Stateful Smart Contracts On Cardano

Part 1. Securing The Distributed State.

Lorenzo Fanton

887857@stud.unive.it

Problem

At the lowest level, we need to:

1. Distribute a smart contract's state over *mutiple* UTxOs, *and*...
2. ... Ensure that it cannot be compromised by an attacker.

Otherwise, it would be pointless to use whatever abstractions we might come up with.

Problem

An informal statement of the problem might be the following.

> “ A smart contract's state, distributed over multiple of UTxOs, should be modified only by transactions validated by the smart contract itself. ”

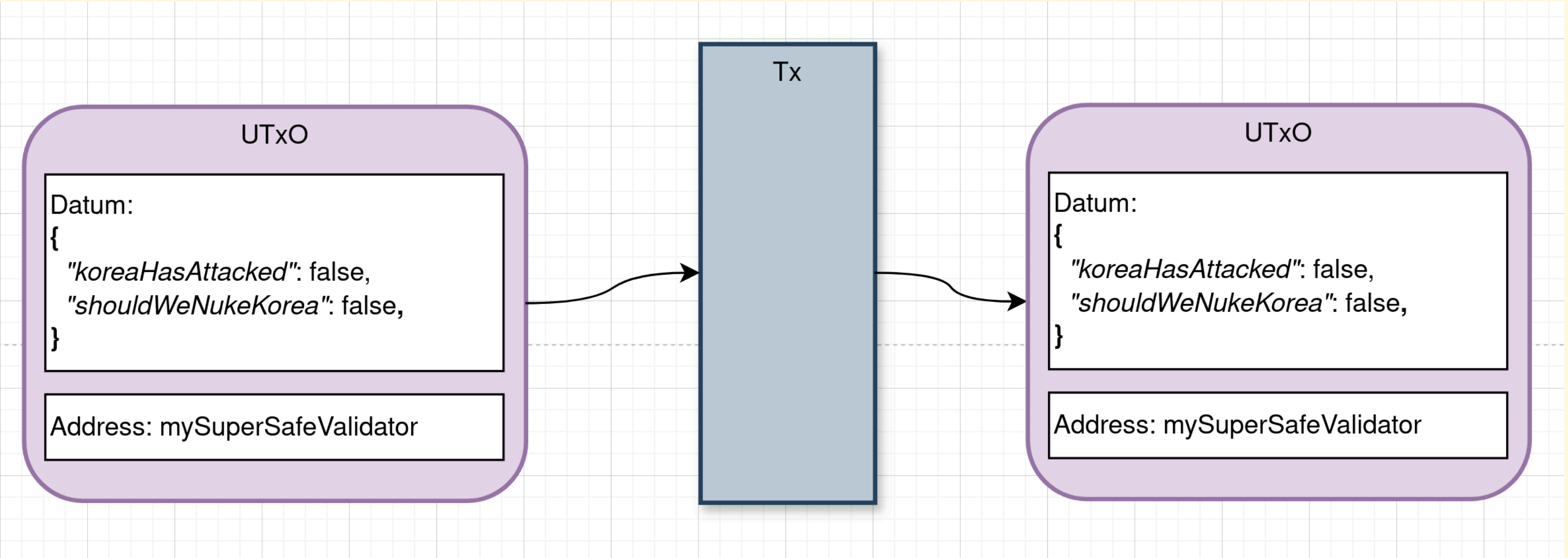
Problem

There are good news and bad news.

- **Good news**: Smart contracts (on-chain) can enforce the recipient(s) of the UTxOs being created, but...
- **Bad news**: ... They have **zero knowledge** about the sender of the UTxOs being spent.

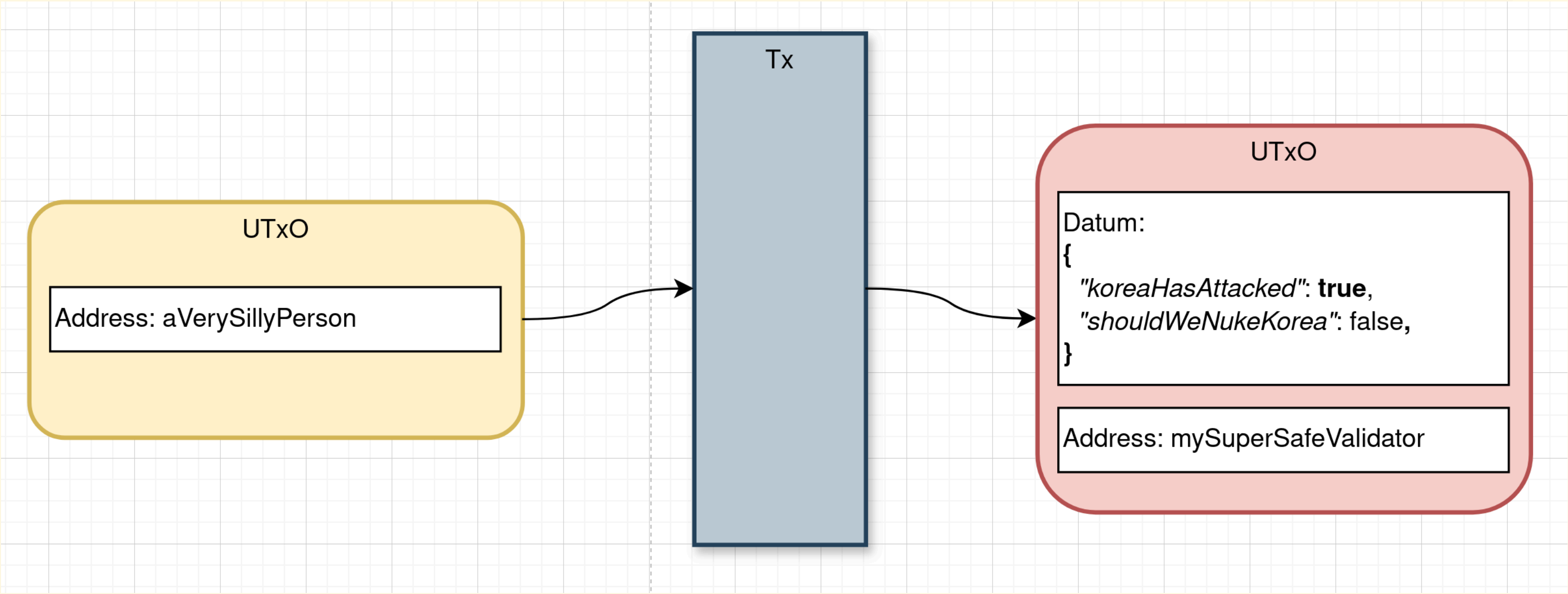
Why is that a problem?

Example: Good State



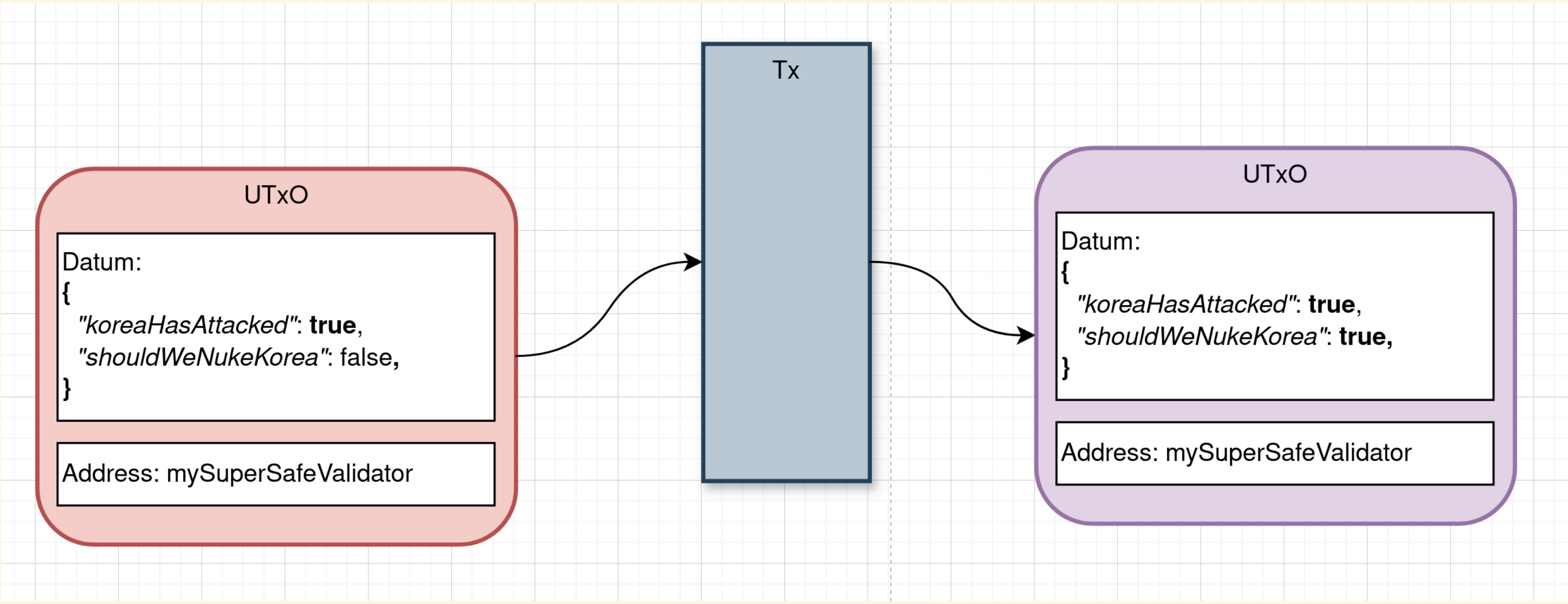
In a normal setup, a stateful smart contract would ensure that the state is propagated to itself.

Example: Attacker Setup



However, an attacker might craft a malicious piece of state and "pay" it to the smart contract. Nothing would prevent them to do so.

Example: (Very) Bad State



Now the smart contract would mindlessly use that piece of state to validate whatever transaction. **The contract's state is now compromised.**

Problem

Compromised state could be the source of other, more serious issues.

What could be worse than WW3? Well, for example:

> “ *You* could be losing money!! ”

While total thermonuclear annihilation might be somewhat tolerable and even fun, losing money is not and we must avoid that at all costs.

Solution

How can we authenticate the UTxOs that get consumed/produced by the transactions validated by our smart contract?

For example, by using a set of unique "tokens" attached to each UTxO, such that:

- They are easily recognizable by the smart contract
- They can be extended without modifying the contract's source code

Enter NFTs.

Native Tokens And NFTs

Native tokens, also called *assets* on Cardano, are (loosely) objects that represent value. Technically, ADA is a (very special) type of native token.

Native tokens are idenfied by their "asset id", of type $\mathrm{AssetId} = \mathrm{PolicyId} \times \mathrm{AssetName}$:

- $\mathrm{PolicyId} = (\mathbb{F}_{256})^{28}$ hash of the minting script;
- $\mathrm{AssetName} = (\mathbb{F}_{256})^{32}$ arbitrary 32-byte string.

Where $\mathbb{F}_q := \{0, \ldots, q-1\}$.

Fungible, Not Fungible

Two tokens are said to be *fungible* if they have the same asset id.

Example:

- If I have 2 of `("0x1", "lorenzo")`, then I have 2 tokens that **are** fungible.
- If I have 1 of `("0x1", "hammad")` and 1 of `("0x1", "lorenzo")`, the two tokens **are not** fungible.
- If I have 1 of `("0x1", "hammad")` and 1 of `("0x2", "hammad")`, the two tokens **are not** fungible.

Minting Native Tokens

Minting is the process of creating new tokens. A minting validator is just a smart contract with the following signature M:

$$M = (\mathrm{Redeemer} \times \mathrm{ScriptContext}) \to \mathbb{B}$$

Minting validators do not take a Datum as argument, because they do not spend UTxOs.

Spending UTxOs

In contrast, spending validators are smart contracts with the following signature V:

$$V = (\mathrm{Datum} \times \mathrm{Redeemer} \times \mathrm{ScriptContext}) \to \mathbb{B}$$

The $\mathrm{Redeemer}$ would be actually not necessary (there exists a second signature without it) but for all our purposes we will use redeemers.

Minting The NFTs

Let OutputReference represent an on-chain reference to an UTxO.

We declare the following functions that produce smart contracts:

- $f_{start,mint} : \text{OutputReference} \to M$
- $f_{add,mint} : M \to M$
- $f_{add,validate} : (M \times M) \to V$

Key Properties

- $o_1 \neq o_2 \iff f_{start,mint}(o_1) \neq f_{start,mint}(o_2)$
- $s_1 \neq s_2 \iff f_{add,mint}(s_1) \neq f_{add,mint}(s_2)$
- $(s_1, a_1) \neq (s_1, a_2) \iff f_{add,validate}(s_1, a_1) \neq f_{add,validate}(s_2, a_2)$

Minting The NFTs

$f_{start,mint}$ takes an $\mathrm{OutputReference}$ `o` and returns a Minting Validator that produces a single token with $\mathrm{AssetName}$ `"Auth"`.

Such script is a **one-time** minting validator, because it ensures that `o` is consumed in the transaction (which can happen only once).

Code: $f_{start,mint}$: $\mathrm{OutputReference} \rightarrow M$

```
validator(o: OutputReference) {
  fn run(_r: Redeemer, ctx: ScriptContext) -> Bool {
    // 0. The output reference is consumed by the transaction
    expect Some(_input) =
      ctx.transaction.inputs
        |> list.find(fn(input) { input.output_reference == o })
    // 1. The transaction's purpose is to mint a new token
    expect Mint(policy_id) = ctx.purpose
    // 2. There is a single NFT named "Auth" in the minted assets
    expect [(asset, amount)]: List<(AssetName, Int)> =
      ctx.transaction.mint
        |> value.from_minted_value()
        |> value.tokens(policy_id)
        |> dict.to_list()
    expect "Auth" == asset && 1 == amount
    // 3. There is a single output with the minted NFT
    expect [output] =
      ctx.transaction.outputs
        |> list.filter(
            fn(output: Output) {
              1 == quantity_of(output.value, policy_id, "Auth")
            },
          )
    expect [] =
      ctx.transaction.outputs
        |> list.filter(
            fn(output: Output) {
              1 != quantity_of(output.value, policy_id, "Auth")
            },
          )
    // 4. The minted NFT is in a UTxO with an empty list as Datum
    expect InlineDatum(datum) = output.datum
    expect []: List<AssetName> = datum
    True
  }
}
```

Code: $f_{add,validate} : (M \times M) \to V$

```
validator(s: PolicyId, am: PolicyId) {
  fn run(d: List<AssetName>, r: AssetName, ctx: ScriptContext) -> Bool {
    // 0. The script's purpose is to spend an UTxO
    expect Spend(outref): ScriptPurpose = ctx.purpose
    // 1. The script is spending the UTxO with the "Auth" NFT
    expect Some(input): Option<Input> =
      ctx.transaction.inputs |> list.at(outref.output_index)
    expect 1 == quantity_of(input.output.value, s, "Auth")
    // 2. The minting validator is involved in the Tx
    expect Some(redeemer): Option<Redeemer> =
      ctx.transaction.redeemers |> dict.get(Mint(am))
    // 3. Both the spend and minting scripts have the same Redeemer
    expect mr: AssetName = redeemer
    expect mr == r
    // 4. There is a single output with the "Auth" NFT
    expect [output] =
      ctx.transaction.outputs
        |> list.filter(
            fn(output: Output) { 1 == quantity_of(output.value, s, "Auth") },
          )
    expect [] =
      ctx.transaction.outputs
        |> list.filter(
            fn(output: Output) { 1 != quantity_of(output.value, s, "Auth") },
          )
    // 5. The Datum of the output UTxO is correctly formed
    expect InlineDatum(inline_datum) = output.datum
    expect datum: List<AssetName> = inline_datum
    let old_assets: List<AssetName> = list.unique(d)
    let new_assets: List<AssetName> = list.unique(datum)
    expect 1 == list.length(new_assets) - list.length(old_assets)
    expect [asset] = list.difference(new_assets, old_assets)
    expect asset == r
    True
  }
}
```

Code: $f_{add,mint} : M \to M$

```
validator(s: PolicyId) {
  fn run(r: AssetName, ctx: ScriptContext) -> Bool {
    // 0. The transaction's purpose is to mint a new token
    expect Mint(policy_id) = ctx.purpose
    // 1. There is a single NFT named as the Redeemer in the minted assets
    expect [(asset, amount)]: List<(AssetName, Int)> =
      ctx.transaction.mint
        |> value.from_minted_value()
        |> value.tokens(policy_id)
        |> dict.to_list()
    expect r == asset && 1 == amount
    // 2. There is a single output with the minted NFT
    expect [_] =
      ctx.transaction.outputs
        |> list.filter(
             fn(output: Output) { 1 == quantity_of(output.value, policy_id, r) },
           )
    expect [] =
      ctx.transaction.outputs
        |> list.filter(
             fn(output: Output) { 1 != quantity_of(output.value, policy_id, r) },
           )
    // 3. There is a single output with the "Auth" NFT
    expect [_] =
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        |> list.filter(
             fn(output: Output) { 1 == quantity_of(output.value, s, "Auth") },
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    expect [] =
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        |> list.filter(
             fn(output: Output) { 1 != quantity_of(output.value, s, "Auth") },
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    // 4. There is a single input with the "Auth" NFT
    expect [_] =
      ctx.transaction.inputs
        |> list.filter(
             fn(input: Input) { 1 == quantity_of(input.output.value, s, "Auth") },
           )
    expect [] =
      ctx.transaction.inputs
        |> list.filter(
             fn(input: Input) { 1 != quantity_of(input.output.value, s, "Auth") },
           )
    True
  }
}
```

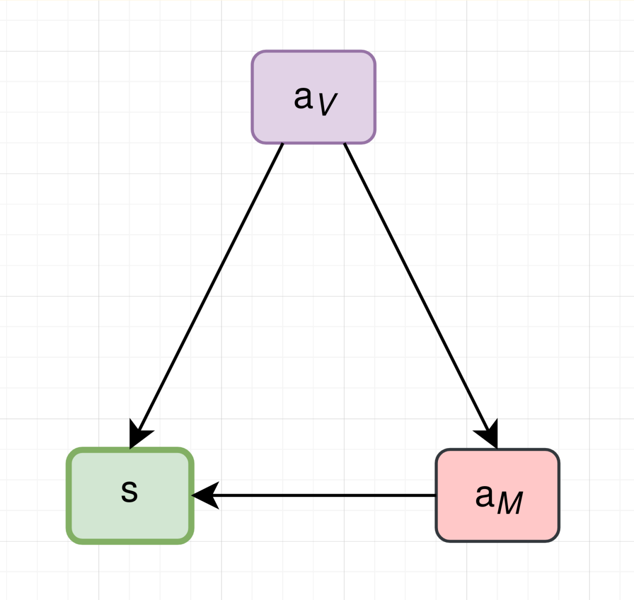
Minting The NFTs

In particular, let $o : \mathrm{OutputReference}$.

We build the following three contracts that will take part in the generation of our NFTs:

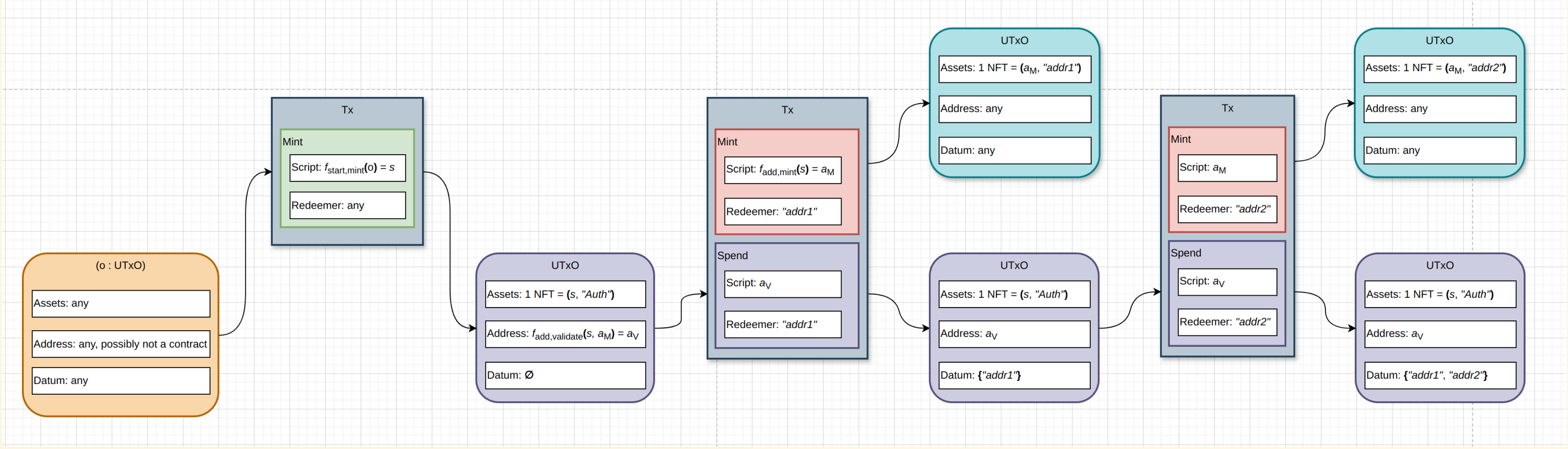
- $(s : M) = f_{start,mint}(o)$
- $(a_M : M) = f_{add,mint}(s)$
- $(a_V : V) = f_{add,validate}(s, a_M)$

Dependencies



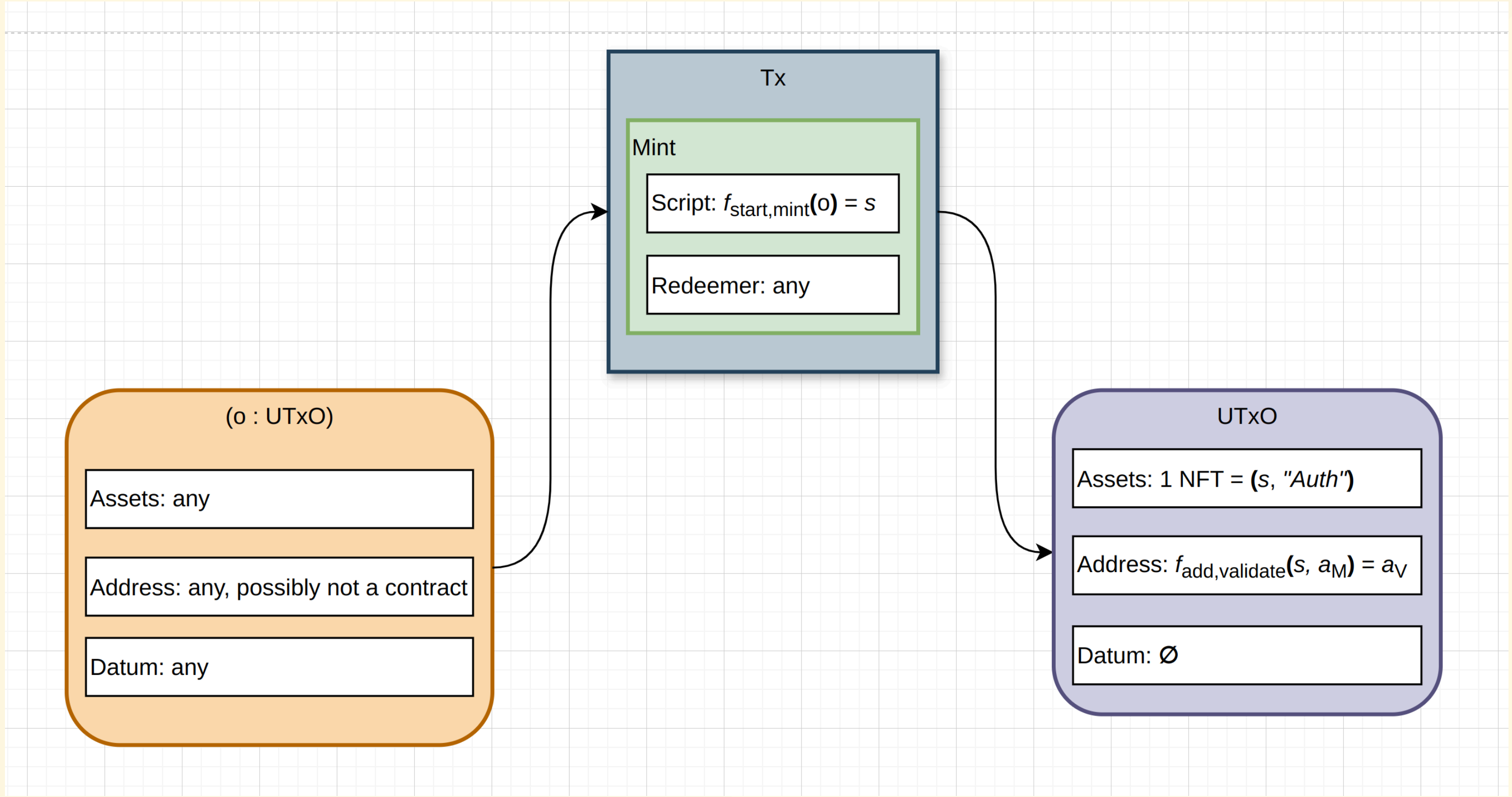
NB: "$\rightarrow$" means "depends on".

Example: Full Example

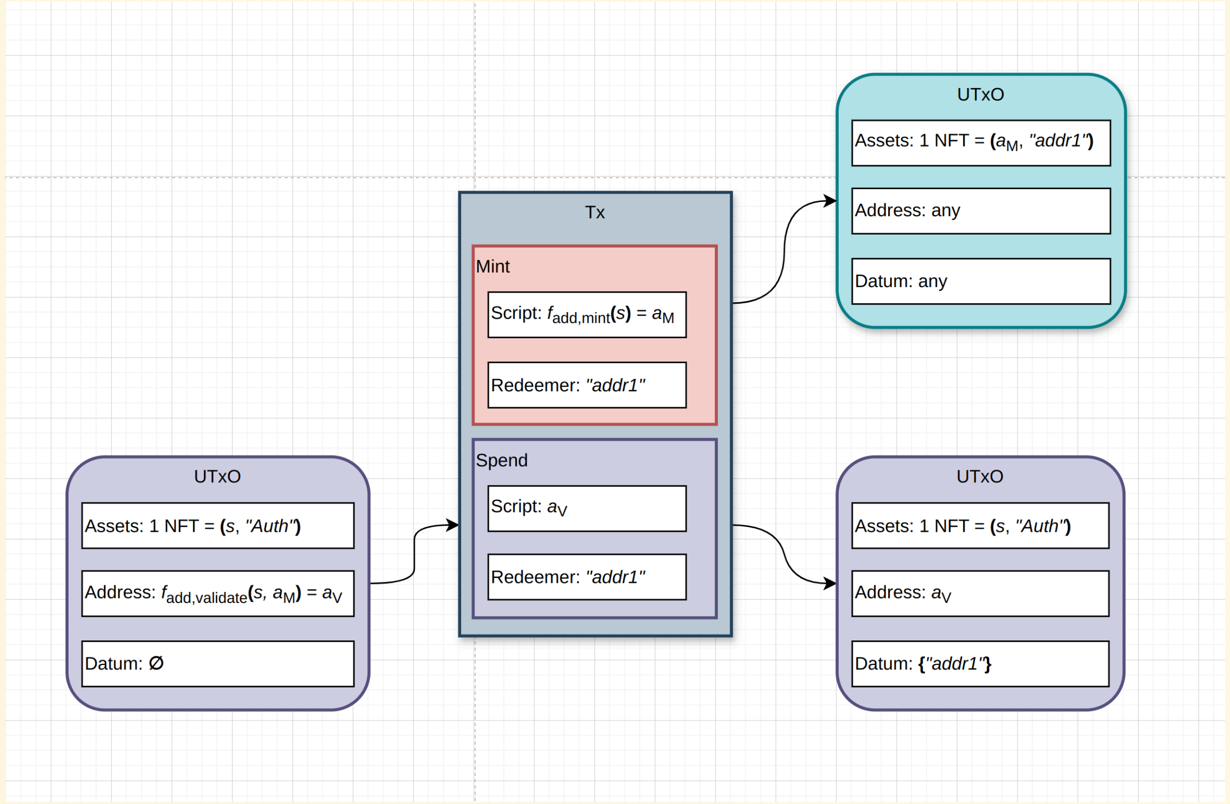


NB Cyan UTxOs contain the minted NFTs that we will use to authenticate our smart contract's state.

Example: Start The Minting Process



Example: Minting The 1st NFT



Example: Minting The 2nd NFT