Structured Contracts on Cardano

Statefulness in the EUTxO model

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Motivation

Evolution of a stateful program (smart contract)

`initState` → `s1` → `s2` → … → `finalState`

Eg. :

- anything implemented with current state machine library
- simulating accounts in EUTxO
- Marlowe?
- Manuel's proposal?

Ledger

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UTxO set

txin ↦ (myScriptAddr, v, d)

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…
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Predicates on ledger and transaction data :

`myScript`` :: Datum -> Redeemer -> Context -> Bool`

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How do we relate the two?!

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  - NFT-based state tracking mechanism
    - NFT indicates **the unique UTxO whose datum specifies the current state** of the SM
  - Along with updated state, returns **predicates on the updating the state transaction** (eg. validity interval must start after a specific time)
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  - Not practical because
    - Constraints library is **not expressive enough**
    - Generated code is **too big** to use on-chain
- There is a **simplified Agda model** of the ledger and the **SM library**
  - This contains a **proof** that starting from a ledger state without the NFT, every state of the SM that can appear on the ledger is one that can be reached by the SM
  - https://github.com/omelkonian/formal-utxo/blob/master/Bisimulation/Soundness.agda

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- The plan is to have a **CI** that tests the **conformance of the implementation to the formal specification**
    - part of the chain of evidence that connects the ledger design to the implementation

Recall the ledger spec…

This is the **small-step-semantics specification** of how to **apply a transaction** to the ledger state

Ledger transition type :

$$\_ \vdash \_ \xrightarrow[\text{LEDGER}]{\_} \_ \subseteq \mathbb{P}\,(\mathsf{LEnv} \times \mathsf{LState} \times \mathsf{Tx} \times \mathsf{LState})$$

`LEDGER` transition (`isValid = True` rule) :

$$\text{ledger-V}\;\frac{\begin{array}{c}\mathsf{isValid}\;tx = \mathsf{True} \\[1em] \begin{array}{c} slot \\ txIx \\ pp \\ tx \\ acnt \end{array} \vdash dpstate \xrightarrow[\text{DELEGS}]{\mathsf{txcerts}\;(\mathsf{txbody}\;tx)} dpstate' \\[1em] (dstate, pstate) := dpstate \\ (\_,\_,\_,\_,\_, genDelegs, \_) := dstate \\ (poolParams, \_, \_) := pstate \\[1em] \begin{array}{c} slot \\ pp \\ poolParams \\ genDelegs \end{array} \vdash utxoSt \xrightarrow[\text{UTXOW}]{tx} utxoSt' \end{array}}{\begin{array}{c} slot \\ txIx \\ pp \\ acnt \end{array} \vdash \begin{pmatrix} utxoSt \\ dpstate \end{pmatrix} \xrightarrow[\text{LEDGER}]{tx} \begin{pmatrix} \boldsymbol{utxoSt'} \\ \boldsymbol{dpstate'} \end{pmatrix}}$$

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  - Can prove desired properties
  - Can go from semi-formal to **mechanized Agda** code later, for higher assurance

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    - Spec-first approach is evidence-based, faster than testing/patching implementation
    - Can prove desired properties
    - Can go from semi-formal to **mechanized Agda** code later, for higher assurance
- Why use **small steps**?
    - We can relate directly to the ledger formalism without translation
    - Once contract specs are in Agda, can **link** it directly **to the current ledger Agda spec**

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> **“Any state transition system that can be simulated by the ledger”**

We use the term **structured contract** here to describe such a state transition system

- instead of state machine or stateful contract - because contracts are **not truly stateful** in an EUTxO ledger (they are simulated)

We call the following function which defines the simulation relation the **implementation** of the contract

- `pi : LState -> State`

Instance of a structured contract

An EUTxO structured contract is given by specifying the following data :

(i) Surjective projection $\pi_{\mathsf{State}} \in \mathsf{UTxOState} \to \mathsf{State}$

(ii) Surjective projection $\pi_{\mathsf{Input}} \in \mathsf{TxInfo} \to \mathsf{Input}^{?}$

(iii) Some set of inference rules that specify the transition of type `SMUP` $\_ \vdash \_ \xrightarrow[\text{SMUP}]{\_} \_ \subseteq \mathbb{P}\,(\mathsf{TxInfo} \times \mathsf{State} \times \mathsf{Input} \times \mathsf{State})$

(iv) a proof that the **`StatefulStep`** and **`StatefulNoStep`** property is satisfied by the data in (i), (ii), and (iii)

Structured Contracts Simulation Relation

$\texttt{SMUP}$ is simulated by the ledger when $\texttt{\textbf{StatefulNoStep}}$ and $\texttt{\textbf{StatefulNoStep}}$ are satisfied

$$\text{StatefulStep}\ \frac{\begin{array}{c} \mathit{txInfo} := \mathsf{txInfo}\ \mathsf{EI}\ \mathsf{SysSt}\ \mathsf{Lang}\ \mathit{pp}\ (\mathsf{getUTxO}\ \mathit{utxoSt})\ \mathit{tx} \\ \mathsf{isValid}\ \mathit{tx} = \mathsf{True} \qquad\qquad \pi_{\mathit{Input}}\ \mathit{txInfo} \neq \Diamond \\ \\ \begin{array}{c} \mathit{slot} \\ \mathit{txIx} \\ \mathit{pp} \\ \mathit{account} \end{array} \vdash \begin{pmatrix} \mathit{utxoSt} \\ \mathit{dpstate} \end{pmatrix} \xrightarrow[\text{LEDGER}]{\mathit{tx}} \begin{pmatrix} \mathit{utxoSt}' \\ \mathit{dpstate}' \end{pmatrix} \end{array}}{\mathit{txInfo} \vdash (\pi_{\mathit{State}}\ \mathit{utxoSt}) \xrightarrow[\text{SMUP}]{\pi_{\mathit{Input}}\ \mathit{txInfo}} (\pi_{\mathit{State}}\ \mathit{utxoSt}')}$$

Structured Contracts Simulation Relation

SMUP is simulated by the ledger when **StatefulNoStep** and **StatefulNoStep** are satisfied

This is not a rule, it is a **constraint** that may or may not be satisfied in general

- but has to be, by definition, if SMUP is a structured contract

$$\text{StatefulStep}\ \frac{\begin{array}{c} \mathit{txInfo} := \mathsf{txInfo\ El\ SysSt\ Lang}\ \mathit{pp}\ (\mathsf{getUTxO}\ \mathit{utxoSt})\ \mathit{tx} \\ \mathsf{isValid}\ \mathit{tx} = \mathsf{True} \qquad \pi_{Input}\ \mathit{txInfo} \neq \diamond \\ \begin{array}{c}\mathit{slot}\\ \mathit{txIx}\\ \mathit{pp}\\ \mathit{account}\end{array} \vdash \begin{pmatrix}\mathit{utxoSt}\\ \mathit{dpstate}\end{pmatrix} \xrightarrow[\text{LEDGER}]{\mathit{tx}} \begin{pmatrix}\mathit{utxoSt}'\\ \mathit{dpstate}'\end{pmatrix}\end{array}}{\mathit{txInfo} \vdash (\pi_{State}\ \mathit{utxoSt}) \xrightarrow[\text{SMUP}]{\pi_{Input}\ \mathit{txInfo}} (\boldsymbol{\pi_{State}\ \mathit{utxoSt}'})}$$

Current State Machine Library Small-Steps
See : NFTCE Transition

$$\text{MintsNFT}\ \frac{\begin{array}{c}\text{mints thread token NFT (spends utxoNFT)}\\[1em] \text{puts thread token NFT into UTxO with correct validator}\end{array}}{txInfo \vdash (\diamond) \xrightarrow[\text{NFTCE}]{smi} \begin{array}{c}\textbf{fst initState}\\ \textbf{snd initState}\end{array}}$$

$$\text{PropagatesNFT}\ \frac{\begin{array}{c}\forall p \in \mathsf{buildConstraits}\ txInfo,\ p\ sms\ smi\\[1em] \text{propagates thread token into correct output}\\[1em] txInfo \vdash \begin{array}{c}sms\\ val\end{array} \xrightarrow[\text{SMPEC}]{smi} \begin{array}{c}\boldsymbol{sms'}\\ \boldsymbol{val'}\end{array}\end{array}}{txInfo \vdash \begin{array}{c}sms\\ val\end{array} \xrightarrow[\text{NFTCE}]{smi} \begin{array}{c}\boldsymbol{sms'}\\ \boldsymbol{val'}\end{array}}$$

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See : `NFTCE` Transition

$\boxed{}$ Validator code shows up here

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Current State Machine Library Implementation

- We must also :
  - **specify** the projection functions
  - **prove** that the `NFTCE` relation satisfies **`StatefulStep`** and **`StatefulNoStep`** constraints
    - this proof involves reasoning about the Plutus scripts we construct for `NFTCE` definition

◇ ⟶ `(myScript, myValue + myNFT, initState)` ⟶ … ⟶ …

⟶ `(myScript, myValue + myNFT, myState)`

Example Structured Contract Spec : Account Simulation

$$\text{Open}\ \frac{\begin{array}{c} accIn \in \mathsf{OArgs} \\[1em] \mathsf{pk}\ accIn \in \mathsf{txInfoSignatories}\ txInfo \qquad id := \mathsf{id}\ accIn \qquad id \notin \mathrm{dom}\ accts \\[1em] \mathsf{pk}\ (id,\ newAcct) = \mathsf{pk}\ accIn \qquad\qquad \mathsf{val}\ newAcct = \mathsf{zero} \end{array}}{txInfo \vdash \left(accts\right) \xrightarrow[\text{ACCNT}]{accIn} \left(accts \cup \{id \mapsto newAcct\}\right)}$$

$$\text{Close}\ \frac{\begin{array}{c} accIn \in \mathsf{CArgs} \\[1em] \mathsf{id}\ accIn \mapsto acntToClose \in accts \\ \mathsf{pk}\ accIn \in \mathsf{txInfoSignatories}\ txInfo \qquad \mathsf{val}\ acntToClose = \mathsf{zero} \end{array}}{txInfo \vdash \left(accts\right) \xrightarrow[\text{ACCNT}]{accIn} \left((\mathsf{id}\ accIn) \ntriangleleft accts\right)}$$

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- **Prove** things about contracts at spec level
  - **translate** these properties to **ledger**-implemented contracts
  - allow for **different implementations** (each with its own simulation proof obligation)
  - Examples : **accounts** (naive vs … vs multi-threaded),
    - **messages-passing** (eg. all messages in one UTxO or one message per UTxO)

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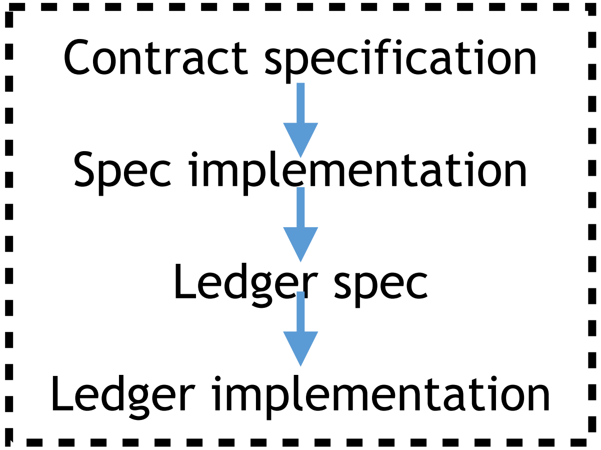
- **Chain of evidence** that connects a program and its implementation on the ledger



But…

- This still **doesn’t guarantee** we will have usable/expressible enough state-simulating mechanisms
    - but it helps use look, and specifies what it means to simulate state
- **Devs** would have to learn **Agda** and this **specification** style
    - will have to develop tools to make this easier (like the current CEM library but more general)
- Might have to **translate** Agda validator predicates to Plutus by hand?
    - more tools for this?
- Right now, this says nothing about **liveness**
    - liveness is hard!
- Proofs about the **real ledger** (rather than a simplified Agda model) are hard!

… → ?? → ?? → ?? → QUESTIONS???