Automata for smart contracts...and more

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joint work with

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A tutorial @ FORTE 2025, Lille

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What's up doc?

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Prologue · · · · · · · · · · · · · · · · An inspiring initiative

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Epilogue · Work in progress

– Prologue –

[An inspiring initiative]

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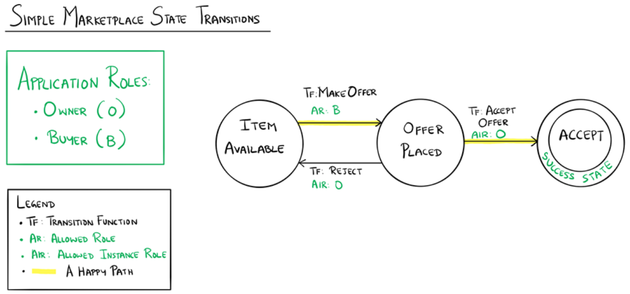
A nice sketch! [3, 4]

A smart contract among Owners and Buyers



initially buyers can make offers
then
- **either** an owner can accept an offer and the protocol stops
- **or** the offer is rejected and the protocol restarts

A nice sketch! [3, 4]
A smart contract among Owners and Buyers
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What did we just see?

A smart contract looks like

a choreographic model

global specifications determine the enabled actions along the evolution of the protocol

a typestate

In OOP, "can reflects how the legal operations on imperative objects can change at runtime as their internal state changes." [2]

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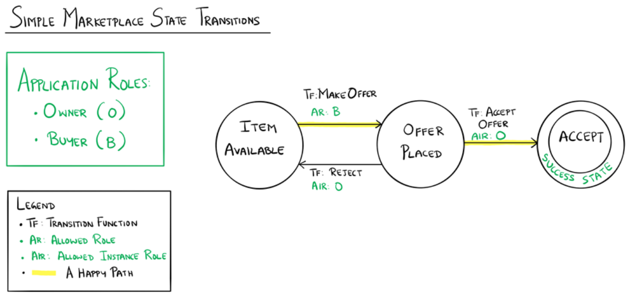

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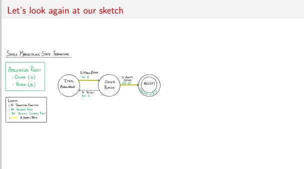

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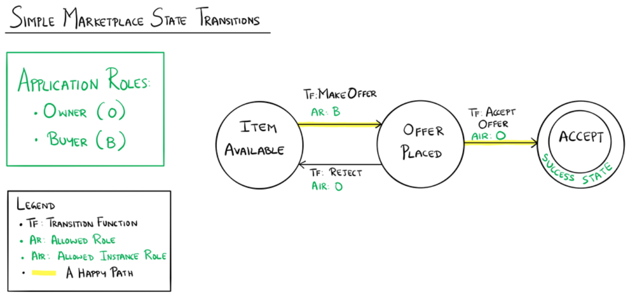


but...

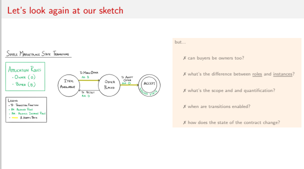
✗ can buyers be owners too?

✗ what's the difference between <u>roles</u> and <u>instances</u>?

✗ what's the scope and and quantification?

✗ when are transitions enabled?

✗ how does the state of the contract change?



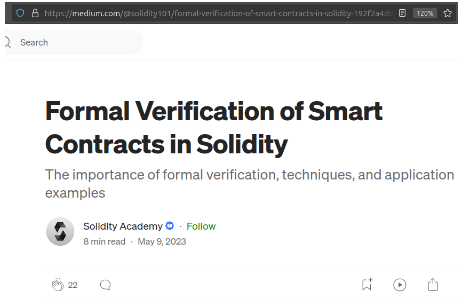
ok

ok

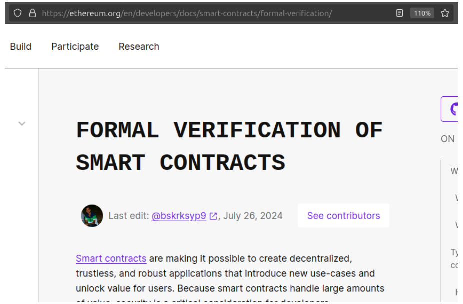
from [4]: "The transitions between the Item Available and the Offer Placed states can continue until the owner is satisfied with the offer made." so, after a rejection, the new offer must be from the original buyer or a new one?

ok

should the price of the item remain unchanged when the owner invokes the Reject?



https://medium.com/@solidity101/formal-verification-of-smart-contracts-in-solidity-192f2a4d0abd



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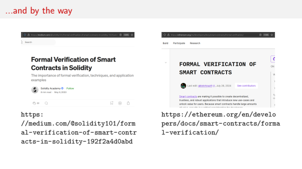

Let's go formal!

Our first attempt was to reuse "our toolboxes", but

- ✗ roles with multiple instances
- ✗ instances with many roles
- ✗ do the known notion of well-formedness make sense?
- ✗ data-awareness is crucial

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– Act I –

[A coordination framework]

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Basic concepts and notation

Participants $\mathsf{p}, \mathsf{p}', \ldots$

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In every assignment $\mathsf{c.x} := \mathsf{e}$ data variables occurring in e must have the old qualifier to refer to their value before the assignments.

We adapt the mechanism based on the old keyword from the Eiffel language [**?**] which, as explained in [**?**] is necessary to render assignments into logical formulae since e.g., $x = x + 1 \Leftrightarrow$ False. This will be used in **??**.

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DAFSMs are finite-state machines whose transitions are decorated with specific labels

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$$\xrightarrow{\nu\ p : R \triangleright \mathsf{start}(c, \cdots c.x_i : T_i \cdots)\ \{\cdots c.x_i := e_i \cdots\}} \circ$$

initial state of the contract c freshly created by p with state variables $c.x_i$ initialised by the assignments $c.x_i := e_i$

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each state variable is declared and initialises with type-consistent expressions

start is a “build-in” function name

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$$\circ \xrightarrow{\{\mathsf{g}\}\ \pi \triangleright \mathsf{f}(\cdots \mathsf{y}_i : T_i \cdots)\ B} \circ$$

where g (ie a boolean expression) is a guard and

$$\pi \ ::= \ \nu\ \mathsf{p} : \mathsf{R} \ \mid \ \mathsf{any}\ \mathsf{p} : \mathsf{R} \ \mid \ \mathsf{p}$$

is a qualified participant invoking operation f with parameters $\mathsf{c}.\mathsf{y}_\mathsf{i}$

state variables are reassigned according to B if the invocation is successful

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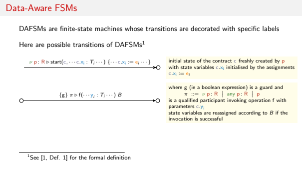

g predicates over state variables and formal parameters; guards have to be satisfied in order for the invocation to be enabled: an invocation that makes the guard false is rejected

$\nu\ \mathsf{p} : \mathsf{R}$ specifies that p must be a fresh participant with role R
any $\mathsf{p} : \mathsf{R}$ qualifies p as an existing participant with role R
p we refer to a participant in the scope of a binder
invocations from non-suitable callers are rejected

the variables occurring in the right-hand side of assignments in B are either state variables or parameters of the invocation

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$$\bigcirc \xrightarrow{\ell} \circledcirc$$

accepting states denoted as usual

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Exercise: modelling

Give a DAFSM for the following contract protocol:

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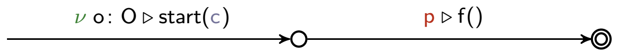
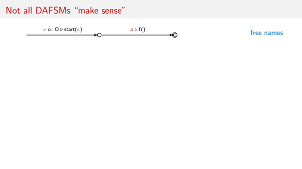
Give a DAFSM for the following contract protocol:

let them play with qualified participants

Not all DAFSMs "make sense"



free names



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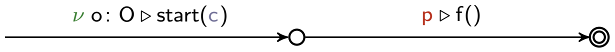

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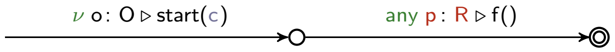
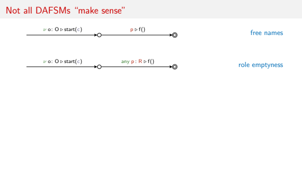


role emptyness



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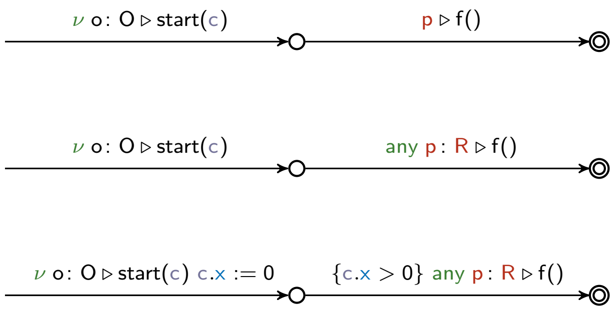

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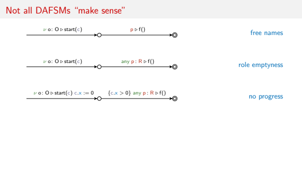

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$$\xrightarrow{\nu\ \mathsf{o} : \mathsf{O} \triangleright \mathsf{start}(\mathsf{c})} \bigcirc \xrightarrow{\mathsf{p} \triangleright \mathsf{f}()} \circledcirc$$

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$$\xrightarrow{\nu\ \mathsf{o} : \mathsf{O} \triangleright \mathsf{start}(\mathsf{c})\ \mathsf{c.x} := 0} \bigcirc \xrightarrow{\{\mathsf{c.x} > 0\}\ \mathsf{any}\ \mathsf{p} : \mathsf{R} \triangleright \mathsf{f}()} \circledcirc$$

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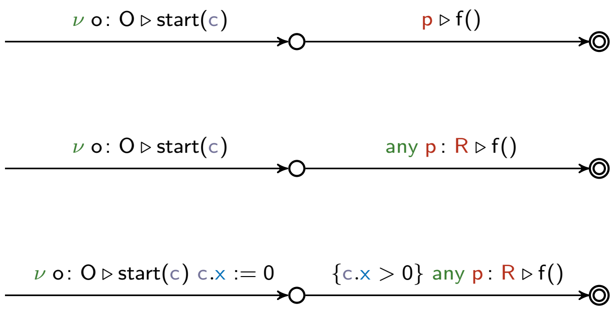

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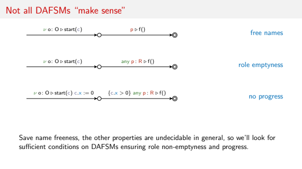
Save name freeness, the other properties are undecidable in general, so we’ll look for sufficient conditions on DAFSMs ensuring role non-emptyness and progress.



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The occurrence of p is <u>bound</u> in a path $\sigma \circ \xrightarrow{\{g\}\ p \triangleright f(\cdots y_i : T_i \cdots)\ B} \circ \sigma'$ if p is bound in a transition of σ

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A DAFSM is closed if all occurrences of participant variables are bound in the paths of the DAFSM they occur on

Roles non-emptyness

A transition $\circ \xrightarrow{\{g\}\ \pi \triangleright f(\cdots y_i : T_i \cdots)\ B} \circ$ <u>expands</u> role R if $\pi = \nu\ p : R$ or there is i s.t. $y_i = p$ and $T_i = R$

Role R is <u>expanded</u> in a path $\sigma \xrightarrow{\{g\}\ \text{any}\ p : R \triangleright f(\cdots y_i : T_i \cdots)\ B} \sigma'$ if a transition in σ expands R

A DAFSM <u>expands</u> R if all its paths expand R and is <u>(strongly) empty-role free</u> if it expands all its roles

Roles non-emptyness

A transition $\circ \xrightarrow{\{g\}\ \pi \triangleright f(\cdots y_i : T_i \cdots)\ B} \circ$ expands role R if $\pi = \nu\ p : R$ or there is i s.t. $y_i = p$ and $T_i = R$

Role R is expanded in a path $\sigma \xrightarrow{\{g\}\ \text{any}\ p : R \triangleright f(\cdots y_i : T_i \cdots)\ B} \sigma'$ if a transition in σ expands R

A DAFSM expands R if all its paths expand R and is (strongly) empty-role free if it expands all its roles

Progress

A DAFSM with state variables $X = \{\mathsf{c}.\mathsf{x}_1, \ldots, \mathsf{c}.\mathsf{x}_\mathsf{n}\}$ is consistent if it is closed and the following implication holds for each transition $\circ \xrightarrow{\{\mathsf{g}\}\ \pi \triangleright \mathsf{f}(\cdots \mathsf{y}_i : T_i \cdots)\ B} \textcircled{s}$

$$\forall(\mathsf{c}.\mathsf{x}, \mathsf{old}\ \mathsf{c}.\mathsf{x})_{\mathsf{c}.\mathsf{x} \in X}\ \exists \ldots, \mathsf{y}_i, \ldots\ :\ (\mathsf{g}\{\mathsf{old}\ \mathsf{c}.\mathsf{x}/\mathsf{c}.\mathsf{x}\}_{\mathsf{c}.\mathsf{x} \in X} \wedge \mathsf{g}_B) \implies \mathsf{g}_\mathsf{s} \qquad \text{where}$$

$$\mathsf{g}_\mathsf{s} = \begin{cases} \text{True} & \text{if s is accepting} \\ \text{the disjunction of guards of the outgoing transitions of s} & \text{otw} \end{cases}$$

$$\mathsf{g}_B = \bigwedge_{(\mathsf{c}.\mathsf{x} := \mathsf{e}) \in B} \mathsf{c}.\mathsf{x} = \mathsf{e} \ \wedge \bigwedge_{\mathsf{c}.\mathsf{x} \notin B} \mathsf{c}.\mathsf{x} = \mathsf{old}\ \mathsf{c}.\mathsf{x}$$

$$\text{with} \quad \mathsf{c}.\mathsf{x} \notin B \iff (\mathsf{c}.\mathsf{y} := \mathsf{e}) \in B \implies \mathsf{x} \neq \mathsf{y} \quad \text{and} \quad \mathsf{old}\ \mathsf{c}.\mathsf{x} \text{does not occur in } \mathsf{e}$$

Progress
A DAFSM with state variables $X = \{\mathsf{c}.\mathsf{x}_1, \ldots, \mathsf{c}.\mathsf{x}_\mathsf{n}\}$ is consistent if it is closed and the following implication holds for each transition $\circ \xrightarrow{\{\mathsf{g}\}\ \pi \triangleright \mathsf{f}(\cdots \mathsf{y}_i : T_i \cdots)\ B} \textcircled{s}$
$\forall(\mathsf{c}.\mathsf{x}, \mathsf{old}\ \mathsf{c}.\mathsf{x})_{\mathsf{c}.\mathsf{x} \in X}\ \exists \ldots, \mathsf{y}_i, \ldots\ :\ (\mathsf{g}\{\mathsf{old}\ \mathsf{c}.\mathsf{x}/\mathsf{c}.\mathsf{x}\}_{\mathsf{c}.\mathsf{x} \in X} \wedge \mathsf{g}_B) \implies \mathsf{g}_\mathsf{s}$ where
$\mathsf{g}_\mathsf{s} = \begin{cases} \text{True} & \text{if s is accepting} \\ \text{the disjunction of guards of the outgoing transitions of s} & \text{otw} \end{cases}$
$\mathsf{g}_B = \bigwedge_{(\mathsf{c}.\mathsf{x} := \mathsf{e}) \in B} \mathsf{c}.\mathsf{x} = \mathsf{e} \ \wedge \bigwedge_{\mathsf{c}.\mathsf{x} \notin B} \mathsf{c}.\mathsf{x} = \mathsf{old}\ \mathsf{c}.\mathsf{x}$
with $\mathsf{c}.\mathsf{x} \notin B \iff (\mathsf{c}.\mathsf{y} := \mathsf{e}) \in B \implies \mathsf{x} \neq \mathsf{y}$ and $\mathsf{old}\ \mathsf{c}.\mathsf{x}$does not occur in e

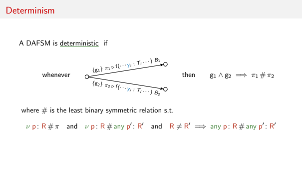
Determinism

A DAFSM is deterministic if

whenever
$$\begin{tikzcd} & \circ \\ \circ \arrow[ur, "\{g_1\}\ \pi_1 \triangleright f(\cdots y_i : T_i \cdots)\ B_1"] \arrow[dr, "\{g_2\}\ \pi_2 \triangleright f(\cdots y_i : T_i \cdots)\ B_2"'] & \\ & \circ \end{tikzcd}$$
then $g_1 \wedge g_2 \implies \pi_1 \# \pi_2$

where $\#$ is the least binary symmetric relation s.t.

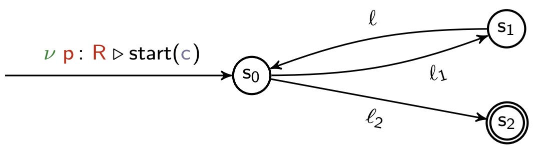
$\nu\ p : R \# \pi$ and $\nu\ p : R \# \text{any } p' : R'$ and $R \neq R' \implies \text{any } p : R \# \text{any } p' : R'$



transitions from the same source state and calling the same function

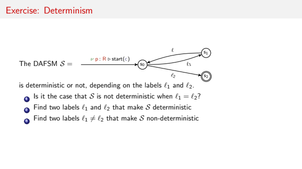
Exercise: Determinism

The DAFSM $\mathcal{S} =$



is deterministic or not, depending on the labels ℓ_1 and ℓ_2.

1. Is it the case that $\mathcal{S}$ is not deterministic when $\ell_1 = \ell_2$?
2. Find two labels ℓ_1 and ℓ_2 that make $\mathcal{S}$ deterministic
3. Find two labels $\ell_1 \neq \ell_2$ that make $\mathcal{S}$ non-deterministic



1. no: eg for $\ell_1 = \ell_2 = \nu$ p : R $\mathcal{S}$ is deterministic
2. $\ell_1 = \ell_2 = \nu$ p : R ▷ f($\cdots$ y_i : T_i $\cdots$) make $\mathcal{S}$ deterministic because the next state is unambiguously determined by the caller which is fresh on both transitions
3. $\ell_1 = \{x \leq 10\}$ p ▷ f(x : Int) and $\ell_2 = \{x \geq 10\}$ p ▷ f(x : Int) make $\mathcal{S}$ non-deterministic because the guards of ℓ_1 and of ℓ_2 are not disjoint therefore the next state is not determined by the caller of c.g. because guard $x \leq 10$ leading to s_1 and guard $x > 10$ leading to s_2 are disjoint; therefore the next state is determined by the value of the parameter x, and every value enables at most one transition.

Also, taking ℓ_1 as in the latter case and $\ell_2 = \{x \geq 10\}$ o ▷ c.g(x : Int) would make $\mathcal{S}$ non-deterministic

Well-formedness

A DAFSM is well-formed when

- it is empty-role free
- it is consistent, and
- it is deterministic

Well-formedness
A DAFSM is well-formed when
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– Act II –

[A tool]

– Act II –
[A tool]

– Act III –

[A little exercise]

– Act III –
[A little exercise]

– Epilogue –

[Work in progress]

– Epilogue –

[Work in progress]

Thank you

2025-01-06

Automata for smart contracts...and more

References I

[1] J. Afonso, E. Konjoh Selabi, M. Murgia, A. Ravara, and E. Tuosto. TRAC: A tool for data-aware coordination - (with an application to smart contracts). In I. Castellani and F. Tiezzi, editors, *Coordination Models and Languages - 26th IFIP WG 6.1 International Conference, COORDINATION 2024, Held as Part of the 19th International Federated Conference on Distributed Computing Techniques, DisCoTec 2024, Groningen, The Netherlands, June 17-21, 2024, Proceedings*, volume 14676 of *Lecture Notes in Computer Science*, pages 239–257. Springer, 2024.

[2] R. Garcia, E. Tanter, R. Wolff, and J. Aldrich. Foundations of typestate-oriented programming. *ACM Trans. Program. Lang. Syst.*, 36(4), Oct. 2014.

[3] Microsoft. The blockchain workbench. https://github.com/Azure-Samples/blockchain/tree/master/blockchain-workbench, 2019.

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[4] Microsoft. Simple marketplace sample application for azure blockchain workbench. https://github.com/Azure-Samples/blockchain/tree/master/blockchain-workbench/application-and-smart-contract-samples/simple-marketplace, 2019.