Pluralize: a Trustworthy Framework for High-Level Smart Contract - Draft

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Abstract

The paper presents Pluralize, a formal logical framework able to extend the execution of blockchain transactions to events coming from external oracles, like external time, sensor data, human-made declarations, etc. These events are by essence non-reliable, since transaction execution can be triggered by information whose veracity cannot be established by the blockchain. To overcome this problem, the language features a first-order logic and an authority algebra to allow formal reasoning and establish accountability of agents for blockchain-enabled transactions. We provide an accountability model that allows to formally prove the accountability of agents by a formal proof locally executable by each agent of the blockchain.

1 Introduction

Blockchains promise to increase the level of trust among actors that do not trust each other. This promise is often misunderstood, especially when smart contracts come into play. Smart contracts are pieces of code that run in an actively replicated fashion in the blockchain, but current platforms do not offer any native support for software verification/validation, so that bugs can affect the smart contracts behavior. Moreover, in many industrial applications smart contracts react to information coming from external sources (sensors, human interfaces, other applications), often called oracles in the blockchain jargon, which amplifies their vulnerability.

Another difficulty is that smart contracts are commonly associated to Ethereum-based ones, which depart considerably from the transactional nature of protocols they should support. Those contracts propose indeed a diametrical opposite paradigm where the smart contract plays the role of mediator between parties. Very popular are, for instance, many forms of auctions, where a smart contract auction will be called by any wallet – a client – to register a bet and the smart contract will gather all the bets and elect the winner. In a way the concept of an application-level “transaction” between symmetric parties, triggered only when certain conditions are met, must be twisted in a very different semantics because a transaction becomes a client call to the smart contract. The mismatch between paradigms create a lot of confusion and difficulties to use smart contracts in a proper way.

We advocate that the first step for better design, and hence safety and security, of smart contracts is to stick as much as possible to the Bitcoin transactional model. In Bitcoin, transactions are transfers of ownership of tokens – Bitcoins – through both asymmetric cryptography and a replicated shared memory – the blockchain –, which stores enough information in order to recompute/validate each transfer. This memory is shared by agents part of a peer-to-peer network, where each agent is represented by an address, i.e. the wallet. A transfer of a quantity of Bitcoins from a wallet to another is guarded by a condition that has to be satisfied – a guard. For the Bitcoin system to be safe, guards must be identically evaluated by each peer. Currently, identical and correct evaluation of guards relies on the autonomous evaluation
of the guard by each peer, which is deterministic and closed to the current knowledge of the blockchain. More specifically, guards in Bitcoin can trigger the execution of a transaction upon the evaluation of simple conditions, as signature integrity and timelocks, stating that a transfer must be authorized by the owner of the transferred tokens and after a certain time (in general measured as a number of blocks).

1.1 Motivation

In [12], the author presents a protocol that involves different parties in a transfer of a car and cryptocurrencies ownership in a sort of chained transactions loop such that either all the transactions take places or none. Let us consider the following scenario:

- Carol wants to sell a Cadillac for bitcoin;
- Alice wants to buy Carol’s Cadillac, but with alt-coin;
- Bob wants to trade alt-coin for bitcoin.

All the parties do not trust each other and the protocols explicit how to enforce trust between them thanks to cryptography. The motivation example in [12] specifies the transfer of an asset via smart contracts: scripts published on the blockchain that establish and enforce conditions necessary to transfer the asset from an agent $A$ to another agent $B$. In particular $A$ publishes a smart contract that locks the asset to transfer along with two conditions to execute the transfer to $B$: a hashlock $h$ and a timelock $t$. Hashlock $h$ means that if $B$ provides a secret $s$ such that $H(s) = h$ before $t$ expires then the asset ownership is transferred from $A$ to $B$. If the timelock $t$ is not satisfied, the asset returns to $A$. The timelock enables to encode synchronization and sequentialization of the smart contracts transactions. So, Alice will transfer her alt-coin to Bob that will convert them into bitcoin and transfer them to Carol that will transfer her ownership title for the Cadillac to Alice.

The trade takes place on the blockchain, there is no third trusted-party, and Alice, Bob and Carol do not trust each other. Hence, they use smart contract to secure and enforce the transactions between them. Let $\Delta$ be the time for one agent to publish a smart contract on a blockchain and for the other agent to detect the change. For simplicity, in this work we consider that all parties have perfectly synchronized clocks. The protocol becomes:

- Alice generates a secret $s$, and publishes the transaction of her alt-coin to Bob triggered by the hashcodelock of $s$, $h = H(s)$, and a timelock of $6\Delta$;
- When Bob confirms that Alice’s smart contract has been published, Bob publishes a contract that transfer to Carol the bitcoin triggered by $h$ and the timelock of $5\Delta$;
- When Carol confirms that Bob’s smart contract has been published, Carol publishes a smart contract that transfer the Cadillac ownership title to Alice with the same $h$ and a timelock of $4\Delta$;
- When Alice confirms that Carol’s smart contract has been published, Alice send the secret $s$ to unlock the $h$ and trigger the transaction of the Cadillac ownership title;
- Carol sends $s$ to Bob in order to obtain her bitcoin;
- Bob sends $s$ to Alice in order to obtain his alt-coin.

Thanks to the refund in case of timelock expiration, this protocol works even if one agent halts. Timelock are used to enforce the sequential order of transactions. Finally, the only irrational behavior that can corrupt the protocol is Alice revealing the secret too earlier and in that case she is the unique victim of it. This protocol is an implementation of smart contracts that are autonomously executes on blockchains and that establishes and enforces contractual conditions. However, nothing bad happen as long as we consider only digital assets, i.e., if something goes wrong, then the digital asset ownership goes back to the previous owner. Now, let us consider the following scenario in which Alice instead of buying the Cadillac is renting it with the condition that is in a good state. In this case it is necessary to have an

\footnote{Note that such guards are encoded in Bitcoin scripts, called Opcodes that compile to an abstract machine that every peer has locally.}
attestation declaring the state of the car as an extra condition such that the transaction take place in the blockchain. Suppose that the Cadillac is equipped with IoT sensors so that the information about the state is automatically computed and provided to the blockchain as a transaction. Those sensors work like a specific agent in the protocol. Such computation, being out of the blockchain is not reliable. It follows that the current state of the Cadillac may not be good when Alice receives it. Then, Alice as well, can provide her observation of the current state of the Cadillac. Then the protocol has to enable Alice to take countermeasures if needed, e.g., being refund and return the Cadillac.

In such context, a naive protocol can be the following:

- Alice generates a secret $s$, and publishes the transaction of her alt-coins to Bob triggered by the hashcode of $s$, $h$, and a timelock of $7\Delta$, and a declaration about the good state of the Cadillac from its IoT sensors;
- When Bob confirms that Alice’s contract has been published, Bob publishes a contract that transfer to Carol the bitcoin triggered by $h$, the timelock of $6\Delta$;
- When Carol confirms that Bob’s smart contract has been published, Carol publishes a smart contract that state the renting contract between her and Alice with the same $h$, a timelock of $5\Delta$ and a declaration about the good state of the Cadillac from its IoT sensors;
- When the IoT sensors confirm that Carol’s smart contract has been published, the IoT sensors compute and publish a smart contract declaring the Cadillac current state with the same $h$ and a timelock of $4\Delta$;
- When Alice confirms that Carol’s and IoT sensors smart contracts have been published, Alice observes the Cadillac. Two cases can occur:
  - the IoT sensors declaration matched with the Alice observation, then she accepts the renting contract and sends the secret $s$ to unlock the $h$;
  - Carol sends $s$ to Bob in order to obtain her bitcoin;
  - Bob sends $s$ to Alice in order to obtain his alt-coin.

Otherwise:

- otherwise Alice does not release the secret $s$.

This naive protocol presents some limitation. First of all, when we consider the physical world we have to estimate in a different manner the timelock. Alice might take more than $\Delta$ time to receive and observe the Cadillac. Second, in such scenario there are two unreliable conditions that trigger transactions: IoT sensors computation and Alice observation, both performed outside of the blockchain. Thus, it is not possible to establish who is telling the truth: Alice may lie and/or the IoT sensors can be bugged. Naively, assuming declarations out of the blockchain as true as trigger of transactions may introduce contradiction in the blockchain, leading to inconsistencies and lost of reliability of the information in the blockchain. IoT sensors, as the Alice observations, are referred as Oracle in the blockchain jargon. Triggers (transactions) coming from physical world Oracles cannot be validated against all the blockchain information and can not be evaluated as valid by default. To avoid having contradictions in the blockchain the validation of such triggers has guarantees that adding a new information into the blockchain is not going to invalidate something that is already present in the blockchain. To do so, at each validation of a claim $claim$, the validation mechanism of the blockchain $V$ has to make sure that no already validated transaction is invalidated by $claim$. In that case, $V$ returns the list of discord – the list of claims that are in contradiction. We call this computation the proof-of-discord. In our example, the proof-of-discord returns IoT sensors declaration and Alice observation. The proof-of-discord enables to manage conflicts. Notice, the conflict management, being application and physical world dependent, is out of the scope of this paper.
1.2 Our Contribution

The main challenge for smart contracts is to extend the Bitcoin paradigm to guards whose evaluation that are not closed to the blockchain, going far beyond the simple semantics of Bitcoin scripts and matching requirements of most industrial applications. This possibility rises the problem of the reliability of the guards execution, that can be triggered upon lies declared by the external agent/oracle, not detectable at the time of validation by blockchain peers.

To solve this issue, we introduce a logical framework called Pluralize. Pluralize features a formal language, Plurality, for smart contracts expressed as token transfers with guards whose evaluation is not closed to the blockchain. To cope with the possible unsafe execution of those non-closed guards, Plurality semantics relies on a formal accountability model for transactions, based on Cyberlogic [17] for the management of agents accountability. More specifically, we establish an accountability model to infer accountability of agents basing on their actions: submitting, validating, executing transactions, providing additional information for non-closed guards. In case of logical contradictions, i.e. discords, thanks to the Cyberlogic authority algebra and our Coq theorem prover, it is possible to trace back the chain of trust, i.e., formally proving the agents accountable for the discording logical properties through a formal mathematical certificate. Being a certificate means that the formal proof is locally checkable by any agent, for this reason we will call it in the reminder of the paper proof-of-discord.

The main technical challenge in this demarche is the formalization of the accountability model because it depends on the execution model of transactions, which in turn depends on the execution and validation blockchain model. Since the Pluralize framework wants to be technology agnostic, i.e. be instanciable on different types of blockchain, it is not possible to built upon a specific execution and validation model, as Bitcoin or Ethereum.

To overcome that difficulty we propose an operational semantics of the Plurality language built upon the blockchain abstraction provided in [1], called the Blockchain Abstract Data Type (ADT). Following the [1]'s construction, each submitter $A$ of the transaction $T : A \rightarrow B$ that wants to append the transaction to the blockchain has to successfully call the blockchain ADT. Interestingly, the blockchain ADT allows to pass as parameter application specific validation rules for transactions, i.e. the guards, and blockchain specific rules, such as the longest chain rule, for blockchain consistency.

The paper is organised as follows: Section 2 gives an overview of Pluralize, Section 3 introduces the technical background, Section 4 the language to define transaction-based protocols along with its semantics based on Cyberlogic and the Blockchain ADT, Section 5 discusses related work and Section 6 concludes the paper.

2 Overview

Pluralize is a formal framework that provides cooperation and composition of formal methods in order to conciliate the gap between higher-level smart contracts expectations of the collective belief – and smart contracts in the blockchain ecosystem. Pluralize features a dedicated formal language, Plurality, that is more suitable to higher-level smart contracts. Plurality features claimed and closed guards. Pluralize enriches a host blockchain in order to benefit its information reliability with more complex validation mechanisms. The validation mechanism is enriched with a first-order-logic (FOL) interpreter for closed guards and proof-of-discord for claimed guards. To reach the same level of reliability that current bitcoin-like smart contract, (i) Plurality smart contract are certified-by-construction, (ii) proof-of-discord are also certified and (iii) the execution model of Pluralize is based on a abstraction compatible with the distributed nature of the blockchain.

Validation of Closed Guards Currently, the autonomously evaluated guards of bitcoin-like transaction are scripts. A script is a sequence of opcodes that is able to verify on cryptographical conditions. Enriching the script expressiveness with first-order boolean logic closed to the blockchain knowledge increases the autonomy and reliability of smart contract while decreasing the need of oracles. Pluralize features closed guards. At implementation level, A Plurality smart contract comes with its set of logical definitions, the set of predicates needed to validate its closed guards. To evaluate validity of closed guards, Pluralize enriches the validation mechanism $V$ of the host blockchain with an interpreter for
first-order logic. This interpreter knows the set of logical definitions of the smart contract and evaluates closed guards.

**Validation of Claimed Guards** Reliability of information coming from agents that works in “black-box” style involved in a shared computation is addressed in security thanks to accountability and trust management. Accountability designates the responsibility of an agent for an information. In case of problem, it is then possible to identify the agents involved by tracing back the chain of trust: computing the list of elementary data involved in the problem and identify the agents that are accountable for them.

A claimed guard is very similar to a computation in ”black-box” style: it is a statement of an agent and its validity is guaranteed by this agent: its accountable.

A trust management tool is a policy language – a formal language dedicated to formalize security policy of a whole system – that enables to address several security language in a same policy language. A Trust Management (introduces inPolicyMaker [5]), features an authority algebra that enables to explicit the accountability of the different agents or components involved in a system.

Pluralize features claimed guards. At implementation level, Plurality is a dialect of a trust management logical framework, Cyberlogic [17] presented in [3]. A claimed guard is a claim \( \text{claim} \) of a property \( p \) by an agent \( A \), denoted \( A \uparrow p \) in Plurality (as in Cyberlogic). A claim is validated only if it is not in discord with an already validated claims. \( \Gamma_{\text{claim}} \) denotes the already validated claims. To validate a claim \( \text{claim} \) Pluralize enriches \( V \) with the proof-of-discord mechanism. If \( \text{claim} \) is in discord with \( \Gamma_{\text{claim}} \), \( V \) returns the list of claims that are in discord. The validation of \( \text{claim} \) is its confrontation with \( \Gamma_{\text{claim}} \).

As Cyberlogic, Plurality features a first-order logic that enables to reason and drive proof on the authority algebra. \( \Gamma_{\text{claim}} \vdash \neg \text{claim} \) means \( \Gamma_{\text{claim}} \) satisfies \( \neg \text{claim} \): there is a constructive proof in Plurality that satisfies \( \neg \text{claim} \). The set of claims \( \gamma_{\text{claim}} \) that are in discord with \( \text{claim} \) is the subset of \( \Gamma_{\text{claim}} \) used in the proof of \( \Gamma_{\text{claim}} \vdash \neg \text{claim} \). If no proof of \( \Gamma_{\text{claim}} \vdash \neg \text{claim} \) is realised then \( \text{claim} \) is validated.

**Trustworthy of The Validation Mechanism** Pluralize enriches the validation mechanism \( V \) of an host blockchain \( B \). Pluralize enrichment has to be reliable and to preserve the reliability of \( B \). Hence Pluralize execution model has to be able to explicit both (i) \( V \) and (ii) the enrichment. A blockchain is a shared data structure that ensures the immutability of its contains. A blockchain ideally ensures that every agents shared the history (the same contains). In reality, it is now well known that for some blockchain, as bitcoin, several histories might exist: it is possible to have forks. A blockchain ideally ensures that a sequence of transaction is driven by external component, as in the Cadillac example, the existence of several histories can be handle out of the chain. It is then possible to define an execution model as a unique history. Pluralize features claimed and closed guards in order to leverage the autonomy of smart contracts execution through several transactions. In that case, it is not possible to make same assumption. The possibility to have several histories is a property of the host blockchain \( B \). Furthermore, Plurality is not just a DSL built upon smart contracts of \( B \), it requires the enrichment of its validation mechanism \( V \) which is that is defined at \( B \) protocol level. Hence, Pluralize execution model has to be able to abstract underlying properties of \( B \) regarding its capacity of forking and explicit \( V \). Pluralize does not manage the non unicity of the blockchain as it inherits it from \( B \). However, Pluralize cannot make the assumption that its execution model relies on an ideal blockchain.

Abstract Data Structure [15], is a formal specification tool that enables to formalize shared data structure in order to address both (i) the execution model of the data structure for interaction with the agents and (ii) the data structure owned properties as a distributed protocol.

Using an execution model from such a formal specification improves the trustworthy of certified-by-design smart contracts. [1] presents such a formal framework for blockchain. In particular, [1] explicits the abstraction of the validation mechanism of the blockchain that is suitable to formalize the enrichment that Pluralize proposed. Furthermore, such abstraction enables to deal with concurrent histories – viewing a blockchain as a tree – in the execution model. That is complete different from the tradition abstraction of blockchain as an execution model: a sequence of blocks – one unique history. The latter formalization is known as too strong for bitcoin protocol.

Pluralize execution model refers to the blockchain ADT [1]. A quick description is provided in [3].

In Figure [4] is depicted the overview described so far. From a transactional protocol are obtained (i)
the Plurality transactional protocol, with closed and claimed guards and (ii) the logical definition for the closed guards. From those we derive the validation mechanism \( \mathcal{V} \) enriched with a FOL interpreter for closed guards (e.g., agent \( A \) transfers organic cotton to agent \( B \), \( B \) transfers organic dress to agent \( C \).) and proof-of-discord for claimed guards (e.g., IoT sensors agent assesses that the Cadillac is in a good state). Proof-of-discord fetches from the blockchain the claims already validated. Finally, \( \mathcal{V} \) publishes on the blockchain only validated information. In case of information invalidation by proof-of-discord, \( \mathcal{V} \) returns to the conflict manager (out of the scope of this work) the list of discording claims.

3 Technical Background

The Pluralize framework is a formal framework for accountability of blockchain transactions based on Cyberlogic [17]. Pluralize consists of (i) a host blockchain \( B \) (the blockchain target for the smart contract execution), (ii) execution and validation mechanisms for transactions –enriching \( B \) with guards based on accountability– and (iii) a formal language, Plurality. This language allows to define smart contracts featuring such guards. Plurality is a shallow-embedding in the Coq theorem prover, being executable and providing a proof environment for establishing proof-of-discord. Pluralize features as well an execution model based on the Blockchain ADT. In the following we present the technical background of Pluralize, introducing more in detail Cyberlogic along with the principles to establish a proof-of-discord in Section 3.1 and the Blockchain ADT in Section 3.2.

3.1 Formal Accountability Management

Cyberlogic. Cyberlogic [17] is a trust management formal framework. Traditional trust management tools enables to specify and monitor security property. Cyberlogic is a formal language that features both an authority algebra and a first-order logic, which allows to specify and verify distributed protocols with explicit accountability of agents, called authorities.
Cyberlogic formula: $A \triangleright d$, also called a claim, states that $A$ claims $d$, a property, and therefore $A$ is accountable for it. Cyberlogic is particularly adequate to specify transactional protocols endowing cryptography mechanisms where transactions react to non-reliable events [17]. In particular, in the context of a transaction where the satisfaction of the guard $gd$ triggers the transaction execution, it is possible to model a satisfied guard $gd$ as a claim; the validity of the guard is then endorsed by an agent: $\Omega_k \triangleright gd$ means that $\Omega_k$ claims that $gd$ is true.

[9] presents a shallow-embedding of Cyberlogic in the Coq theorem prover that makes it possible to certify Cyberlogic protocols and claims. The Coq theorem prover realizes the isomorphism of Curry-Howard – typing is proving: it is based on Calculus of Inductive Construction CiC [7]. In such theorem prover proofs are programs that are computable and checkable on any machine. Such proof are formal certificate. Plurality is a dialect of Cyberlogic, means that every smart contract design and implemented in Plurality are certified-by-design. Furthermore, the claimed guards are also Cyberlogic claims, means that every reasoning on the authority algebra is also certified.

The proof-of-discord. The logical rules of Cyberlogic enable to reason on the authority algebra in a manner that it is possible to trace back the chain of trust, leveraging on the fact that the derivation tree contains Cyberlogic claims. Technically, it is to trace-back in the derivation tree of the claims used for establishing a property. In particular, a property $p$ claimed by an authority $A$ that does not contradict any hypothesis of the proof context is considered as an axiom. The reduction of the proof context to the hypotheses, involved in the proof, is the tracing-back of the chain of trust. The Cyberlogic implementation in Coq enables to formally certify the chain of trust of Cyberlogic protocols or claims. Tracing back the chain of trust enables to formally detect conflicts and point-out the accountable agents in the conflicts. A conflict is a set of Cyberlogic claims that are in contradiction with each other. The agents involved in this set are the potential accountable for this contradiction. Detecting that a property $p$ is in contradiction with a set of claims $\Gamma$ means to verify that $\Gamma$ satisfies $\neg p$ denoted by $\Gamma \vdash \neg p$. If the verification succeeds by a proof $\pi$, then the claims of $\pi$ are in contradiction with $p$. It is exactly how the proof-of-discord work with the validation of claimed guards.

Accountability at run-time. If on one hand Pluralize defines a formal language for transaction protocols based on blockchains, on the other hand the proof-of-discord needs to store specific information in the blockchain and mechanisms to deal with agent actions at run-time. In particular, claimed guards must be continually checked at run-time against the blockchain state. Logical contradictions must be detected automatically, but the proof-of-discord can be obtained only with an interactive theorem prover – not automatically, in the general case. Said that once the proof-of-discord is established by a peer, the others can autonomously validate the proof and revert to a previous state if needed and according to the semantics defined in case of contradictions (if any). In the following we abstract the run-time management of Pluralize through the operational semantics of the language, leaving out of the scope of this paper its actual implementation.

3.2 Blockchain Specification

In [11] the authors present an abstract data type to formally model the blockchain object and its admissible behaviors. A blockchain is specified as a BlockTree ADT (BT-ADT) – specifying the blockchain object – augmented with a Token Oracle ADT (Θ-ADT) – specifying the validation mechanism of blocks composing the blockchain. In such context, the validation mechanism is made explicit due to its importance, that is, it is the main actor in determining the blockchain object behavior. That abstraction of the blockchain that explicitly formalized the validation mechanism enables us to formalized the enrichment of the validation mechanism to manage the autonomous and unreliable guards. Moreover, the ADT enables to consider the properties of the blockchain as a shared data structure and its interface as an execution models. The benefits is the guarantee to consider in a same formalization the consistency of the host blockchain and the formalization of its enrichment. As a consequence, Pluralize is technology agnostic as it can be parametrized by the host blockchain BT-ADT intanciation.

\[\text{CiC is } \lambda-\text{calculus with types as first class citizens}\]
The BlockTree ADT: BT-ADT. In [1], the data structure implemented by blockchain-like systems is a directed rooted tree called **BlockTree**. BT-ADT specifies a blockchain-like system through the specification of the semantic of the **read** and **append** operations. BT-ADT is parametrized by (i) the predicate $P$ that has to be satisfied to validate a block and (ii) the selection function $f$ that selects, in a BlockTree $bt$ the blockchain $b_h$ where the next append has to be performed.

**Token oracle: $\Theta$-ADT.** The $\Theta$-ADT formalizes the interaction between the validation of blocks and their publication in the blockchain data structure. In few words, the Token oracle is a way to abstract the process of appending new blocks, proposed by agents, to the blockchain. Either only one block can be appended to the same block (already in the blockchain) or more than ones, in both cases all blocks has to be valid. The Oracle provides tokens to agents willing to append a new block but limits the number of tokens that can be consumed, i.e., a token is consumed when a new block is appended. In such a way the Oracle manages the number of blocks that can be appended to the same block already in the blockchain. More formally, in [1], the authors abstract this implementation-dependent process by assuming that an agent obtains the right to chain a new block in the blockchain. More formally, in [1], the authors abstract this implementation-dependent process by assuming that an agent obtains the right to chain a new block $b_l$ to $b_h$ if it successfully gains a token $tkn_h$ from $\Theta$-ADT for such block. A token can be consumed at most once and the proposed block $b_l$ along with $tkn_h$, denoted $b^l_{tkn_h}$ is considered as valid. That means it can be appended to $b_h$. More formally, $\Theta$-ADT specifies two operations $\text{getToken}$ and $\text{consumeToken}$. $\text{getToken}$ inputs two blocks $b_h$ and $b_l$ where $b_l$ is the block to append to $b_h$ which is the last of $f(bt)$. $\text{getToken}$ outputs $b^l_{tkn_h}$ which satisfies $P$, in other words, it is a valid block. $\text{consumeToken}$ inputs a valid block $b^l_{tkn_h}$ and enables the consumption of tokens. A maximum number of maximum number of tokens $k$ for a block can be consumed

$$\text{BT-ADT augmented with } \Theta\text{-ADT. } \mathcal{R}(BT-ADT, \Theta)$$ BT-ADT augmented with $\Theta$-ADT is a refinement that, once instantiated with a predicate $P$ and a selection function $f$, gives the specification of a blockchain-like system $S$ as an execution model. Specifically, in [1], the authors define a refinement of the $\text{append}(b_l)$ operation of the BT-ADT with the oracle operations which triggers the $\text{getToken}(b_h \leftarrow \text{last block}(f(bt)), b_l)$ operation as long as it returns a token on $b_h$, i.e., $b^l_{tkn_h}$ which is a valid block. Once obtained, the token is consumed and the append terminates, i.e. the block $b^l_{tkn_h}$ is appended to the block $b_h$ in the blockchain $f(bt)$. We indicate such append with the following notation $f(bt)^l_b$ (slightly simplified with respect to the one in [1]) that we call concrete append in this paper. Notice that those two operations and the concatenation occur atomically.

4 **Pluralize smart contracts: language and execution model**

Pluralize is a formal framework for higher level blockchain protocol equipped with a smart contract formal language, called Plurality. In this section, we give a brief overview of Plurality, just to illustrate the transfer of ownership between agents and the two kind of guards. In this language, agents submit transactions to the blockchain and are notified when transactions are published in the blockchain. The notification mechanism is out of the scope of this paper but introduce in order to illustrate the expressiveness of Plurality. We also assume that Pluralize features a synchronisation mechanism that enables to cause causal order between transaction of a same smart contract. At execution, we assume that the notification mechanism ensures the synchronization that are work in progress for Pluralize.

A transaction is a transfer of ownership of a quantity of tokens from an agent source to an agent sink guarded by a property that has to be validated. A Plurality smart contract is a distributed protocol of such transactions between agents in a network. As a dialect of Cyberlogic, Plurality is a shallow-embeding formal language in the Coq Theorem prover, its semantics is then given in terms of Coq language. However, its execution models abstracts (i) the host blockchain protocol, (ii) validation mechanism and (iii) the enrichment of Pluralize. As Plurality smart contract can benefits the extraction mechanism of The Coq Theorem Prover, once extracted in an executable language, a Plurality smart

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3 More into details and out of the scope of this paper, in [1] the authors defined two different typologies of $\Theta$-Oracle. The Prodigal Oracle, $\Theta_{prod}$-Oracle in which an unbounded number of tokens can be consumed for each block, and the Frugal Oracle, $\Theta_{frug}$-Oracle, that allows at most $k$ tokens to be consumed for each block, i.e., at most $k$ blocks can extend the same block.

4 Please notice that this concept of token is different from the one used by the Token Oracle.
contract will be executed in **Plurality** execution framework: the host blockchain equipped with an enriched validation mechanism to handle claimed and closed guards validations.

Section 4.1 presents the core of **Plurality**. Section 4.2 gives some examples of smart contracts. Section 4.3 presents **Plurality** execution model for **Plurality** smart contracts and details the operational semantics of transaction.

### 4.1 The Kernel of the **Plurality** Formal Language

**The syntax elements of the Kernel**

The BNF of the kernel of **Plurality** is defined as follow:

agent $\mathcal{A} ::= A, B, \Omega_i$

guard $gd ::= \Omega_i \triangleright gd$

endorsement $claim ::= \Omega_i \triangleright gd$

transaction $T ::= A (gd, q) \triangleright B | A (claim, q) \triangleright B$

actions $C ::= x:=T | \bar{x} \triangleright x:=T$

smartcontract $P ::= C, \ldots, C$

**Plurality** is a dialect of Cyberlogic enabling each agent to submit transactions to the blockchain. Agents of **Plurality** are Cyberlogic authorities. The syntax distinguishes two kind of agents in order to explicit the accountability of both: agents involved in a transaction (as source or sink) and external agents, oracles denoted $\Omega_i$, that endorse guards. Transactions are guarded transfers of ownership from the wallet of $A$ to the wallet of $B$ of an amount $q$ of tokens. The kernel of **Plurality** manages a unique kind of tokens, $\tau$.

**Transaction and their guards.** The syntax of **Plurality** distinguishes two kind of transactions according to the type of guard. $A (gd, q) \triangleright B$ is the transfer of an amount of $q \tau$ from $A$ to $B$ guarded by the closed guard $gd$. $A (claim, q) \triangleright B$ is the transfer of an amount of $q \tau$ from $A$ to $B$ guarded by the claimed guard $claim$.

**Submission of transactions.** An agent that owns a wallet in the blockchain can submit transactions in two different manners. \(x:=T\) is the submission of the transaction $T$ by the source of $T$, the transaction is bound to the identifier $x$. We assume that each identifier is unique. $\bar{x} \triangleright x:=T$ is the submission of $T$ by its source after that all transactions of $\bar{x}$ have been published in the blockchain.

We denote as $|W|$ the current balance of the agent $W$. For example, $\bar{x}:=A (|B| < 2, 5) \triangleright B$, is the submission by the agent $A$ of the transaction $x$ of $5 \tau$ from $A$ to $B$ guarded by the closed guard $|B| < 2$. This transaction can either be validated or not. If it is validated, $A$ can publish it on the blockchain.

\(x:=A (\Omega_Bk > account(B) < 2, 3) \triangleright B\), is the submission by the agent $A$ of the transaction $x$ of $2 \tau$ from $A$ to $B$ guarded by the claimed guard $\Omega_Bk \triangleright account(B) < 2$, the bank $\Omega_Bk$ endorses that $B$ has less than $2$ $\$ on bank account. This transaction can either be validated or not. If it is validated, $A$ can publish it on the blockchain. Here, $\Omega_Bk$ is an oracle that endorses the guard of the transaction.

\([x] \triangleright y:=B (K_i > bill[day, 3]) \triangleright C,\) is the submission by $B$ of the transaction $y$ of $3 \tau$ from $B$ to $C$ if the time oracle $K_i$ states that it is the $bill[day]$. To submit $y$, $B$ has to wait that $x$ has been published. We denoted $[]$ as a list and $[x]$ the list that contains only the element $x$.

The validation mechanism and the publication of transactions are detailed in the section [4.3](#).

### 4.2 **Plurality** Smart Contract examples

This section aims at presenting the different kind of guards in the core of **Plurality** concentrated on guards and their validations. Please notice that the transactional expressiveness of **Plurality** is very light and is a work in a progress out of the scope of the paper. In particular **Plurality** does not yet feature alternative choices. Moreover, we do not have detail temporality of guards for the sake of clarity, but as a dialect of Cyberlogic, **Plurality** and more specifically, the claimed guards are able to reason about time thanks to the specific $K_i$ authority of Cyberlogic: the time oracle. Finally, as detail bellow, the semantics of **Plurality** is given in CPS style, this formalism enables to disjoin concurrent execution. According the the consistency of the host blockchain, a **Plurality** smart contract will be able or not to present divergent...
history, for the sake of simplicity, in the following example, we assume that $\mathcal{B}$, the host blockchain is an ideal blockchain.

**The Fair Pocket Money.** A family $F$ uses the blockchain to distribute the pocket money of their two kids $A$ and $B$ in $\tau$. Their pocket money budget, $50$ $\tau$ is stored in the wallet $W$. The distribution of the pocket money is fair: both receive $20$ $\tau$.

\[
x := F \xrightarrow{(\tau, 50)} W; \quad x \not\succ y := W \xrightarrow{(\tau, 20)} A; \quad x \not\succ z := W \xrightarrow{(\tau, 20)} B;
\]

Note that in this smart contract guards are always at true, but a specific order on transactions is specified. The smart contract contains 3 transaction submissions: $x$ is the submission of the transfer of the pocket money budget from the family $F$ to its pocket money wallet $W$, $y$ is the submission of the transaction of the part of the pocket money to $A$ after the publication of $x$, and $z$ is the submission of the transaction of the pocket money to $A$ after $x$ publication.

**The Studious Pocket Money.** The family $G$ distributes the pocket money according to school merit: if the grade of the kid at school is greater to 10 then the kid receives 20 otherwise only 10. In this example, we suppose that the current balance of $S_A$, $|S_A|$ contains a amount of $\tau$ that applies to $\text{as\_grate}$ encodes the grade of $A$. The transaction $s$ is the submission from the school to $S_A$ that updates the grade.

\[
x := F \xrightarrow{(\tau, 50)} W; \quad [x; s] \not\succ y := W \xrightarrow{\text{as\_grate}(|S_A|)>10 \land 20} A \quad [x; s] \not\succ z := W \xrightarrow{\text{as\_grate}(|S_A|)<10 \land 10} A
\]

As for the fair pocket money smart contract, in $x$ the family provides 50 in their pocket money wallet. $y$ is the submission of the transaction from $W$ to $A$ 20 $\tau$ under the condition that her rate is superior to 10. The submission of $y$ by $W$ is possible only if the transaction $x$ and $s$ has been published. Hence, if the guard $\text{as\_grate}(|S_A|) > 10$, which is a closed guard is validated, $W$ publishes $y$: the wallet of $A$ is updated of 20 more $\tau$. $z$ very similar to $y$ except that its guard is $\text{as\_grate}(|S_A|) <= 10$ and in case of validation followed by publication: the wallet of $A$ is only updated of 10 more $\tau$.

**The evidential Pocket Money.** The family $L$ will only give the pocket money to a kid if it obtains its driving license.

\[
x := F \xrightarrow{(\tau, 50)} W; \quad [x; a] := W \xrightarrow{(\Omega_X \triangleright \text{license}(A) \land 20)} A
\]

$a$ can be submitted only if $x$ has been published. The validation of $a$ is the validation of $\Omega_X \triangleright \text{license}(A)$, the endorsement of the agent $\Omega_X$, an oracle, that $A$ has her license. Suppose that none of the already published transactions can be contradicted by $\Omega \triangleright \text{license}(A)$. Hence, $a$ can be validated by the validation mechanism and published by $A$.

**The Competitive Pocket Money.** The family $M$ has 2 kids, $A$ and $B$, in the same class $C$. $M$ gives a pocket money to a kid only if he is the top of the class. In the first version, the rank of a kid in $C$ is computable in the blockchain by the predicate $\text{rank}(C, X)$ the rank of the student $X$ in $C$. $\operatorname{rank}$ ensures that each position in the rank owns to only one student.

\[
x := F \xrightarrow{(\tau, 50)} W; \quad [x; a] := W \xrightarrow{\text{rank}(C, A) = 1 \land 20} A \quad [x; b] := W \xrightarrow{\text{rank}(C, B) = 1 \land 20} B
\]

In this smart contract $\text{rank}(C, X) = 1$ is decidable and only one $X$ can satisfy $\text{rank}(C, X) = 1$. Hence, if $x$ is published, it is not possible that both, $a$ and $b$ are validated: either $A$ or $B$ does not receive a pocket money – rank is not 1 for both $A$ and $B$ – or only one of them receives it – $A$ or $B$ rank is 1.

\[^{5}\text{That is feasible if for any student of } C, X, \text{ her/his marks are readable and used to compute the ranking of students of } C, \text{ this computation is closed to the blockchain.}\]
In the second version, $\Omega_e$ endorses the kids rank.

$$x := F \xrightarrow{(T, 50)} W ;$$

$$[x] \not\vdash a := W \xrightarrow{(\Omega_e, \triangleright \text{rank}(C, A) = 1, 20)} A$$

$$[x] \not\vdash b := W \xrightarrow{(\Omega_e, \triangleright \text{rank}(C, B) = 1, 20)} B$$

Suppose that $x$ and $a$ have been published. $b$ can also be submitted. Suppose now, that $\Omega_e$ endorses that $B$ is the first in the rank: $\Omega_e \triangleright \text{rank}(B) = 1$. If $b$ is validated, it would contradict $a$: either $A$ or $B$ can be ranked as the first student in the class but not both of them. In that case, the validation mechanism has to prevent the publication of $b$. The validation will formally detect that $b$ contradicts $a$ and $b$ will not be validated. This detection is computed by the proof-of-discord, the part of the validation mechanism dedicated to the validation of claimed guards. Notice, that this detection does not indicate which between $a$ or $b$ is false. In case of a proof-of-discord, the conflict has to be managed. The proof-of-discord is detailed in Section 4.3.

4.3 Pluralize Formal Execution Models

Semantically, a Pluralize smart contract executes on the execution model of Pluralize. Pluralize is a combination of its host blockchain $\mathcal{B}$ and the validation mechanism $\mathcal{V}$ that validates guards of submitted transactions. Plurality mainly manipulate transactions, then the crucial point of the operational semantics of Plurality is the specification of the different steps of a transaction execution. We call these steps the execution steps. (i) the submission of a transaction by its source, (ii) the validation of a submitted transaction by $\Theta_{\mathcal{B}}$, and (iii) the publication a validated transactions in the blockchain by its source. While each step can be performed by different agents, their executions must happen in a sequential specific order. A relevant technique to specify such operational semantics is the Continuation Passing Style, CPS [10].

As a dialect of Cyberlogic which is implemented in the Coq theorem prover, Plurality is a functional language – a programing language with functions as first-class citizen based on $\lambda$-calculus [3]. A relevant technique to specify concurrency in functional languages is the Continuation Passing Style, CPS [10]. CPS explicits the evaluation order, this is truly relevant for actions that have to be executed in a specific order but that are performed by different agents. We specify each execution step as a Cyberlogic continuation that manipulate the execution model.

A continuation captures the context at some given point in the program: it implicitly records the current instruction and the local state. Continuations are therefore perfectly suited to implementing concurrency. If the call to function were a cooperation point in a threaded program for instance, saving its continuation would be enough to resume execution after a context switch. Continuations are most often used in functional programming languages. Some of them, like Scheme [13] or Scala [14], provide first-class continuations with control operators, such as call/cc or shift and reset respectively, that allow a program to capture and resume its own continuations. Cooperative threads and other concurrency constructs are then built on top of these operators [11]. In functional languages that do not provide first-class continuations, continuations are encoded using other features such as first-class functions or monads. These constructs can then be used to implement concurrency libraries: concurrency monads in Haskell [6], or lightweight lwt threads in OCaml [20]. In Javascript, callback are continuation and in new version Promise and Asyc/await are some kind of explicit concurrent monad.

The semantics of Plurality is given in CPS-style Cyberlogic formula and is built upon Coq terms semantics (as it is a shallow-embedding implementation). In other words, a Plurality smart contracts is correct if the type checker of Coq checks it: that brings a high level of formal guarantee and gives Plurality a well-founded semantics. The crucial point is the abstraction of the execution models. Thanks to the blockchain ADT, that formalization is quite elegant.

Further in this section we present Pluralize as an execution model for Plurality transactions. First, we define the blockchain specification of Pluralize. Then, we give the specification of the execution steps in the execution model. Finally, we detail the validation mechanism $\mathcal{V}$.

Pluralize blockchain specification. The specification of Pluralize is the BT-ADT [1] instantiated with $f$ the selection function of $\mathcal{B}$ and $\mathcal{V}$ the validation predicate. $\mathcal{V}$ validates both the closed guards thanks
Transfer of ownership as a Cyberlogic formula. We define Account as the interpretation of a Plurality transaction \( T \). Account defines the semantics of Plurality transaction in Cyberlogic. As Cyberlogic is a shallow embeding in Coq, the semantics of Plurality is defined in the semantics of CiC \[7\]. Hence, a Plurality transaction becomes:

\[
\text{Account}(A, q, B) = \Theta \triangleright \forall (c) = T \rightarrow A \triangleright \text{updates}(A, q, B)
\]

where \( \text{updates}(A, q, B) \) is the transfer of ownership of \( q \) \( \tau \) from the wallet of \( A \) to the wallet of \( B \).

Submission continuation. \( \kappa_{\text{sub}} \) is the continuation that defines the semantics of the submission of a transaction. \( \kappa_{\text{sub}}(T, \kappa_{\text{V}}) = \text{let } b_t = \text{Account}(T) \text{ in } \kappa_{\text{V}}(b_t) \)

\( \kappa_{\text{sub}} \) inputs a transaction \( T \) and a validation continuation \( \kappa_{\text{V}} \). \( \kappa_{\text{sub}} \) makes a logical formula \( b_t \) from the transaction \( T \) thanks to the function \( \text{Account} \), and passes \( b_t \) to \( \kappa_{\text{V}} \). Hence, the semantics of a submission of the transaction \( T \) is the application of \( \kappa_{\text{sub}}(T) \) that waits for the application to a validation continuation \( \kappa_{\text{V}} \) that can be processed by \( \Theta_{\text{B}} \).

Validation continuation. \( \kappa_{\text{V}} \) is the continuation of validation that inputs the Cyberlogic formula of a submitted transaction \( b_t \) and a continuation of publication \( \kappa_{\text{pub}} \). \( \kappa_{\text{V}} \) requests a token \( b_t^{\text{tkn}} \) to \( \Theta \). If the token is obtained, \( \kappa_{\text{V}} \) applies it to \( \kappa_{\text{pub}} \).

\[
\kappa_{\text{V}}(b_t, \kappa_{\text{pub}}) = \begin{cases} 
\text{case } \text{getToken}(b_t, \text{last_block}(f(bf))) = b_t^{\text{tkn}} : \kappa_{\text{pub}}(b_t^{\text{tkn}}); 
\end{cases}
\]

Publication continuation. \( \kappa_{\text{pub}} \), the publication continuation is a consumption of a token of \( \Theta \) and the concrete append of the validated transaction in the blockchain.

\[
\kappa_{\text{pub}}(b_t^{\text{tkn}}) = \text{consumeToken}(b_t^{\text{tkn}}); f(bf)|_{\text{b}} \cdot b_t.
\]

\( \forall \) and the proof-of-discord. We detail the specification of \( \forall \), the validation mechanism of both kind of guards as follows:

\[
\forall(b_t, b_h, \kappa_C) = P_{\text{app}}(b_t) &
\begin{cases} 
\text{case } \text{guard}(b_t) = \text{gd} : P_{\text{gd}}(\text{gd}) \\
\text{case } \text{guard}(b_t) = \text{claim}_{ik} : & \text{pod}(b_t, b_h) = (\top, \emptyset) : \top \\
\text{case } \text{guard}(b_t) = \text{claim}_{ik} : & \text{pod}(b_t, b_h) = (\bot, C_{ik}) : \kappa_C(C_{ik})
\end{cases}
\text{poa}(b \text{ where guard } = \text{claim}_{ik}, b_h, \kappa_C) =
\begin{cases} 
\text{let } \Gamma := \text{make_context}(b_h); \\
\text{case } \Pi(\Gamma \vdash \neg\text{claim}_{ik}) = \emptyset : (\top, \emptyset); \\
\text{case } \Pi(\Gamma \vdash \neg\text{claim}_{ik}) = C_{ik} : (\bot, C_{ik})
\end{cases}
\]

Consider \( P_{\text{gd}} \) as the validation predicate of \( \text{B} \). \( P_{\text{gd}} \) is the conjunction of two predicates: \( P_{\text{app}} \), the predicate that ensures the validation of the append conditions that are specific to \( \text{B} \) and \( P_{\text{gd}} \), the validation of closed guards.

If the guard is an closed guard \( \text{gd} \), then \( \forall \) verifies if \( P_{\text{gd}}(\text{gd}) = \top \). In case of an claimed guard \( \text{claim}_{ik} \), \( \forall \) verifies if \( P_{\text{app}} \) is satisfied by the submitted transaction and tries to obtain a proof-of-discord for \( \text{claim}_{ik} \) from \( \text{pod} \). In order to manage proof-of-discord, the validation mechanism inputs a \( \kappa_C \), the manager of conflict, which is unspecified in this paper. \text{pod} inputs: (i) \( b_t \), the Cyberlogic formula of a submitted transaction and (ii) \( b_h \), the last block of \( f(b) \). \text{pod} makes a proof context from \( b_h \) and asks a formal certificate for \( \Gamma \rightarrow \neg\text{claim}_{ik} \) to \( \Pi \), a specific agent that makes a proof in Coq. If \( \Pi \) fails then \( \text{claim}_{ik} \) is invalid, if \( \Pi \) provides a formal certificate: \( C_{ik} \) then \( \text{claim}_{ik} \) is unvalid and \( \text{poa} \) returns the certificate.

\[6\] The verification that \( \text{claim}_{ik} \) is true in the evaluation context \( \Gamma \)

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5 Related Work

In [9], the authors highlighted the need of accountability for smart contracts that act as evidential protocols and proposed to use the authority algebra of Cyberlogic [17], but without defining a formal language supporting it.

Scilla [18] is a formal intermediate language for Ethereum smart contracts that is a shallow-embedding in Coq. As Pluralize, the Scilla semantics is defined in the semantics of Coq in a CPS style and Scilla smart contract are certified-by-designed. As Solidity smart contracts, Scilla smart contracts are stateful executable object-based code hosted on the blockchain that behaves as an autonomous server which has to be invoked by clients. Contrarily to Scilla, Pluralize is suitable to digitalize real-life transactional protocols: it focuses on smart contracts that are guarded transfers of ownership between agents with accountability as first class citizens.

Typecoin [8] is a protocol built upon Bitcoin, that transfers ownership of properties instead of ownership of amount of token: Typecoin implements proof-carrying authorization upon the Bitcoin protocols. That means that it enables to verified the authorization script that involves cryptographic signature verification. As in Pluralize, Typecoin sees the transaction as a transfer between agents, but reasoning on authorization instead of accountability as we do in Pluralize. Proof-carrying authorization [2] is more dedicated to permission and access properties than accountability and reliability. Typecoin used opcodes and the existing validation mechanism of bitcoin, even if it offers formal guarantee it suffers of the same lack of expressiveness than bitcoin script. Pluralize by enriching the validation mechanism of the host blockchain brings more formal guarantees and increase the reliability of smart contracts.

BitML [4] is a domain-specific language for smart contracts compiled to Bitcoin script. It is defined as a process calculus that is sufficiently expressive to cover most applications proposed in the literature for Bitcoin script. The DSL comes with a symbolic semantics. The paper also defines a computational model and establishes a relationship between the symbolic semantics and the computational model, which they call coherence. Based on this notion of coherence, the paper establishes the soundness of the compiler that takes the DSL into Bitcoin script. BitML offers formal guarantees and higher level expressiveness to implement current Bitcoin smart contract. Pluralize tackles smart legal contract at a higher-level by enriching the validation mechanism to handle claimed and closed guards that are delegated to Oracle in BitML as in the current Bitcoin smart contract. Thanks to the blockchain ADT, the coherence in Pluralize is inherits from the host blockchain and there is no need to establish an equivalence between the symbolic and execution model, as the ADT enables to formalize both in a same abstraction. That enables Plurality to target different blockchain protocols and makes it be technology agnostic. On the other hand, BitML explicits in its language and semantics the concurrency of its protocols while, in its current version, Pluralize does not offer explicit concurrency choices in its syntax. However, using CPS to define its semantics eases this kind of improvement: CPS already allows to express concurrent semantics. Naturally, as Pluralize aims at provide a higher-level smart legal contract language, it also have to feature concurrency in its syntax.

6 Conclusion

In this paper we presented Pluralize, a formal framework for accountability of blockchain transactions that extended Bitcoin paradigm to guards whose evaluation is not closed to the blockchain. Pluralize features a formal language, enabling the implementation of trustworthy smart contracts, called Plurality. Pluralize enables formal features in order to gain trust in smart contracts from their specification to their execution on the blockchain. Plurality is a dialect of Cyberlogic benefiting from the Cyberlogic theorem prover: its smart contracts are certified-by-design and their properties can be formally verified. The idea behind Pluralize is to conciliate the bitcoin-like smart contract with the smart legal contracts as define by [19] and that inspires the industrial predictive usage. Finally, Pluralize features proof-of-discord thanks to the possibility to trace back the chain of trust by interpreting transactions as Cyberlogic claims and either certificate that the blockchain is right or provide the potential guilty claims. Note that this work has been motivated by the needs identified during the development of an industrial prototype [10].

As future work we envisage to generate dynamic monitors for claimed guards. Monitors will be embedded in the run-time environment of the language for run-time identification of conflicts. Note that thanks to our Coq-enabled framework run-time monitors can be generated as correct-by-construction
and a certification of their computation can be provided as a locally-checkable proof. This turns out to obtain proofs about transaction validation/invalidation autonomously checkable by any node in the network.

Another important future work is to increase the expressivity of Plurality for ownership transfers. First, transfer have to be generalized to heterogeneous tokens thanks to a token algebra. Second, the validation mechanism has to handle the validation of smart contract computational guards. Finally, for their deployment, these enriched smart contracts might require side-chains or multi-chain components for complex validation processes and to store heterogeneous tokens. Hence, Pluralize executions model should be extended to several blockchains. Correctness of such extension will depends on the consistency of blockchains and consistency of their interaction. Formalization of those blockchains and their interaction requires to be able to compose BT-ADT instantiations.

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