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From Domain Specific Language to Code: Smart Contracts and the Application of Design Patterns

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Abstract—
Smart contracts are self-executing computer programs that stipulate and enforce the negotiation and execution of (legal) contracts. Today, one of the most prominent smart contract ecosystems is Ethereum, a blockchain based distributed computing platform, that can be used to capture and express contract terms, for instance, in the platform's leading programming language, Solidity. Due to the conceptual discrepancy between legal contract terms and corresponding code, it is difficult to easily comprehend smart contracts and write them efficiently without errors. After all, blockchain-based contract execution, lacking programming abstractions, and constantly changing platform capabilities and security aspects, make writing smart contracts a difficult undertaking. To address these problems, this article proposes smart contract design patterns and their automated application, by means of code generation and the use of a domain-specific language.

■ **SMART CONTRACTS** based on blockchain technologies have received a lot of attention in the recent past. Their potential to open up new business applications, by replacing the established trust concept of intermediaries, has sparked a hype around them. However, the initial euphoria was dampened by serious security incidents [1] and the insight that failing contracts can entail huge financial losses. This applies in particular to one of the most prominent implementation platforms for smart contracts, Ethereum. Ethereum is an open source, distributed computing platform, allowing the creation and execution of decentralized programs (smart contracts) in its own blockchain [2]. Nowadays, creating such smart contracts that convert legal contracts into a machine readable and executable form is a challenging task. Beyond the conceptual gap between natural (legalese) language and equivalent code, various peculiarities of the underlying blockchain environment complicate the correct and secure creation of smart contracts even further [3]. These include the fixed and autonomous nature of code execution, the lack of high-level coding abstractions, and the rapid progress of the development framework. In view of these problems, it is beneficial to have a foundation of established design and coding guidelines along with a framework for their application. To pursue this goal it is advantageous to base smart contracts on higher-level, well established designs that have emerged as best practices [4]. To this end, we propose design patterns [5] for creating smart contracts in the context of Ethereum and similar platforms. In order to automate the application of these design patterns and to avoid errors due to their manual coding, we also propose a domain-specific language (DSL) for smart contracts and a code generator to generate Solidity code from the DSL. A DSL is a computer programming language of limited expressiveness focused on a particular application domain [6].

Contract Stages

Contracts are usually preceded by an abstract agreement that specifies elementary modalities and actions between parties. In order to avoid the ambiguity of natural language and to explicate terms and conditions as clearly and completely as possible, contracts are written in legalese. This can be understood as a first formalization method. A machine readable representation, usually in a formal language, is retrieved from a conversion of the traditionally written contract, although a contract could be immediately specified in a formal language. A written contract is grounded on law, where enforceability is considered to be *ex post*, i.e. a party can enforce a settlement at court only after a contractual breach. This stands in contrast to the formal machine representation and its realization as a smart contract, where the execution is based on an architecture that by design does not allow non-conformism, hence enforceability is considered to be *ex ante*. The above described principles are depicted in **Figure 1**, which gives an overview of the different contract stages, namely negotiation, formation, and performance.

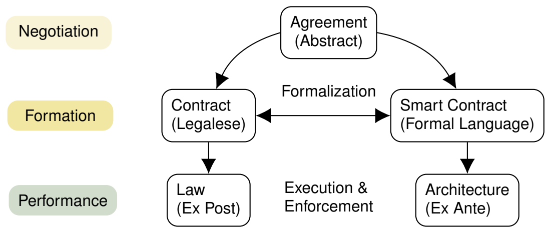


Figure 1: Contract stages and the conceptual relation between traditional and smart contracts.

Smart Contract Design Patterns

Design patterns express an abstract or conceptual solution to a concrete, complex, and reoccurring problem. In the context of Ethereum-based smart contract development we have elaborated several design patterns (see [7], [8] for details). The patterns help to solve commonly recurring application requirements and address common problems and vulnerabilities connected to smart contract design. According to their operational scope they are divided into five categories: *a*) *Action and Control*, *b*) *Authorization*, *c*) *Lifecycle*, *d*) *Maintenance*, and *e*) *Security*. Although some patterns are very basic, their real practical value unfolds when patterns are used as a prerequisite or in combination with other patterns. **Table 1** provides an overview of the pattern categories and associated patterns, including a brief description of the underlying problem and its solution. More details about the patterns along with Solidity coding practices can be studied in [7], [8].

DSLs for Smart Contract Development

DSLs can express a problem discipline in a more natural way for domain experts, making the entire development process more efficient and less error prone. Several smart contract DSLs exist with various language concepts and programming paradigms, like DAML [9] a functional language influenced by Haskell, Ergo [10] an imperative language, and Archetype [11] a declarative and imperative language focusing on formal verification, to just name a few. In contrast to these languages, we propose a DSL called Contract Modeling Language (CML) [12] that builds on a clause grammar close to natural language to mimic the obligations expressed in contracts. The language is implemented in Xtext [13] and available on Github [14].

Table 1: Smart contract design patterns overview.

Action and Control	
Pull Payment	As a send operation can fail, let the receiver withdraw the payment.
State Machine	When different contract stages are needed, these are modeled and represented by a state machine.
Commit and Reveal	As blockchain data is public, a commitment scheme ensures confidentiality of contract interactions.
Oracle (Data Provider)	When knowledge outside the blockchain is required, an oracle pushes information into the network.
Authorization	
Ownership	As anyone can call a contract method, restrict the execution to the contract owner's address.
Access Restriction	When function execution checkups are needed, these are handled by generally applicable modifiers.
Lifecycle	
Mortal	Since deployed contracts do not expire, self-destruction with a preliminary authorization check is used.
Automatic Deprecation	When functions shall become deprecated, apply function modifiers to disable their future execution.
Maintenance	
Data Segregation	As data and logic usually reside in the same contract, avoid data migration on updates by decoupling.
Satellite	As contracts are immutable, functions that are likely to change are outsourced into separate contracts.
Contract Register	When the latest contract version is unknown, participants pro-actively query a register.
Contract Relay	When the latest contract version is unknown, participants interact with a proxy contract.
Security	
Checks-Effects-Interaction	As calls to other contracts hand over control, avoid security issues by a functional code order.
Emergency Stop	Since contracts are executed autonomously, sensitive functions include a halt in the case of bugs.
Speed Bump	When task execution by a huge number of users is unwanted, prolong completion for counter measures.
Rate Limit	When a request rush on a task is not desired, regulate how often a task can be executed within a period.
Mutex	As re-entrancy attacks can manipulate contract state, a mutex hinders external calls from re-entering.
Balance Limit	There is always a risk that a contract gets compromised, thus limit the maximum amount of funds held.

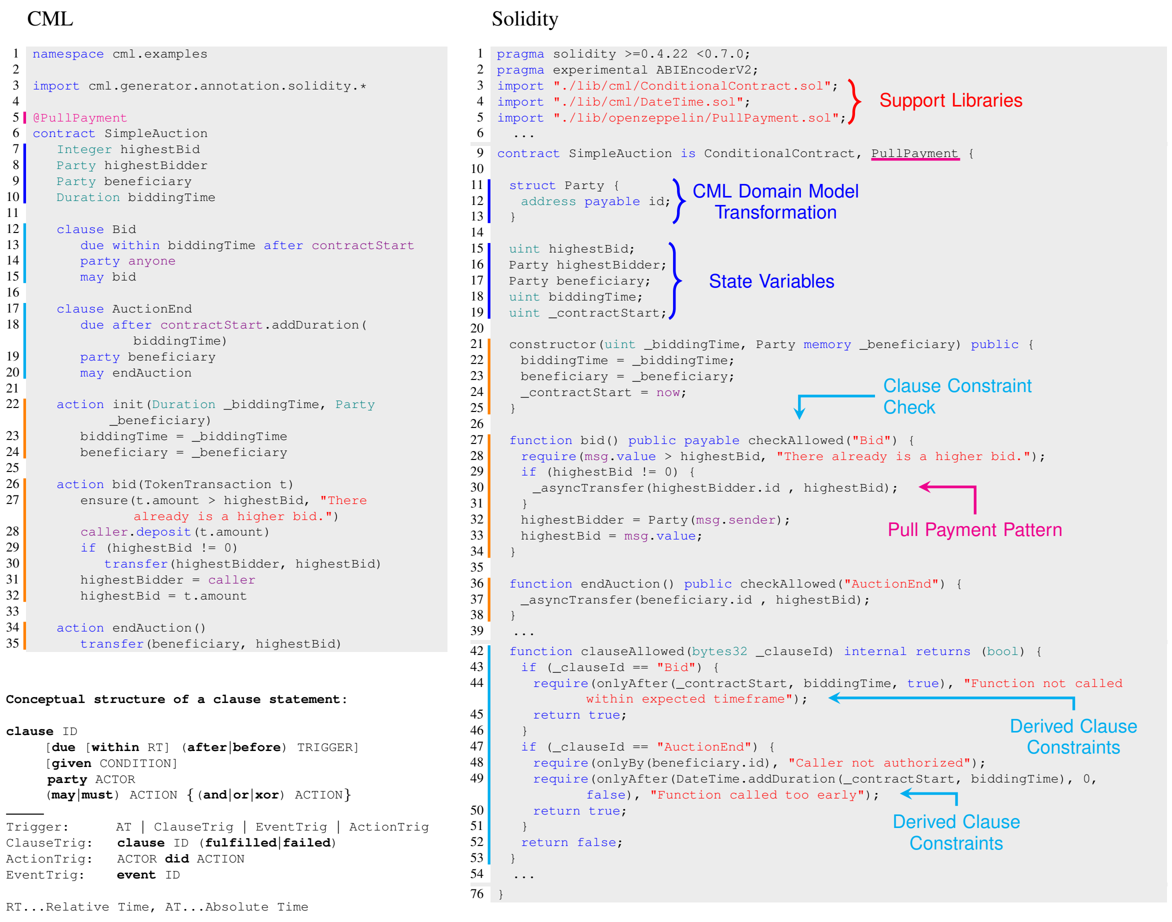
Contract Modeling Language (CML)

CML is a high-level DSL using a declarative and imperative formalization as well as object-oriented abstractions to specify smart contracts. As seen in the exemplary CML contract in **Figure 2** on the left, contracts in CML consist of state variables (line 7-10) and actions (line 22-35), which operate on these. In addition, contracts contain clause statements (line 12-20) that resemble natural language, to mimic and capture contractual obligations of involved parties. More precisely, these statements represent so-called covenants, which are specific contractual clauses that belong to elementary building blocks of contracts and enclose promises to engage in or refrain from certain actions. The conceptual structure of clause statements (see Figure 1 lower left) is derived from an analysis of typical covenant components and looks as follows: Each clause statement must specify at least an actor, an action, and the modality of that action ("may" or "must") and has an unique identifier for referencing. Optional elements include temporal or state constraints. Temporal constrains are indicated by the keyword "due" followed by a temporal precedence (i.e., "after" or "before") and a trigger expression. The trigger expression refers to an absolute time or a construct from which an absolute time can be derived. This includes the performance of a clause, the execution of an action, or the occurrence of an external event. General constraints can be defined after the keyword "given" by multiple linked conditions, which usually refer to the contract state. In general, the described clause statements support a more natural and practical contract representation compared to an unstructured code implementation and offer a better overview of contract behavior at a glance.

To further expand efforts towards abstraction, CML uses a type system that is more closely related to application domain concepts. CML offers not only typical primitive types (*Boolean*, *String*, etc.), but also basic temporal types (*DateTime*, *Duration*), and easily extensible structural composite types (*Party*, *Asset*, *Transaction*, *Event*) to embody common contract-specific concepts and operations. Through these measures a generic framework for contract formalization is provided, that avoids an excessive syntax containing implementation specifics. As a result, higher-level contract specifications can be translated into a desired form of implementation, leading to a decoupling of contract specification and implementation.

CML Code Generation to Solidity

As proof-of-concept, we have implemented a code generator that assigns CML abstractions to appropriate Solidity equivalents. During this procedure, design patterns and other practical coding idioms can be applied. To illustrate this process,



Support Libraries
CML Domain Model Transformation
State Variables
Clause Constraint Check
Pull Payment Pattern
Derived Clause Constraints
Derived Clause Constraints

CML

```
1  namespace cml.examples
2
3  import cml.generator.annotation.solidity.*
4
5  @PullPayment
6  contract SimpleAuction
7     Integer highestBid
8     Party highestBidder
9     Party beneficiary
10    Duration biddingTime
11
12    clause Bid
13       due within biddingTime after contractStart
14       party anyone
15       may bid
16
17    clause AuctionEnd
18       due after contractStart.addDuration(
            biddingTime)
19       party beneficiary
20       may endAuction
21
22    action init(Duration _biddingTime, Party
           _beneficiary)
23       biddingTime = _biddingTime
24       beneficiary = _beneficiary
25
26    action bid(TokenTransaction t)
27       ensure(t.amount > highestBid, "There
            already is a higher bid.")
28       caller.deposit(t.amount)
29       if (highestBid != 0)
30          transfer(highestBidder, highestBid)
31       highestBidder = caller
32       highestBid = t.amount
33
34    action endAuction()
35       transfer(beneficiary, highestBid)
```

```
Conceptual structure of a clause statement:

clause ID
     [due [within RT] (after|before) TRIGGER]
     [given CONDITION]
     party ACTOR
     (may|must) ACTION {(and|or|xor) ACTION}
_____
Trigger:      AT | ClauseTrig | EventTrig | ActionTrig
ClauseTrig:   clause ID (fulfilled|failed)
ActionTrig:   ACTOR did ACTION
EventTrig:    event ID

RT...Relative Time, AT...Absolute Time
```

Solidity

```
1  pragma solidity >=0.4.22 <0.7.0;
2  pragma experimental ABIEncoderV2;
3  import "./lib/cml/ConditionalContract.sol";
4  import "./lib/cml/DateTime.sol";
5  import "./lib/openzeppelin/PullPayment.sol";
6    ...
9  contract SimpleAuction is ConditionalContract, PullPayment {
10
11  struct Party {
12   address payable id;
13  }
14
15  uint highestBid;
16  Party highestBidder;
17  Party beneficiary;
18  uint biddingTime;
19  uint _contractStart;
20
21  constructor(uint _biddingTime, Party memory _beneficiary) public {
22   biddingTime = _biddingTime;
23   beneficiary = _beneficiary;
24   _contractStart = now;
25  }
26
27  function bid() public payable checkAllowed("Bid") {
28   require(msg.value > highestBid, "There already is a higher bid.");
29   if (highestBid != 0) {
30    _asyncTransfer(highestBidder.id , highestBid);
31   }
32   highestBidder = Party(msg.sender);
33   highestBid = msg.value;
34  }
35
36  function endAuction() public checkAllowed("AuctionEnd") {
37   _asyncTransfer(beneficiary.id , highestBid);
38  }
39   ...
42  function clauseAllowed(bytes32 _clauseId) internal returns (bool) {
43   if (_clauseId == "Bid") {
44    require(onlyAfter(_contractStart, biddingTime, true), "Function not called
          within expected timeframe");
45    return true;
46   }
47   if (_clauseId == "AuctionEnd") {
48    require(onlyBy(beneficiary.id), "Caller not authorized");
49    require(onlyAfter(DateTime.addDuration(_contractStart, biddingTime), 0,
          false), "Function called too early");
50    return true;
51   }
52   return false;
53  }
54   ...
76 }
```

Figure 2: An auction contract specified in CML and an excerpt of the generated Solidity code.

Figure 2 shows a simple auction contract in CML and the correspondingly generated output in Solidity. The generator traverses the CML representation to produce Solidity code that relies on static and dynamically created support libraries. These libraries contain the implementation of CML abstractions. As such they embody CML type operations (line 4), or refer to established libraries for smart contract development (line 5). In light of this, type operations in CML are merely declared as method signatures and are implemented in Solidity through library calls. Regarding the structural transformation, CML types are mapped to conceptual Solidity type equivalents (line 11-19), actions are converted to Solidity functions (line 21-38), and clause statements are transformed into declarative checks (line 43-52) that are applied by the `checkAllowed` modifier (line 27, 36) added to those functions. The modifier itself is inherited from `ConditionalContract` and contains a call to `clauseAllowed` (overridden in line 42) as well as code to track the context (e.g. time, caller) of successfully executed functions. During code generation it is also possible to apply design patterns. In the depicted example the Pull Payment pattern is applied to mitigate security risks when sending funds, by switching from a push to a pull payment. An appropriate annotation instructs the generator to incorporate the pattern implementation (line 9) and engage asynchronous payments for all outgoing token transfers (line 30). Various other practical transformation schemes are possible. For example, an automatic application of wrapper calls for arithmetic operations to avoid type overflows and underflows. Also the seamless use of decimal numbers, although not currently supported by Solidity, through fixed point arithmetic, with the generator automatically inducing the appropriate value assignments and arithmetic calculations.

CONCLUSION

In this article we have presented smart contract design patterns and proposed a high level smart contract language called Contract Modeling Language (CML). The patterns provide guidance for addressing common smart contract design challenges in Ethereum, and the DSL provides useful abstractions for the specification of smart contracts. The combined application of both is shown by transferring a CML specification into a Solidity implementation that follows established design recommendations. The associated code generation serves to automate platform-specific implementation steps by mapping abstractions to suitable target equivalents and integrating useful design patterns and coding practices. The proposed approach can reduce the design complexity since an abstract representation, that is very compact and close to the target domain, is translated into a more verbose and low-level implementation. In addition, the approach can reduce the susceptibility to errors, assuming the code generator generates correct code. Overall, the use of a DSL including code generation based on design patterns can increase the efficiency, clarity and flexibility of smart contract development while reducing the susceptibility to errors.

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