Structured Contracts on Cardano

Statefulness in the EUTxO model

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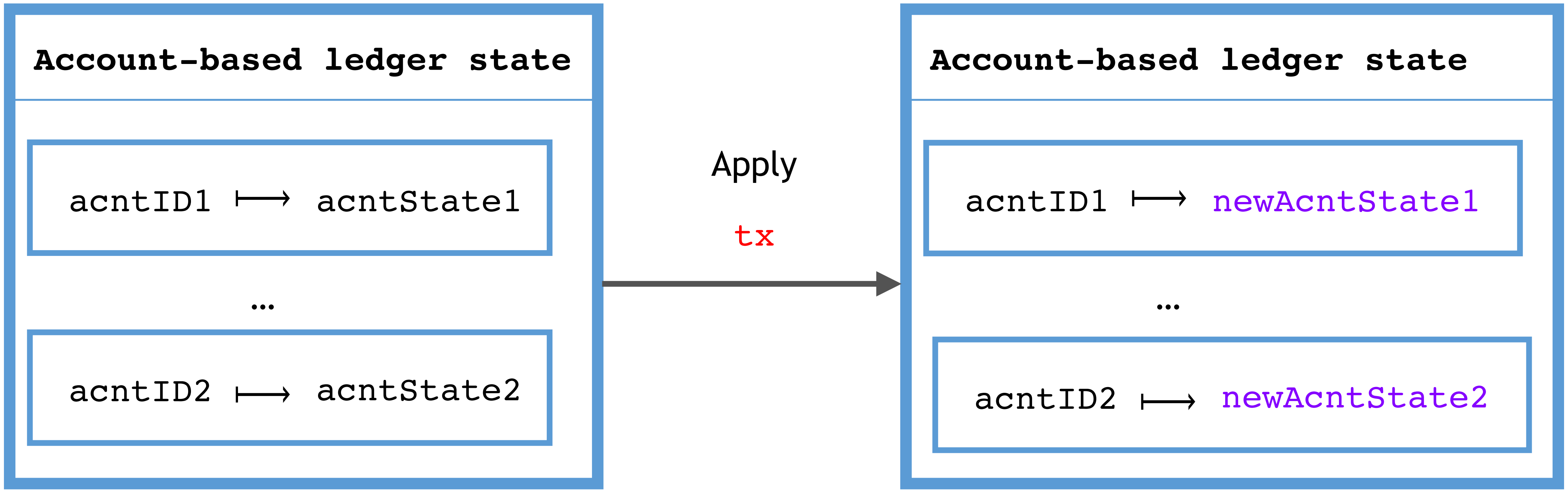
Account-based Ledgers



EUTxO Ledger

```
UTxO set

txin1  ↦  (myScriptAddr1, value1, datum1)

 …

txin2  ↦  (myScriptAddr2, value2, datum2)
```

`txin = (txId, ix)`

- Pointer to a specific output of transaction `tx`

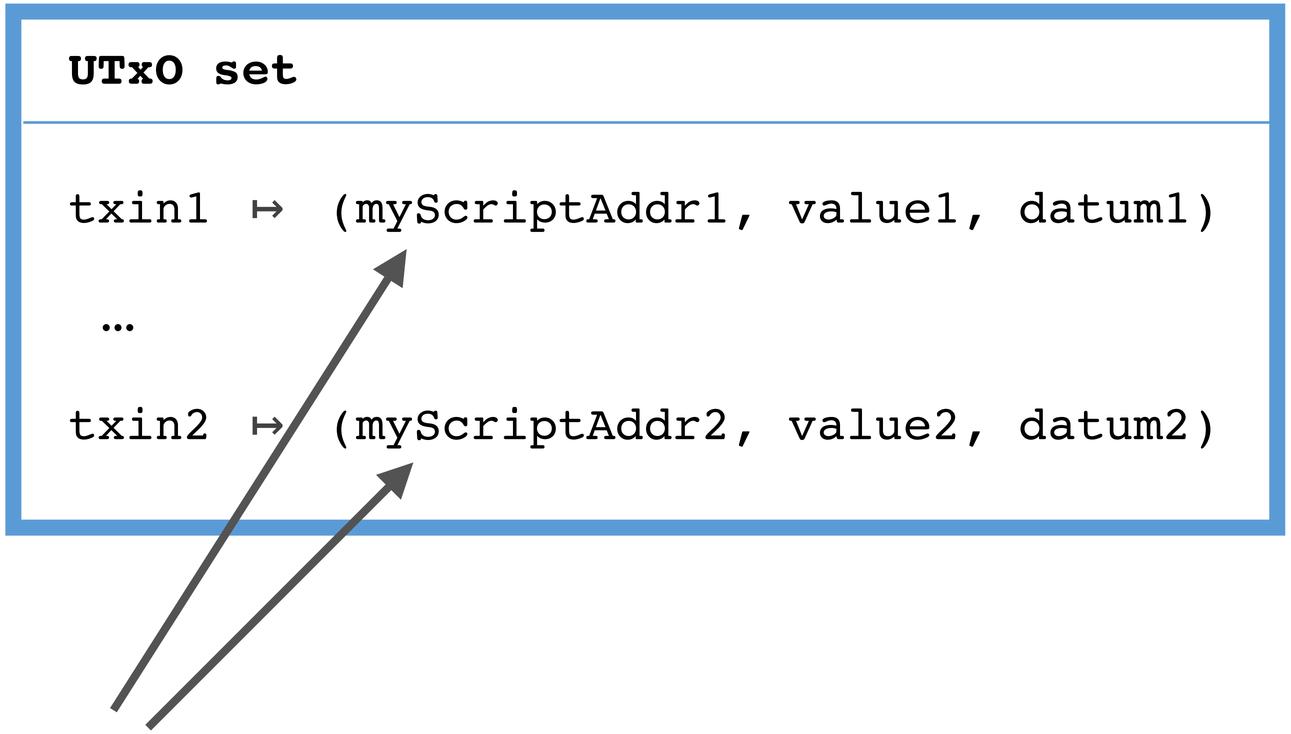
`txID`

- Encoding of the transaction `tx` whose output `txin` points to

`ix`

- Index of corresponding output of `tx` in its list of outputs

EUTxO Ledger



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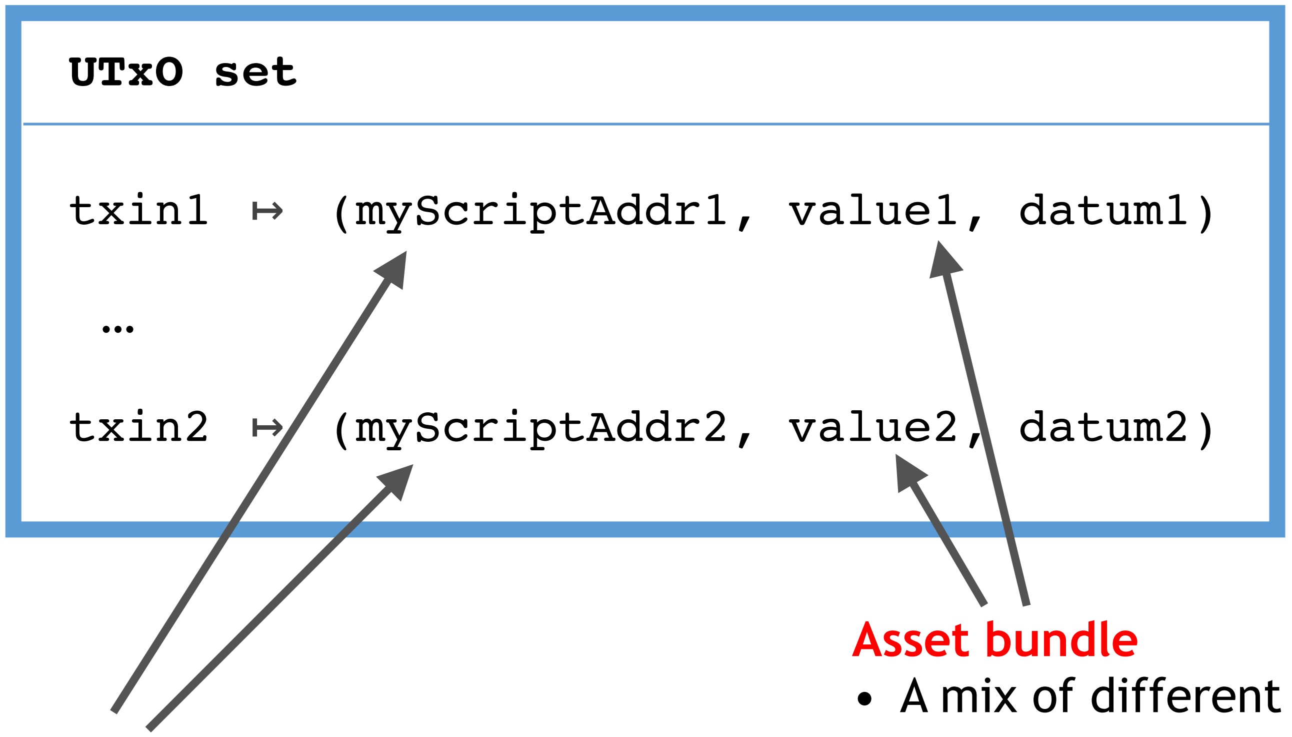
Script

- Stateless user-defined code with a boolean output
- Executed when a transaction spends the UTxO entry

EUTxO Ledger



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Asset bundle

- A mix of different tokens

Script

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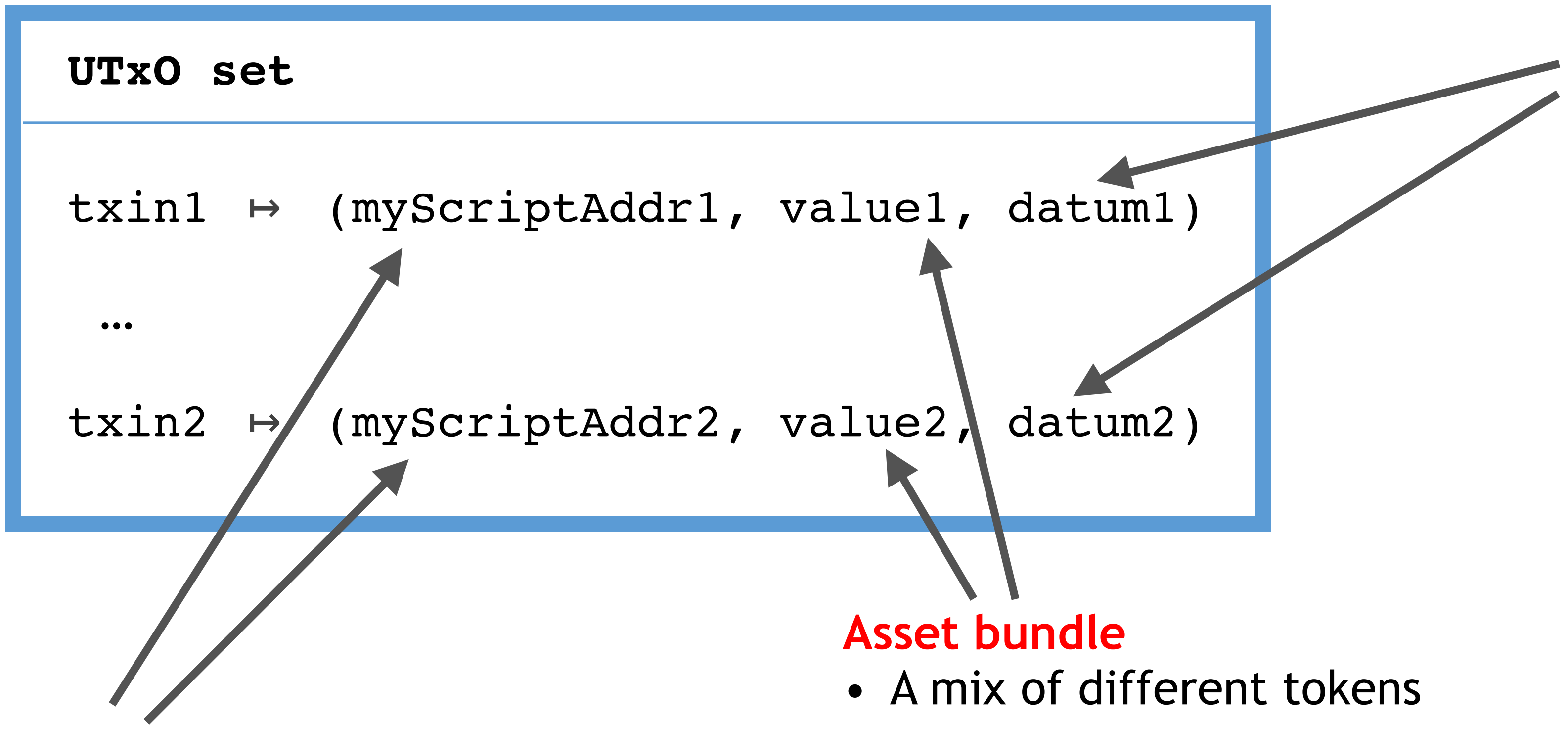
EUTxO Ledger



UTxO set

```
txin1 ↦ (myScriptAddr1, value1, datum1)

 …

txin2 ↦ (myScriptAddr2, value2, datum2)
```

Datum
- Some user-specified data

Asset bundle
- A mix of different tokens

Script
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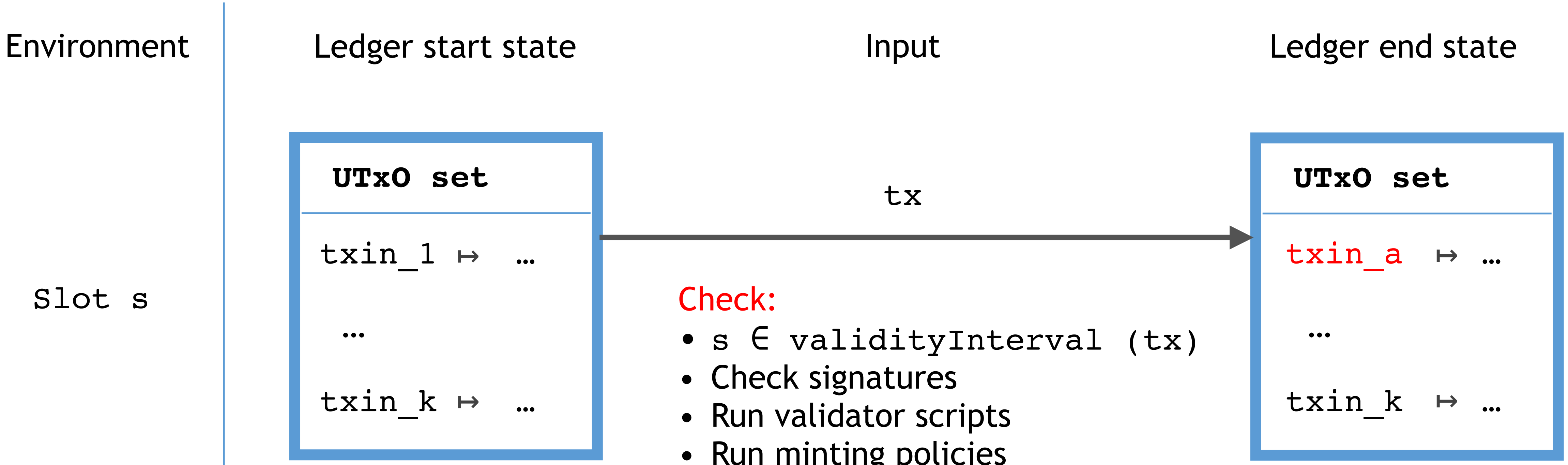
- Executed when a transaction spends the UTxO entry

EUTxO Ledger Update Specification

Using small-step operational semantics



Check:

- `s ∈ validityInterval (tx)`
- Check signatures
- Run validator scripts
- Run minting policies
- Check UTxOs being spent exist
- etc.

EUTxO

Challenges :
- Non-conventional programming **paradigm**
- Programming in **stateless** predicates

Advantages :
- **Predictable**
  - gas cost
  - outcome of contract execution
  - ledger changes made by valid transaction
- Amenable to **formal verification**

Examples :
- Cardano
- Ergo

Account-based

Challenges :
- **Can have unpredictable**
  - gas cost
  - outcome of contract execution
  - ledger changes made by valid transaction
- Formal verification is harder

Advantages :
- **Familiar** programming paradigm
- Straightforward use of **account states**

Examples :
- Ethereum
- Tezos

Motivation : Simulating Accounts

- **Account ID**
- **State** :
  - owner, assets
- **API** :
  - withdraw, deposit, open, close, transfer

EUTxO implementation :
- How do we **specify** this?
- What does it mean to **implement this program** using stateless predicates on transaction data?
- How can we be sure distinct implementations **meet the same specification**?

Motivation : Simulating Accounts

- **State** :
  - unique account ID, owner, assets
- **API** :
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EUTxO implementation :
- How do we **specify** this?
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We need a model of stateful computation here!

Enter “Structured Contracts”

Ledger :

$$\begin{tikzcd} \dots \arrow[r] & \boxed{\texttt{utxo}} \arrow[r, "\texttt{tx1}"] & \boxed{\texttt{utxo'}} \arrow[r, "\texttt{tx2}"] & \boxed{\texttt{utxo''}} \arrow[r] & \dots \end{tikzcd}$$

Enter “Structured Contracts”

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\text{Ledger :} & \dots \arrow[r] & \boxed{\texttt{utxo}} \arrow[r, "\texttt{tx1}"] & \boxed{\texttt{utxo'}} \arrow[r, "\texttt{tx2}"] & \boxed{\texttt{utxo''}} \arrow[r] & \dots \\
\text{Contract Spec :} & \dots \arrow[r] & \boxed{\texttt{state}} \arrow[r, "\texttt{i1}"] & \boxed{\texttt{state'}} \arrow[r, "\texttt{i2}"] & \boxed{\texttt{state''}} \arrow[r] & \dots
\end{tikzcd}$$

Enter "Structured Contracts"

$$\begin{tikzcd}
\text{Ledger :} & \cdots \arrow[r] & \texttt{utxo} \arrow[rr, "\texttt{tx1}"] \arrow[d, "\pi"] & {} \arrow[d, dashed, "\pi_{\mathrm{Tx}}"] & \texttt{utxo'} \arrow[rr, "\texttt{tx2}"] \arrow[d] & {} \arrow[d, dashed, "\pi_{\mathrm{Tx}}"] & \texttt{utxo''} \arrow[r] \arrow[d, "\pi"] & \cdots \\
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Enter “Structured Contracts”

$$\begin{tikzcd}
\text{Ledger :} & \cdots \arrow[r] & \texttt{utxo} \arrow[rr, "\texttt{tx1}", ""{name=A, below}] \arrow[d, "\pi"] & & \texttt{utxo'} \arrow[rr, "\texttt{tx2}", ""{name=B, below}] \arrow[d] & & \texttt{utxo''} \arrow[r] \arrow[d, "\pi"] & \cdots \\
\text{Contract Spec :} & \cdots \arrow[r] & \texttt{state} \arrow[rr, "\texttt{i1}", ""{name=C, above}] & & \texttt{state'} \arrow[rr, "\texttt{i2}", ""{name=D, above}] & & \texttt{state''} \arrow[r] & \cdots
\arrow[from=A, to=C, dashed, "\pi_{Tx}"]
\arrow[from=B, to=D, dashed, "\pi_{Tx}"]
\end{tikzcd}$$

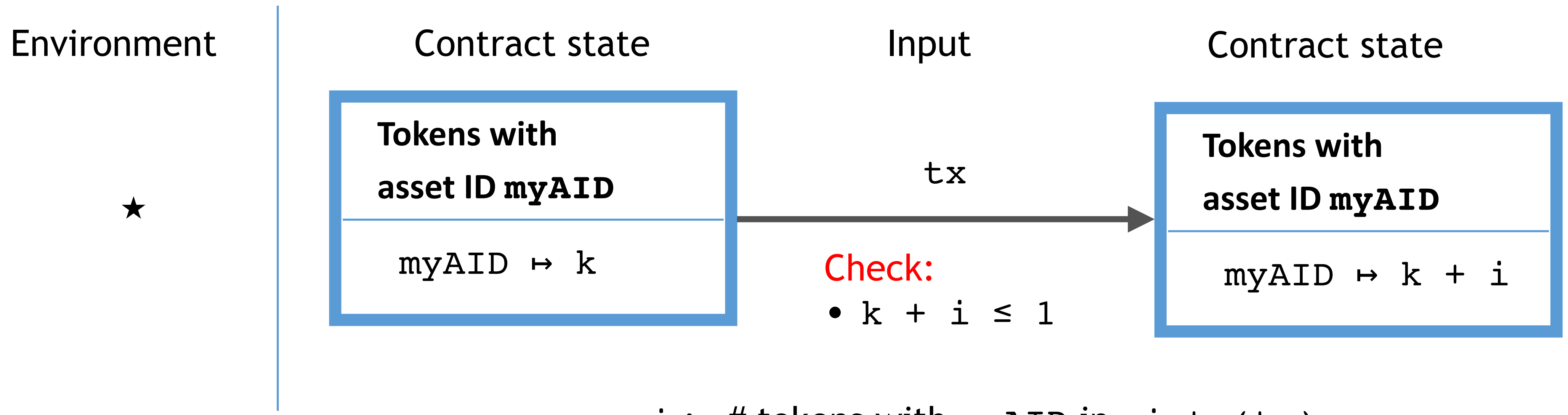
An **instance** of a structured contract requires :

- **Specification** (in small-step operational semantics)
- **Projections** π (partial function), π_{Tx}
- **Proof** of commutativity of any square

Example 1 : NFT

Defining property :

- “If one exists on the ledger, another one cannot be minted”
- suggests a state transition system
- can specify and implement



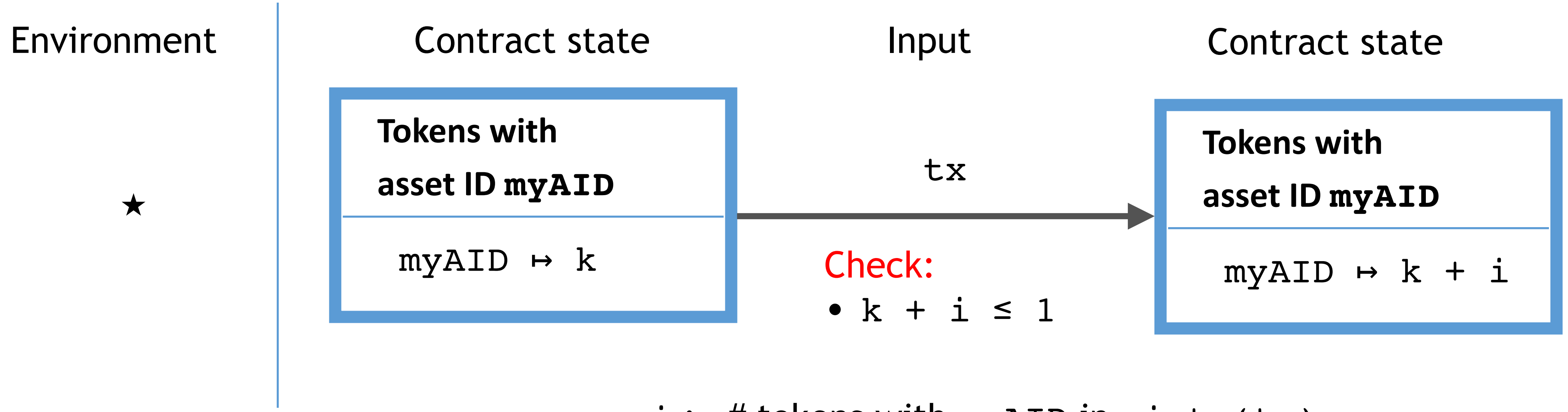
`i` := # tokens with `myAID` in `mint (tx)`

Example 1 : NFT

Defining property :

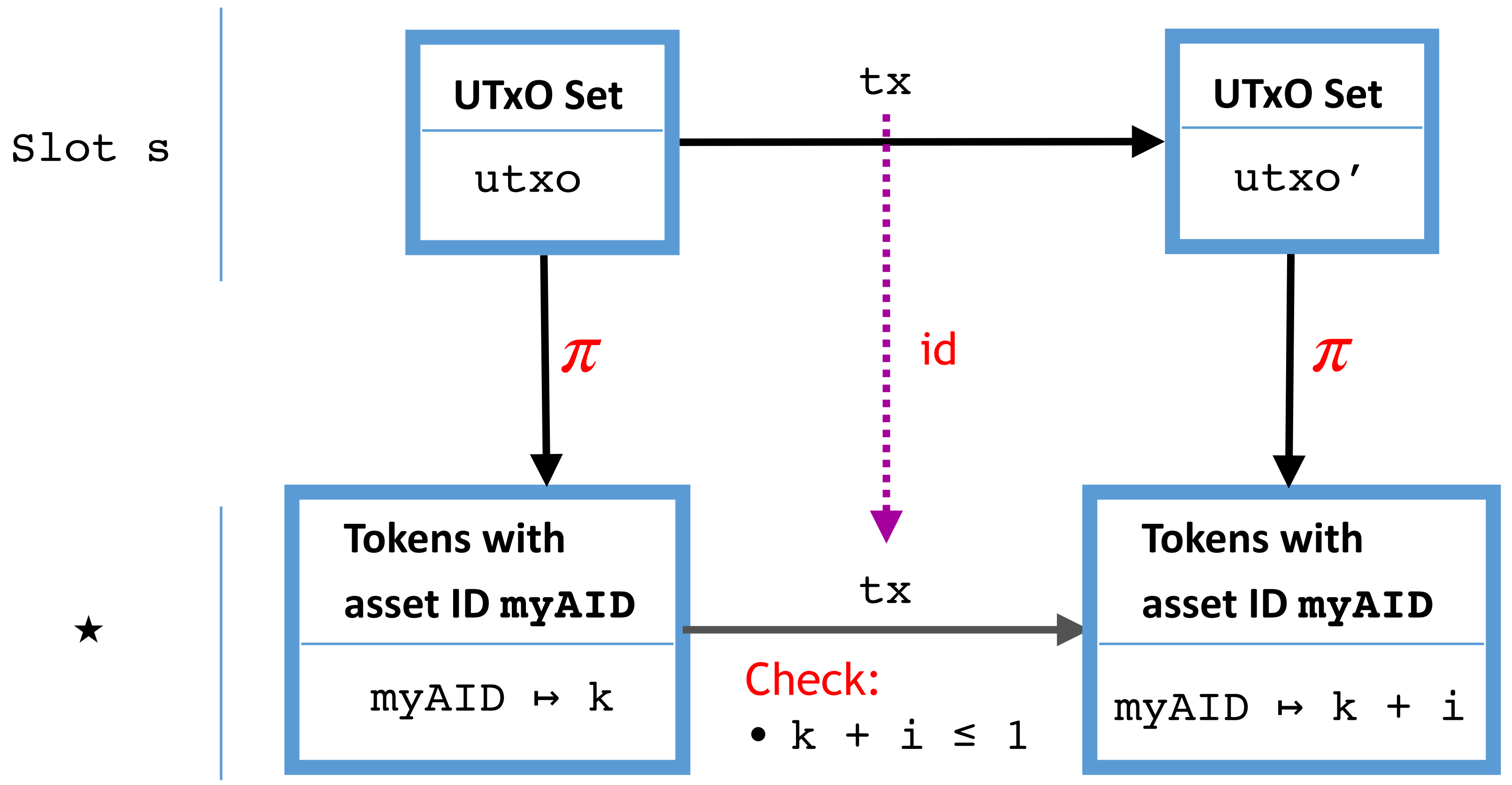
- “If one exists on the ledger, another one cannot be minted”
- suggests a state transition system
- can specify and implement

THERE CAN BE ONLY ONE



`i` := # tokens with `myAID` in `mint (tx)`

NFT Implementation

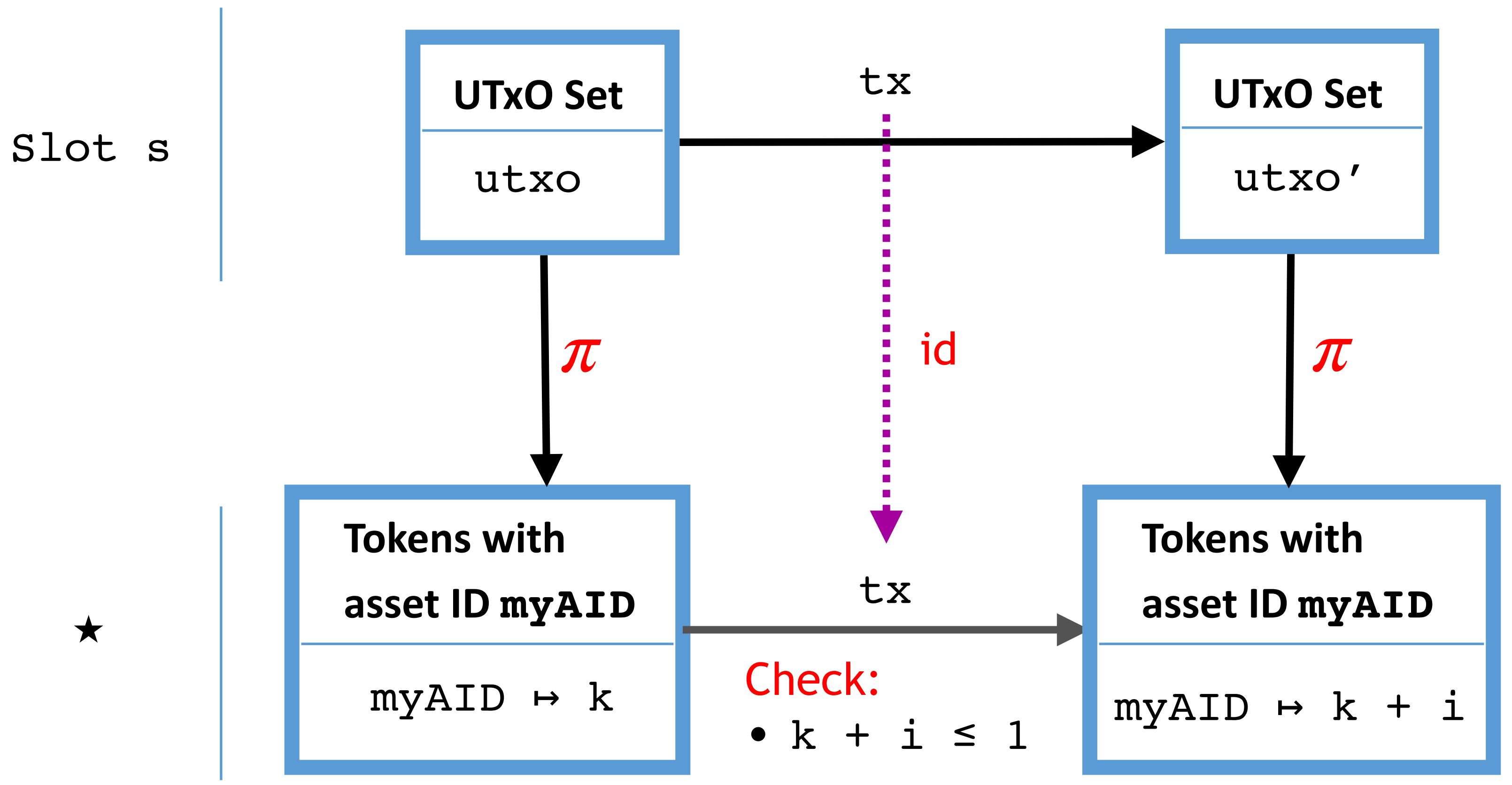


Need to :

- Define π
- Prove square commutes

i := # tokens with `myAID` in `mint (tx)`

NFT Implementation



i := # tokens with myAID in mint (tx)

π (utxo) :=

myAID ↦ k if (k ≤ 1) & …

★ otherwise

where

k := # tokens with myAID in utxo

NFT Implementation

Proving correctness

`myAID` includes to a **minting policy**, which checks :

- A **specific UTxO entry** is being spent by `tx`
- The **quantity** of assets with `myAID` being **minted** is 1

To prove commutativity :

- assume **replay protection**
- **exclude** the case where π `(utxo) =` $\star$
  - starting UTxO has at **most 1 token** with `myAID`

$$\pi(\texttt{utxo}) := \begin{cases} \texttt{myAID} \mapsto \texttt{k} & \text{if } (\texttt{k} \leq 1)\ \&\ \ldots \\ \star & \text{otherwise} \end{cases}$$

where

`k` := # tokens with `myAID` in `utxo`

NFT Defining Property

- From definition of π, we have :

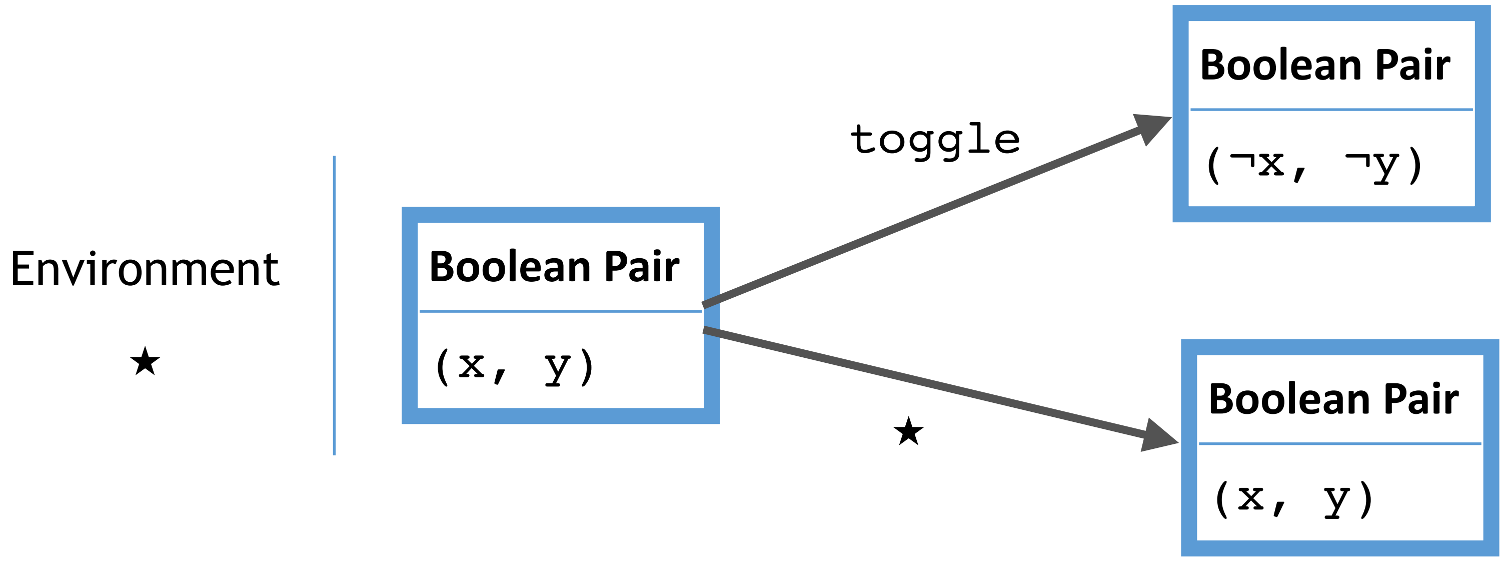
For any `utxo`,

$$\pi\,(\texttt{utxo}) \neq \star \quad \Rightarrow \quad \pi\,(\texttt{utxo}) \leq (\texttt{myAID} \mapsto 1)$$

- **Commutativity of square** implies that

$$\pi\,(\texttt{utxo}) \neq \star \quad \Rightarrow \quad \pi\,(\texttt{utxo'}) \leq (\texttt{myAID} \mapsto 1)$$

Example 2 : TOGGLE



TOGGLE Implementations

Naive

```
UTxO set
txin ↦ (toggleVal, NFTpointer, (x, y))
```

Distributed

```
UTxO set
txin_x ↦ (toggleVal', NFTpointerX, x)
txin_y ↦ (toggleVal', NFTpointerY, y)
```

TOGGLE Implementations

Naive

UTxO set

```
txin ↦ (toggleVal, NFTpointer, (x, y))
```

Distributed

UTxO set

```
txin_x ↦ (toggleVal', NFTpointerX, x)
txin_y ↦ (toggleVal', NFTpointerY, y)
```

Not pictured here : `NFTpointer`, `NFTpointerX`, and `NFTpointerY` policy code, `toggleVal` code, and commutativity proof obigation

TOGGLE Implementations

Naive

```
UTxO set
txin ↦ (toggleVal, NFTpointer, (x, y))
```

Distributed

```
UTxO set
txin_x ↦ (toggleVal’, NFTpointerX, x)
txin_y ↦ (toggleVal’, NFTpointerY, y)
```

- Both implement the **same spec**
- Developers can **compare** implementations across memory use, parallelizability, etc.

Structured contracts (SCs)

As a model of stateful computation on the EUTxO ledger

- **Generalization** of constraint-emitting machines (CEMs), in which :
  - projections π, π_{Tx} are **fixed**
  - implementations are **fixed** and **automatically generated**
- **Principled, uniform** approach to reasoning about stateful computation
- SCs define a class of **all stateful contracts**
  - that can be implemented via **user-defined scripts**
  - where correct **ledger** evolution $\Rightarrow$ correct on-chain **contract state** evolution
- Enable **comparison** of implementations if a given spec

Structured contracts

Limitations

- **No automation** for implementation of simulation proof
    - difficult b/c user decides on the implementation
    - Future work

- Hard to guarantee **existence of valid transaction** corresponding to given state update
    - Even more difficult **in practice** : user has no control over UTxO state, slot, fees, etc. that their transaction will actually be applied to
    - Also future work!

Structured contracts

Mechanized in Agda

https://omelkonian.github.io/structured-contracts/