Abstract
Sharding is a popular way to achieve scalability in blockchain protocols, increasing their throughput by partitioning the set of transaction validators into a number of smaller committees, splitting the workload. Existing approaches for blockchain sharding, however, do not scale well when concurrent transactions alter the same replicated state component—a common scenario in Ethereum-style smart contracts.

We propose a novel approach for efficiently sharding such transactions. It is based on a folklore idea: state-manipulating atomic operations that commute can be processed in parallel, with their cumulative result defined deterministically, while executing non-commuting operations requires one to own the state they alter. We present CoSPLIT—a static program analysis tool that soundly infers ownership and commutativity summaries for smart contracts and translates those summaries to sharding signatures that are used by the blockchain protocol to maximise parallelism. Our evaluation shows that using CoSPLIT introduces negligible overhead to the transaction validation cost, while the inferred signatures allow the system to achieve a significant increase in transaction processing throughput for real-world smart contracts.

CCS Concepts: • Computing methodologies → Distributed programming languages.

Keywords: Smart Contracts, Static Analysis, Parallelism

1 Introduction
The idea of Nakamoto consensus (aka blockchain) has been instrumental for enabling decentralised digital currencies, such as Bitcoin [48]. The applications of blockchains have further expanded with the wide-spread adoption of smart contracts [62]—self-enforcing, self-executing protocols governing an interaction between several mutually distrusting parties. The Ethereum blockchain has provided a versatile framework for defining smart contracts as blockchain-replicated stateful objects identified by their account numbers [65].

The open and decentralised nature of Nakamoto consensus comes at the price of throughput scalability. At a high level, in order for a sequence of transactions (so-called block) to be agreed upon system-wide, the system’s participants (so-called miners) have to validate those transactions, with each miner executing them individually [4]. As a result, the throughput of blockchain systems such as Bitcoin and Ethereum does not improve, and even slightly deteriorates, as more participants join the system: Bitcoin currently processes up to 7 transactions per second, while Ethereum’s throughput is around 18 transactions per second. Even worse, popular smart contracts may cause high congestion, forcing protocol participants to exclusively process transactions specific to those contracts. This phenomenon has been frequent in Ethereum: in the past, multiple ICOs (Initial Coin Offering, a form of a crowdfunding contract) and games, such as CryptoKitties, have rendered the system useless for any other purposes for noticeable periods of time [14].

Sharding in Blockchains. One of the most promising approaches to increase blockchain throughput is to split the set of miners into a number of smaller committees, so they can process incoming transactions in parallel, subsequently achieving a global agreement via an additional consensus mechanism—an idea known as sharding. Sharding transaction executions, as well as sharding the replicated state, has been an active research topic recently, both in industry [23, 30, 39, 51, 60, 64, 67] and academia [1, 17, 36, 45, 66].

Many of those works focus exclusively on sharding the simplest kind of transactions—user-to-user transfers of digital funds—which are paramount in blockchain-based cryptocurrencies, while ignoring sharding of smart contracts [36, 45, 66, 67]. Existing proposals tackling smart contracts impose
heavy restrictions on contract-manipulating transactions, for instance, requiring the accounts of both the contract and its user to be assigned the same shard, or processing all such transactions in a specialised shard [17, 30, 39]. Other solutions assume a complex cross-shard communication protocol to reconcile possible conflicts [23, 30, 51, 60, 64], or adopt a contract design very different from Ethereum [1].

To the best of our knowledge, none of these approaches allows for parallel sharded executions involving the same smart contract. That is, none solve the mentioned congestion problem in Ethereum, caused by highly-popular contracts.

In this work, we describe a novel approach for significantly increasing the throughput of blockchains for smart contract-manipulating transactions. To achieve this, instead of treating contract implementations as “black boxes” (as do all the works mentioned above), we design a solution based on PL techniques, specifically, on static program analysis.

**Our Approach.** Why can user-to-user money transfers be sharded efficiently without complex inter-shard communication, and how can we generalise (perhaps, conservatively) this logic to shard arbitrary smart contracts?

Consider a transaction $tx_1$ that manifests a transfer of 10 units of some digital currency from the user $A$ to $B$, and a transaction $tx_2$ that states that $A$ transfers 20 units to $C$. In order to ensure that $A$ does not double-spend, both $tx_1$ and $tx_2$ have to be executed in the same shard—the one that owns $A$’s account and keeps track of $A$’s balance. However, neither $B$ nor $C$ need to be owned by $A$’s shard: as long as $tx_1$ and $tx_2$ are validated within $A$’s shard, the positive deltas to $B$ and $C$’s accounts can be simply broadcast through the network, so their balances are increased accordingly with no extra inter-shard interaction.

Now consider a transaction $tx_3$, in which $D$ transfers 15 units to $C$. Notice that it does not matter in which order $tx_1$ and $tx_3$ are going to be processed, as they commute: either of their relative orderings will increase $C$’s balance by 35.

The notions of state ownership and operation commutativity have been central in a number of works dedicated to reasoning about deterministic parallelism and proving correctness of concurrent programs [19, 20, 22, 34, 40, 44, 50]. In those works, the ownership discipline determines what parts of the shared state need to be manipulated sequentially by the same thread, while commutativity allows certain actions to be executed in concurrent threads in parallel, with a deterministic result. The virtues of commutative operations have also been studied in the systems community for scaling concurrent software [3, 13, 52, 55] and achieving faster consensus in replication protocols [11, 37, 42, 47]. However, to the best of our knowledge, no attempts to automatically leverage commutativity in user-defined replicated computations (e.g., smart contracts) have been made to date.

In this work, we present CoSplit—a static analysis tool that soundly infers both ownership and commutativity information from source code of smart contracts and translates it to sharding signatures. The signatures are used, upon the deployment of a contract, to define a sharding strategy for the contract-manipulating transactions via the following rules:

- All transactions touching parts of a contract’s state owned by a shard $S$ must be executed in this shard;
- Transactions executed in different shards are guaranteed to commute. Their cumulative result can be obtained by means of “joining” their respective contributions in a way prescribed by the sharding signature.

These two rules allow the system to enjoy a notion of consistency for parallel transaction executions adopted from works on the semantics of concurrent revisions [7, 8, 43]:

1. Potentially conflicting contract-manipulating transactions will be executed in some globally-agreed order.
2. Commuting transactions can be executed in parallel, as their effect does not depend on their order.

As we will discuss in Sec. 2, popular Ethereum-style contracts often allow for a “logical split” of their state into disjointly owned components, which is much more fine-grained than assigning an entire contract to a single shard. This split makes it possible to process transactions affecting those contracts in parallel in different shards, thus providing a practical solution to scale up the network throughput.

**Our Contributions.** The contributions of this work are:

- Identifying logical state ownership and operation commutativity as enabling mechanisms for sharding Ethereum-style contracts, and demonstrating adequacy of those notions for real-world Ethereum-style contracts (Sec. 2).
- A compositional static analysis that infers ownership and commutativity signatures for contracts written in Scilla [57] and translates them to shard allocation strategies (Sec. 3).
- An implementation of the analysis and of the algorithm for deriving sharding strategies in the tool called CoSplit and an end-to-end integration of CoSplit with a production-grade shard-based blockchain protocol [45, 67] (Sec. 4). The archived software artefact is publicly available [53].

- Evaluation of parallelism enabled by CoSplit-inferred signatures, demonstrating a consistent increase in system throughput with increasing the number of shards (Sec. 5).

## 2 Motivation and Key Ideas

### 2.1 Contract Usage in Ethereum

To motivate the design of our approach for sharding, we first present the trends for smart contract usage in Ethereum. Since there are over 700 million Ethereum transactions to date, processing all the execution traces is too computationally expensive. Therefore, we selected a random sample of
16,611 blocks, containing 1.1M transactions. The sample was collected in January 2020 and includes transactions up to block 9.25M, representing 0.17% of the total number of transactions up to that point and giving our measurements a 1% margin of error at a 99% confidence level.\footnote{The Ethereum dataset and analysis are part of the archived artefact [53].} As the left plot in Fig. 1 shows, ordinary user-to-user transfers are on a solid downward trend. Moreover, single-contract transactions take up to 55% of the recent blocks in our sample.

In this work we focus on sharding single-contract transactions. The right plot in Fig. 1 shows the dominance of a specific type of such transactions that represent token transfers in a special kind of contract—ERC20 token contracts [24]. ERC20 and other similar standardised contracts pose a big bottleneck to the network throughput: each of them requires sequential processing of all transactions that affect it.

### 2.2 Towards Sharding an ERC20 Contract

Fig. 2 shows a fragment of the implementation of an ERC20 token contract [24] in Ethereum’s high-level language Solidity [25]. The contract’s replicated state is represented by two mutable fields: the mapping balances that contains data about the amount of tokens owned by token holders; and the mapping allowances that captures the amounts of tokens authorised for third-party transfers by their holders. The state manipulations are done by transactions initiated by users (aka senders) calling one of the functions: transfer for transferring tokens, approve for granting the transfer rights for a certain amount of tokens to a third party, and transferFrom for transferring tokens on behalf of the user identified as sender. The subtractions in lines 16 and 21 will fail if the approved spender (resp. the sender) does not have enough allowance, thus preventing double-spends.

The design of the ERC20 contract provides ample opportunities for shard-based parallelism. Consider the left part of Fig. 3 that shows a fragment of the mutable ERC20 state: the balances field mapping account addresses A–E (top part of each box) to the respective token balances (bottom part of the box), and allowances, which is a mapping from addresses (e.g., A) to mappings of amounts allowed to transfer by third parties (e.g., D and E) on their behalf. Now consider the following four single-contract transactions accessing that state concurrently by invoking functions from Fig. 2: $t_1 = \text{transfer}_A(B, v_1)$; $t_2 = \text{transfer}_C(A, v_2)$; $t_3 = \text{transferFrom}_D(A, C, v_3)$; $t_4 = \text{approve}_E(A, v_4)$. Here, a subscript denotes the transaction sender’s address (accessed via \_msgSender(\) in Fig. 2), while $v_i$ stand for various non-negative amounts, whose exact value is not important. All those transactions alter the contract state; the left part of Fig. 3 shows their corresponding footprints, i.e., components of the state that they interact with. It is easy to see that the footprints of, e.g., $t_1$ and $t_3$ are disjoint, thus, their effects on the contract’s state commute. Therefore, assuming the system provides an operation to join (i.e., merge) updates
on the “logically disjoint” state components, it should be possible to execute, e.g., \(tx_1\) and \(tx_4\) in different shards.

**Sharding Strategy 1: Disjoint State Ownership.** Let us formulate the constraints for parallel execution of the transactions \(tx_1\) and \(tx_4\) from Fig. 3, out of the knowledge that some of them commute, thanks to their disjoint footprint. We will denote by \(\text{Owns}(S, \{f_1, \ldots, f_n\})\) an ownership constraint, meaning that the shard \(S\) logically owns the contract’s state components (fields or map entries) \(f_1, \ldots, f_n\) and, thus, only this shard may alter the values of those components by sequentially processing all the corresponding transactions.

Now consider two shards, \(S_1\) and \(S_2\) and the following set of ownership constraints, where \(bal\) and all denote the corresponding fields balance and allowances:

\[
\begin{aligned}
\text{Owns}(S_1, \{\text{bal}[A], \text{bal}[B], \text{bal}[C], \text{all}[A][D]\}), \\
\text{Owns}(S_2, \{\text{all}[A][E]\})
\end{aligned}
\]

Clearly, \(S_1\) and \(S_2\) own disjoint portions of the contract’s state, thus, it will be safe to assign transactions to shards as \(S_1 \mapsto \{tx_1, tx_2, tx_3\}\) and \(S_2 \mapsto \{tx_4\}\), obtain the final result deterministically by merging their non-conflicting changes. This sharding strategy scales for more shards with designated ownership of the contract’s components and larger number of transactions with logically disjoint footprints.

**Sharding Strategy 2: Commutativity of Addition.** Even though transaction \(tx_2\) modifies the component \(\text{bal}[A]\), it does so in a commutative fashion and, thus, cannot affect the outcome of any other of the listed transactions (ditto for \(tx_3\) and \(bal[B]\)). With this observation, we can refine the transaction footprints and the notion of ownership (Fig. 3, right), allowing for a parallel execution with three shards:

\[
\begin{aligned}
\text{Owns}(S_1, \{\text{bal}[A], \text{all}[A][D]\}), \\
\text{Owns}(S_2, \{\text{all}[A][E]\}), \\
\text{Owns}(S_3, \{\text{bal}[C]\})
\end{aligned}
\]

In the constraints above, \(S_1\) no longer has to own \(\text{bal}[B]\) or \(\text{bal}[C]\), while shard \(S_2\) now needs to own \(\text{bal}[C]\). In order to perform transactions allocated as \(S_1 \mapsto \{tx_1, tx_2\}, S_2 \mapsto \{tx_4\}, S_3 \mapsto \{tx_2\}\), obtaining the same result as in the previous case, we need to redefine the state join operation. Specifically, instead of overwriting the values in entries \(\text{bal}[B]\) and \(\text{bal}[A]\) upon “disjoint merging” as before, we will need to add up the deltas to those components resulting from token transfers in \(tx_1\) and \(tx_3\), similarly to handling ordinary transfers (Sec. 1).

**The Main Idea.** To summarise these observations: contracts such as ERC20, whose operations only manipulate a small part of the state, allow for parallel conflict-free execution of their operations, if these operations commute. The ownership constraints state which parts of a contract’s state a shard must have exclusive access to in order to execute its operations without conflicts with other shards altering the same contract concurrently. The join defines the way to deterministically reconcile outcomes of the parallel executions.

### 2.3 Commutativity and State Ownership

It is common to reason about operation commutativity in terms of action traces [13]. That said, our way of thinking is inspired by the logical abstractions used for compositional verification of heap-manipulating programs [9, 10, 50].

In our setup, we are interested in parallelising executions of a family of single-contract transactions over a state-space \(\Sigma\) of a contract, collectively represented by a function \(\mathcal{F}_x:\Sigma \rightarrow \Sigma\). Here, \(x\) denotes a vector of user inputs, i.e., specifying which contract’s function to call, as well as its inputs. Two transactions identified by different user inputs \(x_1\) and \(x_2\) commute iff for any state \(\sigma\), \(\mathcal{F}_{x_1}(\mathcal{F}_{x_2}(\sigma)) = \mathcal{F}_{x_2}(\mathcal{F}_{x_1}(\sigma))\).

In order to enable parallelism, our goal is to identify a commutative, associative, and partial operation \(\oplus:\Sigma \rightarrow \Sigma\). Such an operation \(\oplus\) must allow for parallel conflict-free execution of the transactions \(\mathcal{F}_x\) in the program logics literature [10], and, when it holds, it enables compositional program analyses [21] and concurrency specifications [44]. The virtue of \(\mathcal{F}_x\)’s locality for our purposes becomes apparent by observing the following chain of equalities for \(\sigma = \sigma_1 \oplus \sigma_2\) when \(\sigma_1\) and \(\sigma_2\) are such that \(\mathcal{F}_{x_1}(\sigma_1)\) and \(\mathcal{F}_{x_2}(\sigma_2)\) are defined:

\[
\begin{aligned}
\mathcal{F}_{x_1}(\mathcal{F}_{x_2}(\sigma)) &= \mathcal{F}_{x_1}(\mathcal{F}_{x_2}(\sigma_1 \oplus \sigma_2)) = \mathcal{F}_{x_1}(\sigma_1 \oplus \mathcal{F}_{x_2}(\sigma_2)), \\
&= \mathcal{F}_{x_2}(\sigma_2 \oplus \mathcal{F}_{x_1}(\sigma_1)) = \mathcal{F}_{x_2}((\sigma_2 \oplus \mathcal{F}_{x_1}(\sigma_1)); \mathcal{F}_{x_1}(\mathcal{F}_{x_2}(\sigma)) \\
&= \mathcal{F}_{x_2}(\sigma_2 \oplus \mathcal{F}_{x_1}(\sigma_1)) = \mathcal{F}_{x_2}(\mathcal{F}_{x_1}(\sigma_2)) \\
&= \mathcal{F}_{x_2}(\mathcal{F}_{x_1}(\sigma_2)) = \mathcal{F}_{x_2}(\mathcal{F}_{x_1}(\sigma))
\end{aligned}
\]

This reasoning demonstrates the desired commutativity, and also provides a recipe for computing the final result in a divide-and-conquer fashion by taking it to be \(\mathcal{F}_{x_1}(\sigma_1) \oplus \mathcal{F}_{x_2}(\sigma_2)\); the order does not matter, as \(\oplus\) is commutative and associative. One can think of \(\oplus\) as both the “logical split and join” operations, while a footprint of a transaction executing \(\mathcal{F}_x\) is the minimal part \(\sigma'\) of the contract state, which must be owned by the shard executing it, so that \(\mathcal{F}_x(\sigma')\) is defined.

Getting back to our motivating example of ERC20 sharding. **Strategy 1** corresponds to \(\oplus\) taken as a disjoint union of the entry sets of the contract’s mapping fields (let’s call it OwnOverwrite). **Strategy 2** corresponds to \(\oplus\) defined as a non-disjoint union with an implicit split of integer values in map entries—this way in the case of concurrent updates, the result can be obtained by summation of the per-shard portions of those values (we will call it IntMerge).

### 2.4 Pragmatic Considerations and Technical Setup

Ethereum is the most popular smart contract platform, and a number of other blockchain ecosystems also use the Ethereum Virtual Machine (EVM). While it would be desirable to implement our ideas directly in Ethereum, unfortunately, its infrastructure is currently unsuitable for our purposes:

---

2Readers familiar with state-of-the art program logics for concurrency can recognise that we are looking for a suitable Partial Commutative Monoid (PCM) [16, 34, 44], which would enable framing of contract operations \(\mathcal{F}_x\).
3 CoSplit Analysis in a Nutshell

3.1 The Language

Scilla is a minimalistic memory- and type-safe functional language, similar to OCaml and Haskell for an account-based (i.e., Ethereum-style) smart contract model. Scilla provides a very small set of state-manipulating primitives for altering contract state (i.e., reading from the blockchain state and changing the values of contract fields). Its pure (i.e., side effect-free) fragment corresponds to System F \[\text{F}\] without recursion (but with bounded iteration). All of the standard library as well as user-defined contract-agnostic computations are implemented in Scilla as pure functions. This design choice removes the need for inter-contract calls for the sake of code reuse and makes contract analysis scale, as pure functions need to be analysed only once.

Contracts in Scilla are encoded as communicating state-transition systems in the style of IO-automata [46]. That is, all interaction between contracts is done by means of message passing. A contract’s state changes as a result of executing its transitions as reactions to received messages from the users or other contracts. While transitions in Scilla contracts are similar to functions in Solidity, they provide stronger encapsulation and atomicity guarantees, in particular, disallowing reentrancy. This model allows one to analyse each contract’s transitions in isolation from any other contract’s code, thus allowing for deriving their signatures statically without over-approximating the effects of the external calls.

Fig. 4 describes the syntax for Scilla statements and expressions, and Fig. 5 shows the code for the \texttt{Transfer} transition of a FungibleToken (i.e., ERC20) contract.

3.2 Inferring Transition Summaries

CoSplit implements a compositional inter-procedural effect analysis [49] inferring transition summaries (a set of effects), which describe, in a symbolic form, (1) the state footprint of transitions and (2) the contributions of the initial values of contract fields, read during a transition’s execution, to the final field values. A transition’s summary is the result of the abstract interpretation \[\text{CoSplit}\] inferring

\[
\begin{align*}
\text{transition } & \text{Transfer}(\text{to: ByStr20, amount: Uint}) \\
\text{get_from_bal} & \leftarrow \text{balances}[\text{sender}]; \\
\text{match get_from_bal with} & \text{\{ Some bal = \}} \\
\lfloor & \text{can_do} = \text{uint_le amount bal;} \\
\text{match can_do with} & \text{\{ True = \}} \\
\text{new_from_bal = builtin sub bal amount;} \\
\text{balances[sender]} & \leftarrow \text{new_from_bal}; \\
\text{get_to_bal = balances[to];} \\
\text{new_to_bal = \{ match get_to_bal with} & \text{\{ Some bal = builtin add bal amount;} \\
\text{match bal with} & \text{\{ None = amount;} \\
\lfloor & \text{balances[to]} \leftarrow \text{new_to_bal;} \\
\text{msg_to_recipient = \{ (_tag : "Accepted"; \_to : to; \ldots);} \\
\text{msg_to_sender = \{ (_tag : "Success"; \_to : \_sender; \ldots;)} \\
\text{send msg_to_recipient; send msg_to_sender} \\
\end{align*}
\]

Fig. 4. Scilla syntax.

**Figure 4.** Scilla syntax.

**Figure 5.** FungibleToken \texttt{Transfer} transition in Scilla.
3.3 State Footprints

Fig. 6 shows the CoSplit abstract domain. The first stage of the analysis computes an over-approximation of the state footprints of contract transitions, expressed as a set of effects (denoted $\varepsilon$). Effects describe how the transition interacts with the blockchain state. For instance, the `AcceptFunds` effect (contributed by the `accept` statement) changes both the contract’s and the sender’s native token balances. Similarly, the `SendMsg` effect (contributed by `send`) might invoke transitions of other contracts or send native tokens. Finally, the `Read` and `Write` effects describe which portions of the contract’s own state may be accessed by the transition. For each transition, CoSplit iterates over every statement in the transition’s code and determines the static over-approximation of that statement’s effect. In some cases, this over-approximation is the uninformative effect $\top$. Due to Scilla’s design, the translation between statements and effects is direct. As an example, we show the analysis rules for map reads and writes, which can be found in the top box of Fig. 7. These rules are applied when analyzing lines 2, 9, and 14 in Fig. 5. The parts shown in grey boxes, including the rule for the non-effectful `Bind` statement, appear due to the second stage of the analysis, explained below.

The `MapGet` and `MapUpdate` rules extend the transition’s summary $\Sigma$ with the appropriate `Read` or `Write` effect, which identifies the portion $f$ (for field) of the contract state that is operated on. For map accesses, $f$ includes the name of the map and the symbolic names of keys $\overline{k}_i$ used to index into the map. For accesses to non-map contract fields, only the name of the field is included.

Whereas contract fields can always be described, the keys used to index into a map can be the result of a computation and may even depend on contract state. As such, we only assign an informative effect $\varepsilon$ to accesses when the keys used to index into the map are `transition parameters`, as they are in Fig. 5. Moreover, for nested maps, we require that the access is bottom-level, i.e., it touches a primitive value rather than a map. These constraints are captured by `CanSummarise`. If the access cannot be summarised, the $\top$ effect is given. Generally, an access can be statically described whenever the keys are not dependent on the contract state, but we limit ourselves to keys that are transition parameters to simplify transaction dispatch, which is described in Sec. 4.3.

3.4 Contribution Types

The summaries produced so far are sufficient to enable the disjoint state ownership sharding strategy. But, as we have seen, we can execute in parallel even transactions with effects over the same state, as long as the effects commute. The second stage of the analysis annotates the effects produced by the first stage with contribution types (denoted $\tau$), which help determining whether they commute. Concretely, for every expression $e$, CoSplit computes a contribution type, an over-approximation of the set of arithmetic operations and of the set of contract state components from the beginning of the transition execution that contribute to $e$’s result.

The type $\tau$ (cf. Fig. 6) ascribed to an expression $e$ indicates, which contribution sources, i.e., parts of the contract state

\begin{verbatim}
Figure 6. Components of CoSplit abstract domain.

Figure 7. Selected rules for statements and expressions.
\end{verbatim}
We lift the addition of a constant $g$ mutes with $\delta$.

For example, the linear function $f$ by a commutative operation (addition), the effect would not potentially different values (e.g. $\omega$). If the $\tau$ ascribed to the value written to field $f$ has as its only exact contribution $field f \mapsto (1, \text{Builtin add})$, and also some constants and transition parameters, the answer is yes.

**The Importance of Cardinalities.** The most important component in the type is the cardinality of $field f$. If $f$ did not show up in $\tau$, then the written value would be a constant, and different writes would not commute, as they might have potentially different values (e.g., different transition parameters). Conversely, if $f$’s contribution was non-linear, i.e., its cardinality is $\omega$ ("many"), then even though $f$ is modified by a commutative operation (addition), the effect would not commute. For example, the linear function $f(x) = x + 1$ commutes with $g(x) = x + 2$, but does not with $h(x) = x + x + 1$, as $f(h(a)) \neq h(f(a))$. The linearity ("used-once") information attached to contribution sources lets us ensure that operations are used in ways that guarantee commutative effects. We lift the $\oplus$ on operations to cardinalities by typing the cardinalities of matching sources and set-unioning their operations, ascribing to the result the $\sqcup$ of their precisions. For $\otimes$, which is defined only between a type and a single contribution, we multiply the cardinalities of the arguments and modify the other components analogously to the $\oplus$ lifting.

**Computing Contribution Types.** The values read from the mutable contract state, literals, transition and contract parameters are all contribution sources. For example, the Literal and MapGet rules in Fig. 7 show how new contribution sources are introduced. A read into a binder $i_1$ from a location that was not overwritten, extends the typing context $\Gamma$ by giving $i_1$ the linear contribution type $\tau$ shown in the rule. The type shows that the value of $i_1$ is the value of the respective "pseudo-field" $\pi_k$ (i.e., a map entry) at the beginning of the transition execution. Contributions from multiple sources are combined with their cardinalities added up point-wise via $\oplus$ operator (cf. Fig. 6). For example, the application of a BuiltIn function adds up the contributions from its arguments and records an application of BuiltIn $\text{blt}$ to each contribution source, recording this in the type.

Functions are given arrow types, EFun $i \tau$, with each formal parameter constituting an artificial contribution source Formal $i$. When the function is applied (rule APP), the arrow type is evaluated by substituting the formal parameter’s contribution with the actual argument’s contributions, multiplying the cardinalities. Our approach supports up to second-order Scilla functions by expressing operations on contribution types ($\oplus$, $\sqcap$, and $\otimes$) at the type level, and deferring normalisation until the arguments are known. For simplicity, we do not show this in the figures. Even though Scilla provides polymorphic functions and type applications (as in System F), they bear no significance for our analysis.

Finally, the types given to MatchC over-approximate the contributions of all clauses, whose types are combined using the MatchC operator defined as follows:

$$
\begin{align*}
\text{MatchC}(x, r; c_1, r_1; c_2, r_2; \cdots) & \triangleq \text{cond} \oplus \sqcup r_i \\
\text{cond} & \triangleq \text{if IsKnownOp}(x, r; r_i) \text{ then } \text{AdaptC}(r_i) \text{ else } (\text{cond}) \text{, Exact} \\
\text{AdaptC}(c_1 \mapsto (\_), \_ & ) \triangleq \text{if SameVars}(r_i) \text{ then } (c_1 \mapsto (0, \text{Cond}), \text{Exact}) \text{ else } (c_1 \mapsto (0, \text{Cond}), \text{Inexact})
\end{align*}
$$

The additional contribution $\text{cond}$ accounts for whether matching over the scrutinee $x$ induces non-trivial data flow (in which case its contribution is determined via AdaptC), or simply "peels off" a constructor of an option value (in which case it has no contribution). The latter is a very common special scenario, (see, e.g., lines 11–13 of Fig. 5), and without this machinery the analysis would lose too much precision.

### 3.5 Calculating Sharding Signatures

From the set of transition summaries of a given contract (one such summary is shown in Fig. 8), and provided with user input as to what transitions to attempt to shard and which fields can be treated weakly for reading (cf. Sec. 4.2.3), CoSplit derives a sharding signature, consisting of a set of constraints $\overline{\epsilon}$ for each transition in the contract and a join
operation $\psi_f$ for each field. The top part of Fig. 9 enumerates the constraints that summaries can impose, as well as join operations we currently support. Constraints are static symbolic representations of conditions that must be satisfied at runtime. They refer to mutable fields or transition parameters as symbolic values, e.g., $\text{Owns}(f)$ and $\text{UserAddr}(x)$. For instance, the $\text{Owns}(\text{balances}[\_\text{sender}])$ constraint denotes that a shard executing the transition must own the $\_\text{sender}$ portion of the balances state component, where $\_\text{sender}$ is replaced at runtime by the actual value given by the transaction. The other constraints are imposed by the blockchain environment, e.g., $\text{SenderShard}$, which must be satisfied if the contract accepts funds, or arise as preconditions for the soundness of our analysis, e.g., that keys used for map accesses do not alias. $\perp$ corresponds to an unsatisfiable constraint, meaning that the transition cannot be executed in parallel with other transactions over the same contract.

Algorithm 3.1 shows the procedure for deriving the sharding signature. The contract developer selects a set of transitions that should be executed in parallel, and the algorithm inspects their summaries to determine what constraints must be satisfied to enable parallel execution. First, it identifies which (if any) contract fields are not written to in the selected transitions, and marks their reads as non-effectual (i.e., it removes them from the summary) and their contributions as constant. Second, looking at each summary in isolation, it identifies using the types, which writes have a commutative effect, e.g. $\text{Write}(\text{balances}[to])$ in Fig. 8. Then, it determines if a join operation exists for every field, i.e., the writes across transitions are compatible, and marks reads that only flow into commutative writes, e.g. $\text{Read}(\text{balances}[to])$ (since $\text{balances}[to]$ does not appear in any other type), as non-effectual.5 Finally, if the developer accepts that reads from fields that are commutatively written to might return stale data (cf. Sec. 4.2.3), the algorithm translates effects into constraints via the mapping in Fig. 9 and by requiring ownership of every field that is read or non-commutatively written to.

4 Enabling Parallelism with CoSPLIT

In this section, we show how the signatures inferred by CoSPLIT, as described in Sec. 3, can be used to allow for parallel transaction execution in a sharded blockchain.

4.1 The Sharding Model

We integrated CoSPLIT with Zilliqa blockchain [67]. Zilliqa is one of the first sharded chains in production. It implements the Elastico protocol for secure sharding [45] and relies on an optimised version of the Practical Byzantine Fault Tolerance (PBFT) protocol for consensus in the network [12, 61]. At the time of writing, Zilliqa mainnet has processed 9.6 million transactions and contained 28 types of unique smart contracts (some of them have many deployed copies). Below, we outline the relevant parts of its architecture and transaction processing logic, referring the reader to the corresponding manuscripts for details (on, e.g., security and epoch-based mining) [45, 67], which are not critical for our presentation.

Network Architecture. The Zilliqa network consists of three main components: the lookup nodes, the shards, and the Directory Service (aka the DS committee) (cf. Fig. 10).

Lookup nodes are the entry-point to the network. Any transaction created by a user has to be sent to the lookup nodes, which thereupon group several transactions together in a packet and dispatch them to one of the shards or the DS committee for processing. Each shard (and similarly the DS committee, which in fact is a special shard) stores the full blockchain state and runs PBFT to reach consensus on validated transactions. It then proposes a MicroBlock (MB) that contains information on the transactions that it has processed. MicroBlocks are then sent to the DS committee together with StateDelta (SD) which encodes the changes in the state of the accounts that were touched by the transactions within a MicroBlock. Once all the MicroBlocks and the corresponding StateDeltas reach the DS committee, the latter combines them all in the form of a FinalBlock (FB) and a FinalStateDelta (FSD). The FinalBlock and FinalStateDelta are then sent back to each shard so that all the shards have the same view of the full global state—Zilliqa shards transaction execution, but not state storage.

The Default Sharding Strategy. A client-issued transaction can be processed either by one of the shards or by the DS committee (Fig. 10). Zilliqa employs a simple deterministic transaction assignment strategy to shards to ensure that double spends are detected within a shard without complex cross-shard communication [39]. User-to-user payment transactions are deterministically assigned to shards based on the sender’s address. That is, all transactions from the

---

5The Condition effect prevents removal of reads that affect control-flow.
same user get handled in the same shard, so any double spend from a specific user can be detected within a single shard in the same way it gets handled in a non-sharded architecture.

For smart contracts, Zilliqa implements a non-efficient conservative strategy. Specifically, the network statically assigns both contracts and end users to shards. Transactions to a contract invoked by users residing in the same shard as the contract are handled within the shard, while transactions to a contract invoked by users from an outside shard are handled in the DS committee. To ensure that shards and the DS do not end up manipulating the state of the same contract concurrently, the protocol requires the DS committee to process transactions assigned to it only after the shards have finished processing their transactions.

Given this simple deterministic assignment, the parallelism achieved for smart contract transaction processing is quite limited. In fact, the more shards there are, the more transactions will need to be processed by the DS committee.

4.2 Revising the Account-Based Blockchain Model

In order to employ the described sharding model for CoSplit-enabled parallelism, we need to revise a few core aspects in the design of Ethereum-style blockchains.

4.2.1 Relaxing the Nonce Mechanism. Ethereum’s account-based model (adopted by Zilliqa and similar systems) uses the nonce mechanism for defining a total order on all transactions emitted by a particular user. Nonces are calculated by counting the number of transactions sent from a user address and are digitally signed, addressing the following design aspects: (a) strict, gap-free, user-defined ordering of transactions, and (b) prevention of replay attacks. Thanks to the nonces, the user can send many transactions with subsequent numbers, and they are going to be processed in this exact order—the protocol will not process transaction with a nonce $n + 1$ before the one with nonce $n$.

Because of aspect (a), nonces pose a bottleneck to shared executions. While in plain Zilliqa all transactions from a single user are guaranteed to be handled in the same shard, the nonce mechanism prevents parallel executing of transactions with the same origin in different shards, as the total order of nonces cannot be communicated. We notice that in practice no applications rely on a specific order of user transactions before they are committed by the protocol. Therefore, it suffices for transactions to be processed in an increasing nonce order, without waiting for all “gaps” to be filled, treating them similarly to ballots in Paxos [41]. This relaxation requires a very small change in the protocol logic. With it, we kept the aspect (b) of the nonce mechanism, while allowing for parallel executions. For instance, this way we can execute in parallel two disjoint sets of commuting transactions from the same user with nonces $\{1, 3, 5\}$ and $\{2, 4\}$, respectively.

4.2.2 Parallel Gas Accounting. Gas accounting is a mechanism to charge users for executing transactions [65]. Such deductions must be treated sequentially to avoid overspending. We circumvent this bottleneck to parallelism by splitting a user’s balance across shards (with a larger fraction given to the shard handling money transfers from that user), so gas costs can be charged without coordinating balance changes.

4.2.3 Weak Reads. In the Transfer transition (Fig. 8), we saw that the write into balances[to] has a commutative effect. As a result, the processing shard does not need to own the field to execute the transition. However, allowing commutative writes means that transitions executing in a different shard might read stale values of balances[_sender]. In our example, this is fine—the sender may have more tokens that she thinks. Yet, in general, introducing commutative writes weakens the semantics of reads and a static analysis cannot determine whether this is “fine” for specific contracts. As a rule of thumb, a read can safely be marked as weak if the contract semantics is “monotone” in the corresponding value with respect to some lattice (as in [40]), i.e., the behaviour of the contract is not affected if a higher value is read and other shards can increase the value, but not decrease it. Ideally, the programming language itself would allow contract developers to mark certain reads as weak, but neither Scilla nor Solidity, both designed with sequential semantics in mind, currently have this feature. For now, we require that weak reads be provided as input to Algorithm 3.1.

4.3 CoSplit in Action

Using CoSplit assumes two modes: offline and online. In the former, the user who is about to deploy her contract to the blockchain, provides hints to the tool in order to choose the most suitable sharding signature (Fig. 11). In the latter, CoSplit is run automatically by the miners as a part of the validation pipeline for contracts proposed to be deployed.

Furthermore, the UTXO blockchain model adopted by, e.g., Bitcoin [48] promotes this kind of weak notion of consistency, in which the user cannot predict the order in which her transactions are committed.
5.1 Evaluating the Analysis

We are interested in quantitative answers to the following questions with regards to the CoSplit analysis:

- Is the analysis fast enough to be used for validating contract-deploying transactions (Sec. 5.1.1)?
- Is the analysis capable of inferring non-trivial sharding signatures for real-world contracts (Sec. 5.1.2)?

To answer these questions, we have run the analysis on all 49 unique contracts from Zilliqa mainnet and testnet.

5.1.1 Analysis Performance

All Scilla contracts, upon deployment to the blockchain, are validated by the miners that are forced to parse their code and run the typechecker. We ran the contract deployment pipeline (comprising...
type-checking, and sharding analysis) for the contracts in our sample and measured how much time is spent in each deployment stage. Fig. 12 shows the performance breakdown of those three components. The numbers were obtained on a PC with an Intel Core i7-8665U CPU by executing the pipeline for each contract a thousand times and averaging the resulting time for each stage. The analysis adds a significant but acceptable overhead of around 46% to the total contract deployment time. Since contract deployments form a very small fraction of all transactions and happen only once during the lifetime of a contract, the analysis can be run by the miners without affecting overall throughput.

5.1.2 Analysis Efficacy. The bar chart on the right summarises the number of transitions (from 1 to 18) for our 49 contracts. While it may be more likely that a contract with a large number of transitions can be sharded efficiently, having many transitions might also indicate having complex logic, making it difficult to infer a useful signature. To quantify the efficacy of the analysis, we introduce some new terminology.

**Definition 5.1 (Hogged fields).** A contract’s transition \( T \) hogs a field \( f \) in a sharding signature \( sg \) iff \( sg \)'s ownership constraints require a shard to fully own \( f \) to execute \( T \).

**Definition 5.2.** A sharding signature \( sg \) is good enough (GE) for its selection of \( k \) contract transitions, iff either
- \( k = 1 \) and the selected transition does not hog fields, or
- \( k > 1 \) and any field is hogged by at most one transition.

Intuitively, a sharding signature is good enough if it allows for the existence of a contract state, in which some \( k \) of the transitions can be run in parallel by different shards. Fig. 13a shows the sizes of the largest good enough signatures for our contract selection. It is worth noting that a larger GE signature (in terms of a number \( k \)) might perform worse under real-world load than one with a smaller \( k \), which shards different but more frequently used transitions. The following definition outlines the signatures worth comparing.

**Definition 5.3 (Maximal GE signature).** A GE sharding signature is maximal if its selection of transitions is not a proper subset of some other GE signature’s selection.

A contract might have a number of maximal signatures of various sizes. The plot in Fig. 13b depicts those numbers for our contracts. Computing the maximal signatures at the mining time is impractical, as it requires making \( \sum_{k=1}^{n} \binom{n}{k} \) queries to the sharding solver (Fig. 11). Luckily, this computation can be done offline by a contract implementer, who decides prior to the deployment which of the signatures to propose. The miners need to validate only that one signature.

These findings suggest that CoSplit indeed uncovers many opportunities for parallel execution of smart contracts.

5.2 Evaluating Sharded Executions

We evaluate the integration of CoSplit with Zilliqa by measuring the impact on throughput for five representative Scilla contracts. The chosen contracts are: (1) the most popular contracts on Zilliqa (e.g., UD), (2) equivalent to their popular counterparts on Ethereum currently (e.g., FungibleToken and NonfungibleToken) and in the past (e.g., Crowdfunding).

The table above summarises contract sizes, number of transitions, largest GE strategy, and the number of maximal GE signatures. We set out to answer two main questions:

- What throughput improvement, in terms of transactions per second, can CoSplit help to achieve (Sec. 5.2.1)?
- What is the impact of the overheads imposed by CoSplit-enabled sharding (Sec. 5.2.2)?
Experimental Setup. To obtain the throughput figures, we deployed small-scale testnets in various configurations on Amazon EC2 containers. Each node runs on a t2.medium machine with 2 logical CPUs and 4GB of RAM, running Ubuntu 16.04. These specifications reflect the minimum requirements needed to run a Zilliqa node. For our benchmarks, we fix the shard size to be 5 nodes per shard and measure the effect on throughput of increasing the number of shards. We use the same shard and DS gas limits as the Zilliqa mainnet.

Selection of Sharding Signatures. We deploy each of the five contracts in two configurations, one with no sharding information (baseline), and one with a “reasonable” sharding signature, informed by expected usage of the contract. For our experiments, we make the choices as follows:

- For FungibleToken (FT, Zilliqa’s ERC20), we shard the Mint, Transfer and TransferFrom, but not IncreaseAllowance, Burn, or other administrative transitions.
- For NonfungibleToken (NFT, Zilliqa’s ERC-721 [59]), we shard Mint and Transfer (which includes transfer-from functionality), but not Burn and Approve.
- For ProofIPFS, we shard the transition that notarises a hash, but not the one that removes it from the contract.
- For the Unstoppable Domains (UD) registry, we shard granting a new domain name and updating the record associated with a name, but not transfers of ownership.

For the Crowdfunding contract, there is only one possible choice, which is to shard the Donate and Claimback (if the goal was not reached) transitions. We argue that our choices reflect what a reasonable contract deployer would select and, as such, the measured throughput reflects probable scenarios.

We remark that we had to slightly rewrite the NFT and UD contracts, compared to their mainnet definitions, to make them shardable. These rewrites did not affect the semantics of the contracts. We discuss the details of the changes, as well as the potential to automate such modifications, in Sec. 6.

5.2.1 Measuring Throughput. After deployment, we subject the contracts, in sequence, to different workloads sustained over 10 epochs (roughly 8.5 minutes) and measure the resulting throughput. As Fig. 14 shows, for most of the workloads in the benchmark, we obtain a roughly linear TPS increase as the number of shards goes up. The two exceptions are the “FT fund” and the “ProofIPFS register” workloads. The former transfers fungible tokens from a single source to multiple destinations (all transactions go to the source’s shard). The latter notarises a hash, but also keeps a list of notarised items for each user, and thus accesses two separate fields, which typically will be owned by different shards, hence many transactions need to be processed by the DS Committee. We note that for workloads that do not shard well, performance does not degrade as compared to the baseline, and in some cases (e.g., ProofIPFS) marginally improves.

5.2.2 Introduced Overheads. Integrating CoSplit adds overheads to transaction dispatch and state delta merging. Concretely, we see transaction dispatch time increase from an average 8 µs to an average 475 µs, and the state delta merging increasing from 0.8 µs to 48.65 µs per changed state field. This amounts to a 60x slowdown of these operations, most of it as a result of serialisation and deserialisation costs, but this is fully justified by the resulting increase in overall system throughput. The overall performance gain comes from the fact that applying a delta is much faster than executing all the transactions that resulted in it. For instance, for FungibleToken, the effects of 50 seconds of transaction execution time can be merged in roughly 0.5 seconds.

5.2.3 Ownership versus Commutativity. In terms of the contribution of the two sharding strategies to the throughput improvement, we observe that contracts that manipulate non-fungible quantities (e.g., NFTs, domains, notary) benefit from the disjoint state ownership analysis and contracts that manipulate fungible quantities (e.g., FT) benefit from the commutativity analysis. Contracts that have a mixture of non-fungible and fungible quantities, e.g., a voting contract.
that keeps track of who voted and of the total number of votes, can benefit from both strategies.

6 Discussion and Future Work

Handling Integer Overflows. CoSplit’s signature inference does not take possible integer overflows into account. Overflows (and underflows) may cause a problem in the case when IntMerge is used to join state deltas from different shards that individually do not cause an overflow, but do so when joined. At the moment, our implementation ignores this issue. A working solution would be to modify the Scilla interpreter, providing it with information about the number \( N \) of shards. Specifically, it should perform additional post-hoc validation of a transaction, which will fail if the difference between the initial (per epoch) value \( z \) of any affected integer-valued component and its value after the transaction is executed exceeds \( \frac{\text{MAX}_N - \text{INT}_N}{N} \). The information about such components is already available in the sharding signatures. Furthermore, a user might be given an option to pay a higher gas fee, in order to reduce a risk for her transaction to be rejected due to this conservative check. Such transactions will be routed directly to the DS committee, and, thus, processed sequentially.

Automated Contract Repair. As mentioned in Sec. 3.3, the analysis can describe map accesses only if the keys used to index into the map are transition parameters. During the evaluation, we discovered a small number of contracts that CoSplit cannot shard due to this limitation, but which can be made shardable by a simple refactoring. For instance, an NFT contract’s \texttt{Transfer} transition ensures that the transaction’s sender is authorized by the token owner to initiate the transfer by checking for inclusion in \texttt{approvals[tokenOwner]}, where \texttt{tokenOwner} is read from the contract’s state. This cannot be shardable. However, if we make \texttt{tokenOwner} a parameter and rewrite the transition to check that the supplied value matches the value in the contract’s state before attempting the transfer (akin to compare-and-swap), the transition becomes shardable. In future work, we plan to address this using program repair techniques, suggesting the shardable contract version to the developer before deployment.

CoSplit and Other Blockchains. As demonstrated in Sec. 3, the core analysis of CoSplit does not rely on any specific features of Scilla but is easy to implement for it due to the language’s minimalism and restrictions (e.g., very limited set of side effects). Should other \textit{account-based} blockchains, e.g., Tezos [28] and Ethereum [65], provide a sharded architecture in the future, we believe a similar analysis could be implemented for them as well. The key challenge of developing CoSplit for Michelson, the language of Tezos [63], is in reasoning about its stack-based executions, tracking the provenance and cardinality of pushed and popped values. Ethereum’s EVM could be supported through decompilation into a high-level language [29]. The approach will most likely have to be restricted to contracts with no external calls.

7 Related Work

Sharding Contracts in Blockchains. Several industry proposals outline approaches for smart contract sharding, yet none of them provide an efficient solution for sharding same-contract transactions. For example, the Elrond protocol moves a smart contract to the same shard where its static dependencies lie [23], which takes at least 5 rounds of consensus for a transaction to be finalised. Harmony [30] allows one to deploy contracts in individual shards, with no cross-shard communication allowed. Ethereum 2.0 proposes a cross-shard yanking scheme where the contract code and data is moved into a shard at runtime [64]. The shard then locks the contract to block any parallel execution of other transactions affecting it. At the time of writing, none of these solutions appear to be fully implemented.

The Chainspace protocol allows for shard execution of smart contracts (as well as state sharding) by representing state evolution as a directed acyclic graph [1], similar to Bitcoin’s UTxO transaction model. In Chainspace, contracts have to be written in a specific fashion, so their execution happens \textit{off the chain}. For an unspecified kind of transaction, the authors of Chainspace report linearly increasing throughput of approximately 75 TPS per each two shards of four nodes in each [1, Fig. 6]. Importantly, Chainspace does not address the scalability problem with same-contract transactions (which we do): under high contention for the same contract the rate of aborted transactions rises. This is because its protocol, S-BAC (a combination of PBFT [12] and Two-Phase Commit for inter-shard communication), implements a variant of optimistic concurrency control, whereas CoSplit allows for pessimistic (race-free) concurrency.

Smart Contracts and Concurrency. Dickerson \textit{et al.} [18] describe a commutativity-based approach where miners execute smart contracts in parallel \textit{locally}, using software transactional memory techniques [31, 32]. Unlike our approach that detects possible transaction conflicts pessimistically by means of a static analysis prior to contract deployment, the work by Dickerson \textit{et al.} exercises the optimistic approach, where conflicts are identified on-the-fly by the miners, with the corresponding executions aborted. It is not clear how to apply these ideas from optimistic concurrency for efficient \textit{sharding} of general smart contracts in a Byzantine setting, where an adversary can craft cheap (in terms of gas costs) conflict-producing transactions that force the shards to re-execute expensive transactions from the same batch. A more fine-grained identification of conflicts would most probably require an analysis similar to ours, as conjectured in [56]. At the same time, our solution is complementary to Dickerson \textit{et al.}’s work and other similar approaches. For instance, one can add single-node parallelism on top of CoSplit-enabled sharding, and the analysis can help identify which transactions are guaranteed not to require rollback and re-execution, even within a single shard.
Recent work by Bartoletti et al. makes an observation similar to ours that commutativity (which they dub swap-pability) of transactions manipulating Ethereum contracts enables their parallel execution [6]. Their syntactic criterion for inferring swap-pability is, however, more coarse-grained than our analysis, and is based on determining disjointness of transaction footprints, without taking into account commutativity of operations such as addition. As such, their approach would not allow to shard individual non-conflicting updates in an ERC20 contract as we do. Bartoletti et al.’s approach has not been implemented in practice.

**Inferring Commutativity.** Reasoning about commutativity between program parts is an important problem with applications including parallelising compilers [38, 55], speculative execution [31], and race detection [19]. Most of existing techniques for inferring commutativity are based on analysing dynamic executions [2, 19, 26] or by solving SMT constraints [5] and, thus, cannot be used efficiently as a part of transaction validation. Our analysis is close in spirit to the work (in [55]) on static analysis to determine operation commutativity for compile-time parallelisation. Our analysis uses simpler abstractions, allowing it to be implemented in a compositional fashion and have linear execution cost.

8 Conclusion

We presented a new approach to shard the execution of smart contracts in an account-based blockchain model, based on inferring ownership constraints and commutativity for state-manipulating contract operations. In our approach, smart contracts are first processed by a static analysis tool that produces their shredding signatures, which are then used for shard allocation that maximises parallelism. We have demonstrated that our approach, when integrated into the shards production-scale blockchain, allows for linear scaling of the transaction throughput for a selection of common smart contracts that were considered unavoidable execution bottlenecks in existing blockchain systems.

Acknowledgments

We thank the OSDI’20 and PLDI’21 PC and AEC reviewers, and our shepherd, Gustavo Petri, for their valuable feedback on earlier drafts of this paper and the artefact. We thank Aquinas Hobor, Yaoqi Jia, and Prateek Saxena who participated in the discussions on smart contract sharding at earlier stages of this work. We are grateful to Haichuan Lian, Antiono Nicolas Nunez, and Jun Hao Tan, for their help in integrating CoSPLIT with the Zilliqa protocol, and to Bryan Tan for conducting preliminary experiments. We benefited a lot from discussions and feedback on preliminary versions of this work by Andreea Costea, Kiran Gopinathan, Jacob Johannsen, Vaivasswatha Nagaraj, and Anton Trunov. Ilya Sergey’s work has been supported by the grant of Singapore NRF National Satellite of Excellence in Trustworthy Software Systems (NSoE-TSS) and by the NUS Crystal Centre.

References


Nick Szabo. 1994. Smart Contracts. Online manuscript.


Nick Szabo. 1994. Smart Contracts. Online manuscript.


Nick Szabo. 1994. Smart Contracts. Online manuscript.


Nick Szabo. 1994. Smart Contracts. Online manuscript.


Nick Szabo. 1994. Smart Contracts. Online manuscript.


Nick Szabo. 1994. Smart Contracts. Online manuscript.


Nick Szabo. 1994. Smart Contracts. Online manuscript.


