Native Custom Tokens in The Extended UTXO Model

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Introduction

Motivation

- Most Ethereum smart contracts manage *user-defined assets*
    - either *fungible tokens* based on ERC-20
    - or *non-fungible tokens* based on ERC-721

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    - either *fungible tokens* based on ERC-20
    - or *non-fungible tokens* based on ERC-721
- Unfortunately non-native, hence inefficient and expensive

This talk

1. Recall EUTXO, an extension of UTXO

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2. Introduce $\mathrm{EUTXO}_{\mathrm{ma}}$ to support **native custom tokens**

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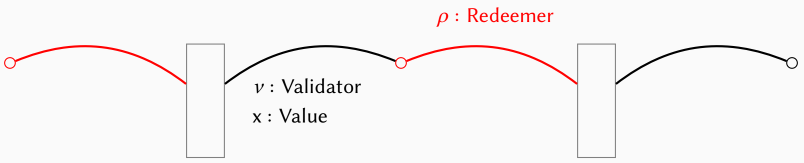
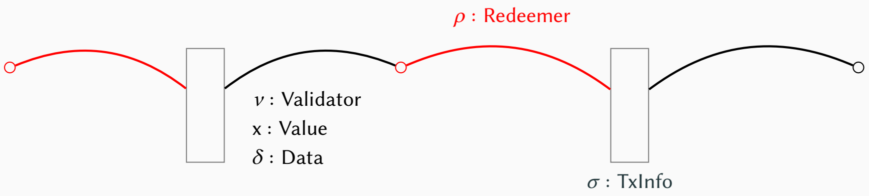
2. Introduce EUTXO$_{\mathrm{ma}}$to support **native custom tokens**
3. Utilise multi-currency features to extend the previous meta-theory and make it more robust

EUTXO

UTXO vs EUTXO

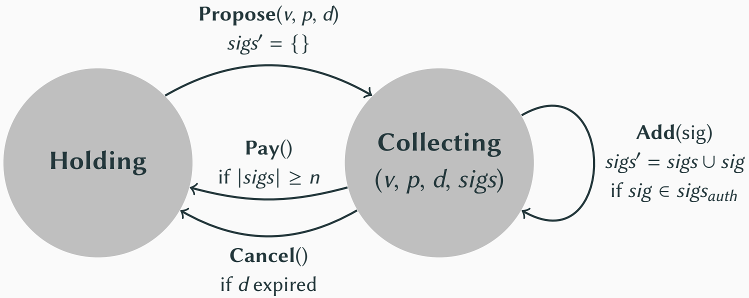


$$\nu(\rho) \overset{?}{=} \text{True}$$

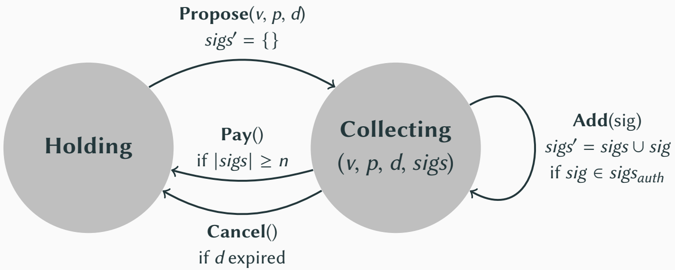


$$\nu(\rho,\ x,\ \delta,\ \sigma) \overset{?}{=} \text{True}$$

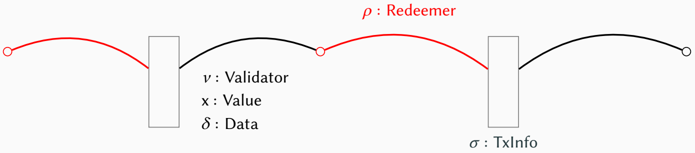
Running Example: Asynchronous Multi-signature Contract



Pay value (v) to payee (p) until deadline (d)



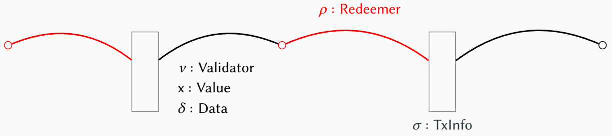
- $\delta \in \{\text{Holding}, \text{Collecting}\}$
- $\rho \in \{\text{Propose}, \text{Add}, \text{Cancel}, \text{Pay}\}$



$$v(\rho,\ x,\ \delta,\ \sigma) \stackrel{?}{=} \text{True}$$

Previous Work [The Extended UTXO Model @ WTSC'20]

- **Detailed description of the Extended UTXO model (EUTXO)**



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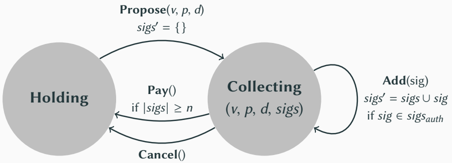
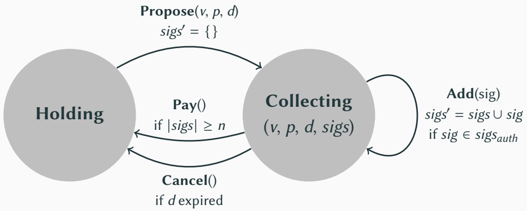
- **Formalization in** Agda

- **Proof of bisimulation with a Constraint Emitting Machines (CEMs)**



Limitation: Initial State



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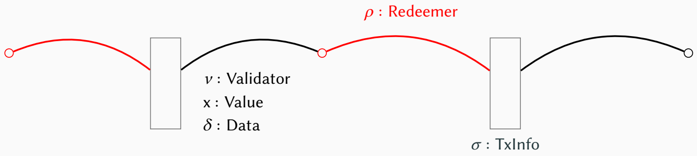

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EUTXO$_{\text{MA}}$

Token Bundles

$$\{₳ \mapsto \{₳ \mapsto 3\}, \mathit{WoW} \mapsto \{\mathit{sword} \mapsto 1, \mathit{shield} \mapsto 1\}\}$$

Operations on Token Bundles

$$
\begin{aligned}
& \{ ₳ \mapsto \{ ₳ \mapsto 3\}, \mathit{WoW} \mapsto \{\mathit{sword} \mapsto 1, \mathit{shield} \mapsto 1\}\} \\
+ & \{ ₳ \mapsto \{ ₳ \mapsto 1\}, \mathit{WoW} \mapsto \{\mathit{armour} \mapsto 1\}\} \\
= & \{ ₳ \mapsto \{ ₳ \mapsto 4\}, \mathit{WoW} \mapsto \{\mathit{sword} \mapsto 1, \mathit{shield} \mapsto 1, \mathit{armour} \mapsto 1\}\} \ .
\end{aligned}
$$

Forging

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- $Tx = \{\ldots forge : \text{TokenBundle}, policies : \sigma \to \text{Bool} \ldots\}$
- $forge \in \mathbb{Z}^+$ for minting, $forge \in \mathbb{Z}^-$ for burning
- $\forall\ p\sharp \in forge.domain : p \in policies \wedge p(\sigma) = \text{True}$

Applications

- Tokenised roles
- Fairness in ICO setup
- Algorithmic stablecoins

$\vdots$

Applications: Threaded State Machines

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  $\Longrightarrow$ can distinguish between different executions

  $\Longrightarrow$ solve the initialisation problem

Meta-theory

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- Trace$(l, o, \blacklozenge, n) = t_0, \ldots, t_i, t_{i+1}, \ldots, t_k$, where
    1. $t_0.\mathit{forge}^{\blacklozenge} \geq n$
    2. $t_i \xrightarrow{\blacklozenge} t_{i+1} \geq n$
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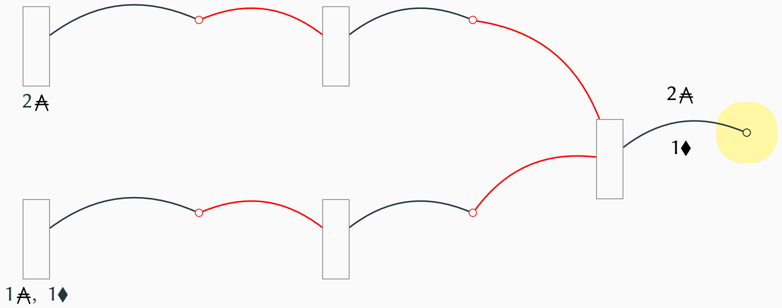
Every output has a provenance

$$\frac{o \in \{t.\mathit{outputs} \mid t \in l\}}{\text{provenance}(l, o, \blacklozenge) : \text{Provenance}(l, o, \blacklozenge)} \; \textsc{Provenance}$$

Example Traces



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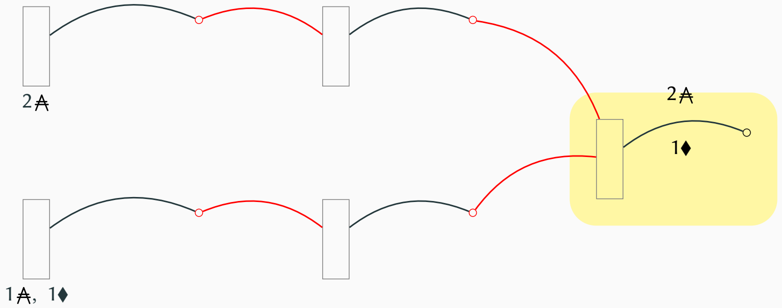

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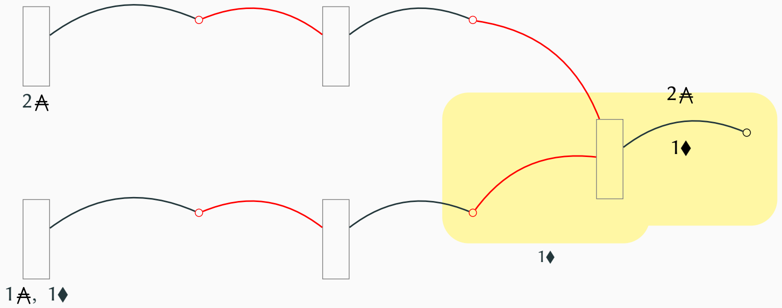

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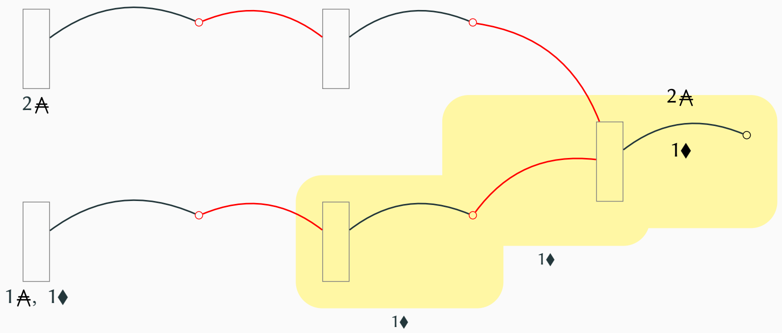

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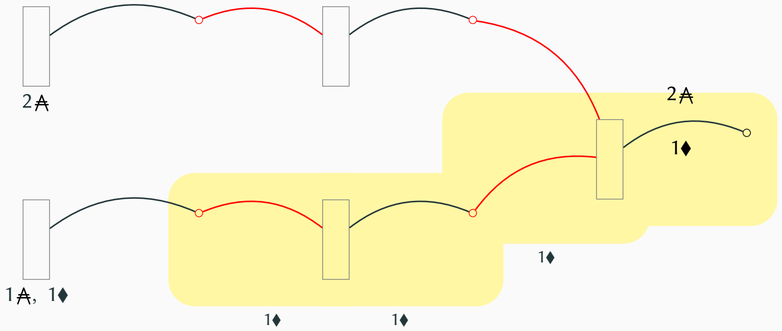

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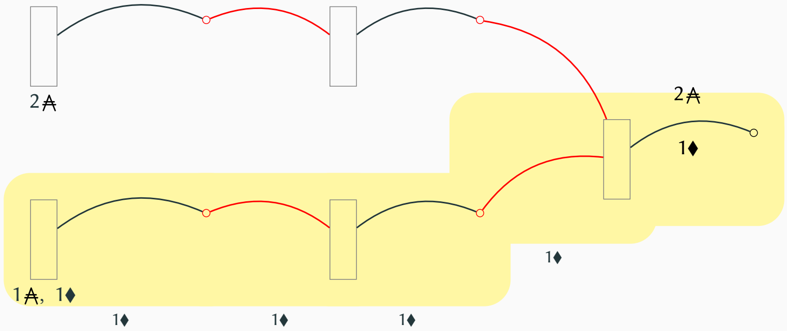

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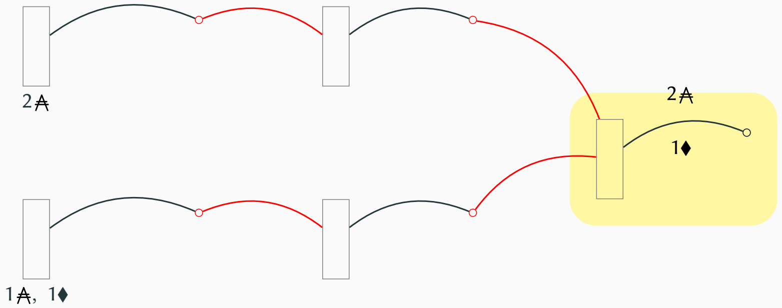

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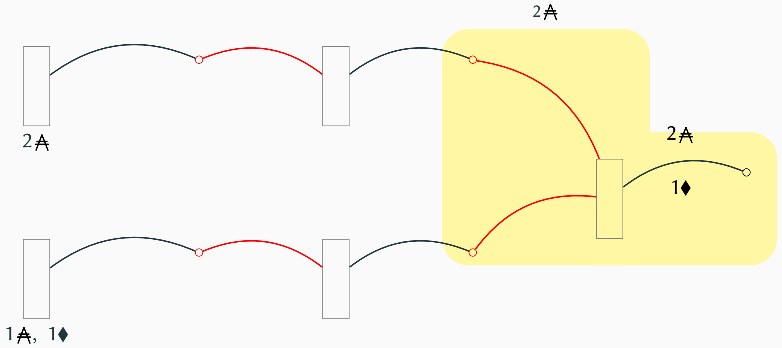

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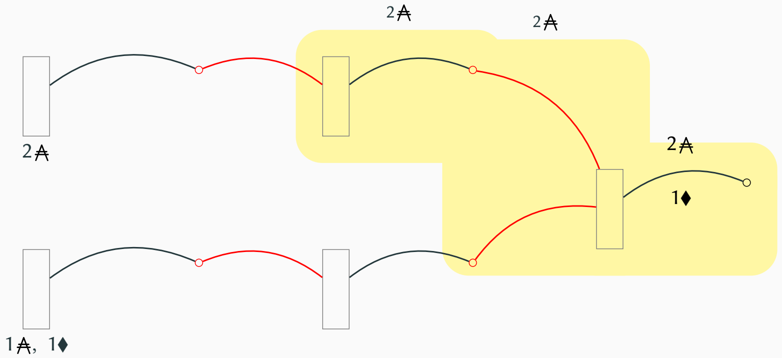

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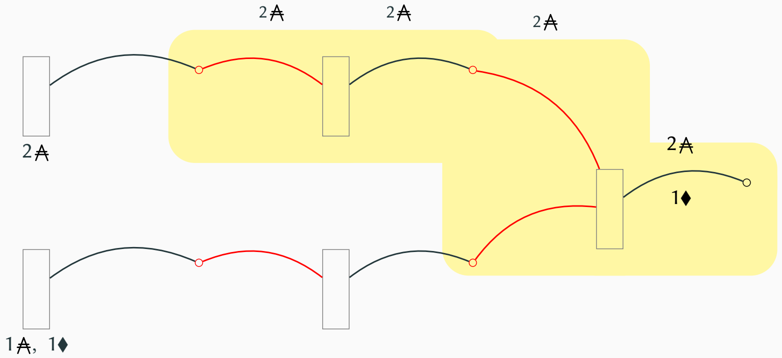

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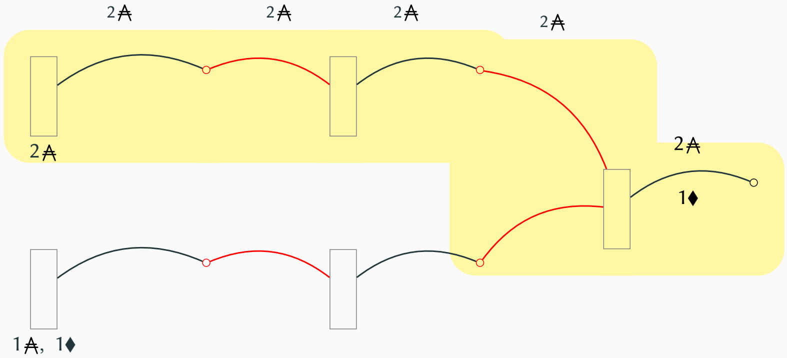

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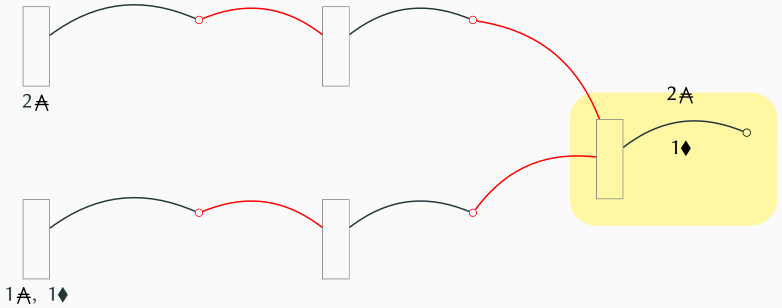

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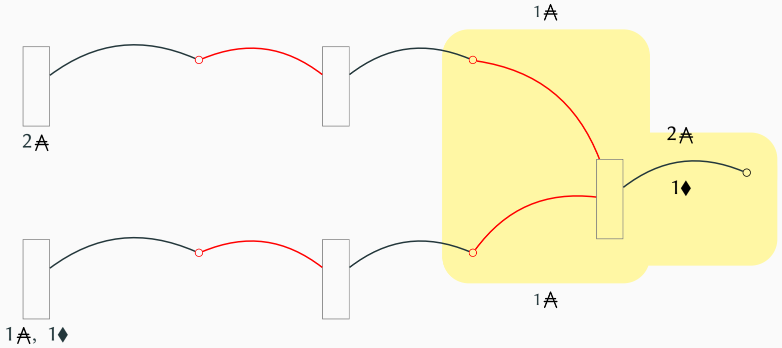

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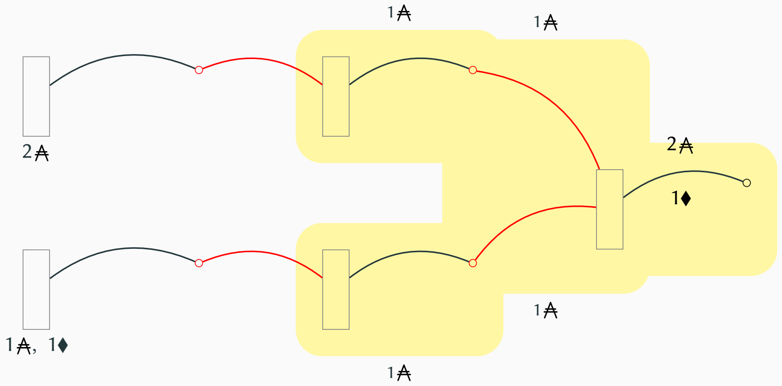

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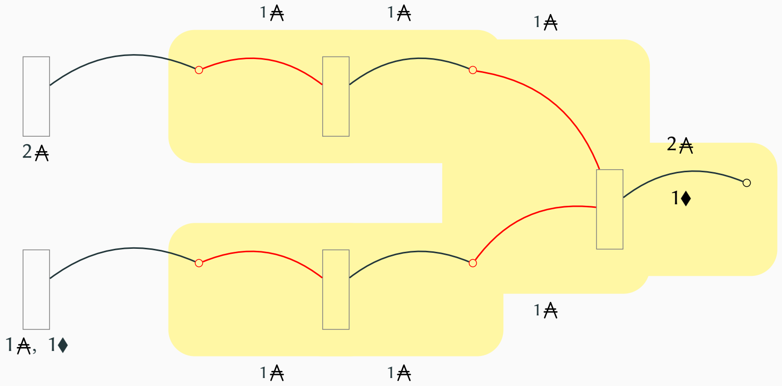

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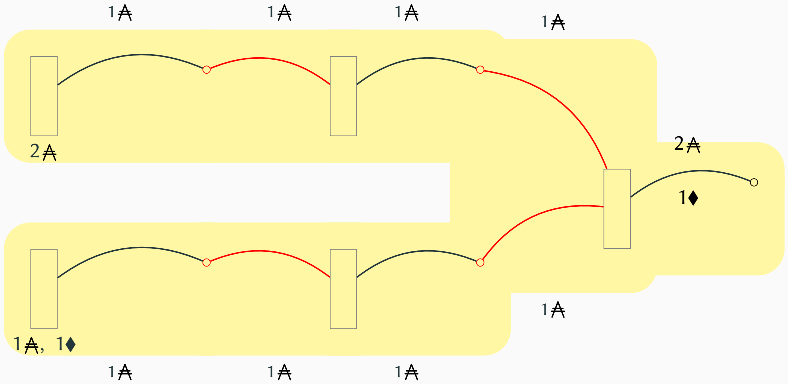

Forging Policies

Provenance is never empty

$$\frac{o \in \{t.outputs \mid t \in l\} \quad o.value^{\blacklozenge} > 0}{|\text{provenance}(l, o, \blacklozenge)| > 0}\ \textsc{Provenance}^{+}$$

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Global Preservation

$$\sum_{t \in l} t.forge = \sum_{o \in \mathrm{unspentOutputs}(l)} o.value$$

Non-fungible Provenance

Provenance for non-fungible tokens

$$\frac{o \in \{t.outputs \mid t \in l\} \quad o.value^{\blacklozenge} > 0 \quad \sum_{t \in l} t.forge^{\blacklozenge} \leq 1}{|\mathrm{provenance}(l, o, \blacklozenge)| = 1}\ \textsc{NF-Provenance}$$

Threaded CEMs

$$\mathrm{policy}_{\mathcal{C}}(\mathit{txInfo}, c) = \begin{cases} \mathrm{true} & \textit{if } \mathit{txInfo}.\mathit{forge}^{\blacklozenge} = 1 \\ & \textit{and } \mathrm{origin} \in \mathit{txInfo}.\mathit{outputRefs} \\ & \textit{and } \mathrm{initial}(\mathit{txInfo}.\mathit{outputs}^{\blacklozenge}) \\ \mathrm{false} & \textit{otherwise} \end{cases}$$

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$$\text{validator}_{\mathcal{C}}(s, i, \mathit{txInfo}) = \begin{cases} \text{true} & \textit{if } s \xrightarrow{i} (s', tx^{\equiv}) \\ & \textit{and } \text{satisfies}(\mathit{txInfo}, tx^{\equiv}) \\ & \textit{and } \text{checkOutputs}(s', \mathit{txInfo}) \\ & \textit{and } \text{propagates}(\mathit{txInfo}, \blacklozenge, s, s') \\ \text{false} & \textit{otherwise} \end{cases}$$

Threaded CEMs: Initiality

All traces originate from initial states

$$\frac{o \in \{t.outputs \mid t \in l\} \quad o.value^{\blacklozenge} > 0}{\exists tr.\ \text{provenance}(l, o, \blacklozenge) = \{tr\} \ \wedge\ \text{policy}_{\mathcal{C}}(tr_0.\text{context}) = \text{true}}\ \textsc{Initiality}$$

Property Preservation

Well-rooted sequences

$$\frac{\text{initial}(s) = \text{true}}{s \rightsquigarrow^* s} \qquad \frac{s \rightsquigarrow^* s' \quad s' \xrightarrow{i} (s'', tx^{\equiv})}{s \rightsquigarrow^* s''}$$

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A property P is invariant when:

$$\frac{\text{initial} \implies P \qquad \forall (s \rightsquigarrow^* s').P(s) \implies P(s')}{\texttt{invariant}\ P}$$

Example: Counter CEM

$$(\mathbb{Z}, \{\mathrm{inc}\}, \mathrm{step}, \mathrm{initial}) \textbf{ where } \mathrm{step}(i, \mathrm{inc}) = \mathrm{just}(i + 1);\ \ \mathrm{initial}(0) = \mathrm{true}$$

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Extracting CEM traces from EUTXO traces

$$\frac{\mathrm{provenance}(l, o, \blacklozenge) = \{tr\}}{tr.source \rightsquigarrow^{*}\ tr.destination}\ \textsc{Extraction}$$

Beyond Safety

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$$\overset{?}{\Longrightarrow}$$ *coinductive* techniques for *infinitary* semantics

Related Work

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    - Ethereum smart contracts as state machines
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  - High-level process calculus > Bitcoin transactions
  - Small-step operational semantics   state machines
  - Support for LTL formulas
  - No (complete) mechanization yet

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- VeriSolid [Mavridou et al. @ FC'20]
    - Solidity contracts as state machines
    - Support for CTL formulas
    - No mechanized meta-theory

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Questions?