for the above problem we believe that a more suitable formal system to specify smart contracts is yet to be identified. It is an interesting research question: how to strike a balance between simplicity and expressivity of this system to allow effective synthesis of practical smart contracts.

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