A Choreographic View of Smart Contracts

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What's up doc?

What's up doc?

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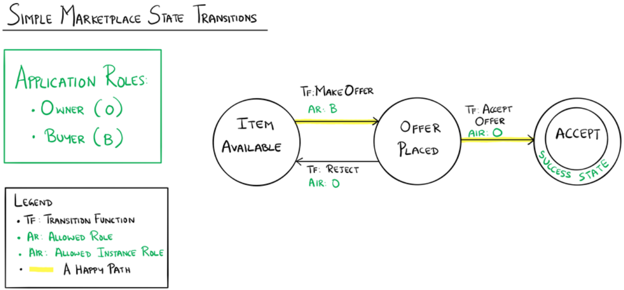
– Prologue –

[An inspiring initiative]

A nice sketch! [6, 7]

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

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." [3]

A new coordination model

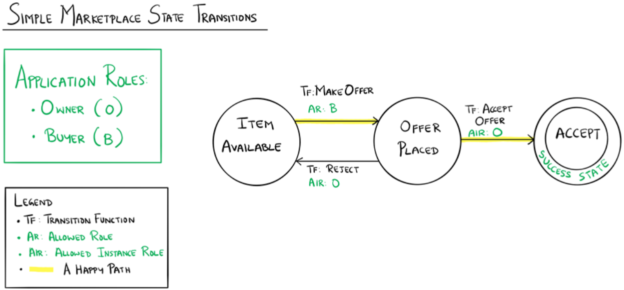
So, we saw an interesting model where

distributed components coordinate through a global specification

which specifies how actions are enabled along the computation

"without forcing" components to be cooperative!

Let's look at our sketch again



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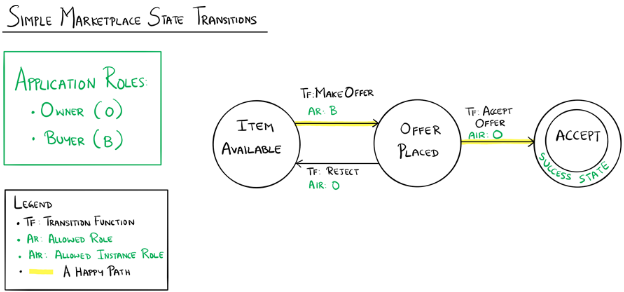

but…

✗ what's the difference between roles and instances?

✗ can buyers be owners too?

✗ what's the scope of quantifications?

✗ when are transitions enabled?

✗ how does the state of the contract change?

Let's go formal!

Our first attempt was to "look for into our toolbox", but

- ✗ are known notions of well-formedness suitable?
- ✗ data-awareness is crucial
- ✓ we got roles okay, but
- ✗ limitations on instances of roles
- ✗ instances can have one role only

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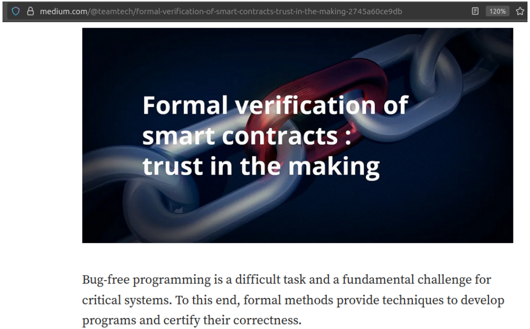
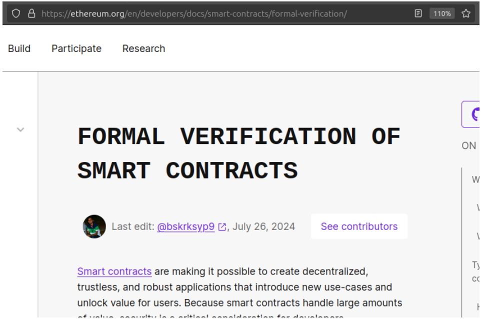
- ✗ instances can have one role only

So we had to came up with some new behavioural types.

...and by the way





https://medium.com/@teamtech/formal-verification-of-smart-contracts-trust-in-the-making-2745a60ce9db

https://ethereum.org/en/developers/docs/smart-contracts/formal-verification/

– Act I –

[A coordination framework]

Basic concepts and notation

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

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$u := e$ is an assignment which updates the state variable u to a pure expression e on
- function parameters
- state variables u or old u (representing the value of u before the assignment) [4, 5]

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- function parameters
- state variables u or old u (representing the value of u before the assignment) [4, 5]

$A, A', \ldots$ range over finite sets of assignments where each variable can be assigned at most once

Data-Aware FSMs

A DAFSM c on roles $R_1, \dots R_m$ and state variables $u_1, \dots, u_n$ is a finite-state machine "instantiated" by a participant p whose transitions are decorated as follows[1]

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$$\xrightarrow{\{\gamma\}\ \text{new R p} \triangleright \text{start}(c, \cdots, T_i\ x_i, \cdots)\ \{\cdots u_j := e_j \cdots\}} \bigcirc$$

c is freshly created by p which also initialises state variables u_j with expressions e_j which are built on state variables and parameters x_i

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$$\bigcirc \xrightarrow{\{\gamma\}\ \pi \triangleright \mathsf{f}(\cdots, T_i\ x_i, \cdots)\ \{A\}} \bigcirc$$

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

$$\pi \ ::= \ \mathsf{new}\ R\ p \ \big|\ \mathsf{any}\ R\ p \ \big|\ p$$

is a qualified participant calling f with parameters x_i state variables are reassigned according to A if the invocation is successful

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

accepting states are denoted as usual

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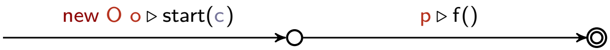
Exercise: modelling

Give a DAFSM for the protocol on slide 7 resolving the ambiguities discussed there.

Not all DAFSMs “make sense”



names’ freeness

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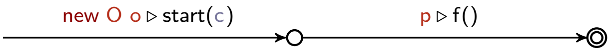

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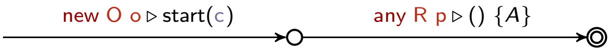

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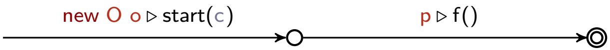

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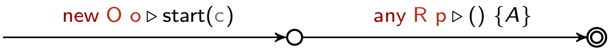

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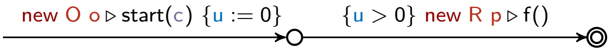

no progress

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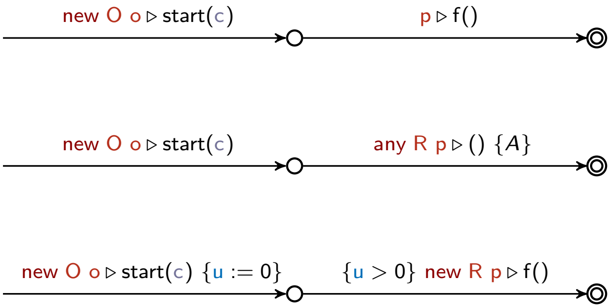

names’ freeness

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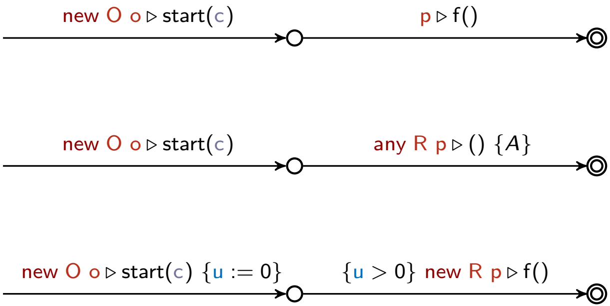

names' freeness

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no progress

Save names' freeness, the other properties are undecidable in general, so we'll look for sufficient conditions to rule out nonsensical DAFSMs

Closed DAFSMs

Binders: parameter declarations in function calls, new R p, and any R p

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p is bound in $\bigcirc \xrightarrow{\{\gamma\}\ \pi \triangleright \mathsf{f}(\cdots, T_i\ \mathsf{x}_i, \cdots)\ \{A\}} \bigcirc$ if, for some role R,

$\pi =$ new R p or $\pi =$ any R p or there is i s.t. $\mathsf{x}_i =$ p and $T_i =$ R

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The occurrence of p is bound in a path

$$\sigma \quad \bigcirc \xrightarrow{\{\gamma\}\ \mathsf{p} \triangleright \mathsf{f}(\cdots)\ \{A\}} \bigcirc \cdots$$

if p is bound in a transition of σ

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$$\pi = \text{new R p} \quad \text{or} \quad \pi = \text{any R p} \quad \text{or} \quad \text{there is } i \text{ s.t. } \mathsf{x}_i = \mathsf{p} \text{ and } T_i = \mathsf{R}$$

The occurrence of p is bound in a path

$$\sigma \quad \bigcirc \xrightarrow{\{\gamma\}\ \mathsf{p} \triangleright \mathsf{f}(\cdots)\ \{A\}} \bigcirc \quad \cdots$$

if p is bound in a transition of σ

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

Role emptyness

A transition $\bigcirc \xrightarrow{\{\gamma\}\ \pi \triangleright \mathsf{f}(\cdots,\, T_i\ \mathsf{x}_i, \cdots)\ \{A\}} \bigcirc$ expands role R if
$\pi =$ new R p or there is i s.t. $\mathsf{x}_i =$ p and $T_i =$ R

Role R is expanded in a path

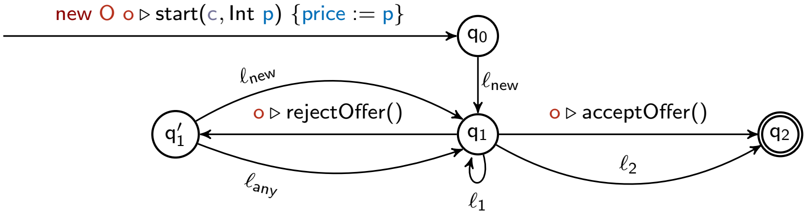
$$\sigma \quad \bigcirc \xrightarrow{\{\gamma\}\ \mathsf{any\ R\ p} \triangleright \mathsf{f}(\cdots)\ \{A\}} \bigcirc \quad \cdots$$

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

Exercise: Role emptyness

Is the DAFSM below empty-role free?



where

$\ell_{\text{new}} = \{\text{newOffer} > 0\}$ new B b ▷ makeOffer(Int newOffer) {offer := newOffer},

$\ell_{\text{any}} = \{\text{newOffer} > 0\}$ any B b ▷ makeOffer(Int newOffer) {offer := newOffer},

$\ell_1 =$ new P p ▷ join()

and $\ell_2 = \{\text{p} > \text{price}\}$ any P p ▷ buy(Int p) .

Progress

A DAFSM with state variables $u_1, \ldots, u_n$ is consistent if

for each $\bigcirc \xrightarrow{\{\gamma\}\ \pi \triangleright \mathsf{f}(\cdots, T_i\ x_i, \cdots)\ \{A\}} (s)$

$$\forall_U \exists_X \left(\gamma\{\text{old } u_1, \ldots, \text{old } u_n / u_1, \ldots, u_n\} \wedge \gamma_A \implies \bigvee_{1 \le j \le m} \exists_{Y_j} \gamma_j\right) \text{ is satisfiable}$$

where

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where

$$U = \{\mathsf{u}_i, \mathsf{old}\ \mathsf{u}_i\}_{1 \le i \le n}$$

$$X = \{\mathsf{x} \mid \exists i\ :\ \mathsf{x} = \mathsf{x}_i\}$$

$$\gamma_A = \bigwedge_{\mathsf{u} := \mathsf{e} \in A} \mathsf{u} = \mathsf{e}\ \wedge\ \bigwedge_{\mathsf{u} \notin A} \mathsf{u} = \mathsf{old}\ \mathsf{u}$$

$$Y_j = \{\mathsf{x} \mid \mathsf{x} \text{ is a parameter of the } j^{\text{th}} \text{ outgoing transition of } \mathsf{s}\}$$

$$\gamma_j = \begin{cases} \text{the guard of the } j^{\text{th}} \text{ outgoing transitions of } \mathsf{s} & \text{if } \mathsf{s} \text{ not accepting} \\ \text{True} & \text{otherwise} \end{cases}$$

Progress

A DAFSM with state variables $u_1, \ldots, u_n$ is consistent if

for each $\bigcirc \xrightarrow{\{\gamma\}\ \pi \triangleright f(\cdots, T_i\ x_i, \cdots)\ \{A\}} \text{(s)}$

$$\forall_U \exists_X \left(\gamma\{\text{old } u_1, \ldots, \text{old } u_n / u_1, \ldots, u_n\} \ \wedge\ \gamma_A \implies \bigvee_{1 \le j \le m} \exists_{Y_j} \gamma_j\right) \text{ is satisfiable}$$

and $\xrightarrow{\{\gamma\}\ \pi \triangleright \text{start}(\cdots, T_i\ x_i, \cdots)\ \{A\}} \text{(s)}$ is such that $\exists_X \gamma$ is satisfiable

where

$$U = \{u_i, \text{old } u_i\}_{1 \le i \le n}$$

$$X = \{x \mid \exists i\ :\ x = x_i\}$$

$$\gamma_A = \bigwedge_{u := e \in A} u = e \ \wedge\ \bigwedge_{u \notin A} u = \text{old } u$$

$$Y_j = \{x \mid x \text{ is a parameter of the } j^{\text{th}} \text{ outgoing transition of s}\}$$

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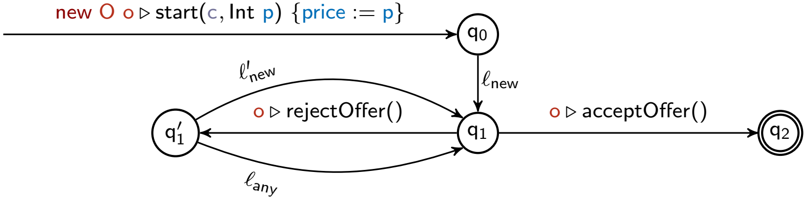
Exercise: Consistency

Is the DAFSM below consistent?



where

ℓ_{new} = {newOffer > 0} new B b ▷ makeOffer(Int newOffer) {offer := newOffer},
ℓ'_{new} = {newOffer ≥ $price * 1.05$} new B b ▷ makeOffer(Int newOffer) {offer := newOffer}, and
ℓ_{any} = {newOffer ≥ $price * 1.05$} any B b ▷ makeOffer(Int newOffer) {offer := newOffer}

Determinism

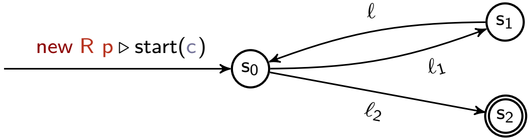
Let $\_\#\_$ be the least binary symmetric relation s.t.

$$\mathsf{new}\ \mathsf{R}\ \mathsf{p} \# \pi \quad \text{and} \quad \mathsf{new}\ \mathsf{R}\ \mathsf{p} \# \mathsf{any}\ \mathsf{R}'\ \mathsf{p}' \quad \text{and} \quad \mathsf{R} \neq \mathsf{R}' \implies \mathsf{any}\ \mathsf{R}\ \mathsf{p} \# \mathsf{any}\ \mathsf{R}'\ \mathsf{p}'$$

A DAFSM is deterministic if

$$\text{whenever} \quad \begin{tikzcd} & \circ \\ \circ \arrow[ur, "\{\gamma_1\}\ \pi_1 \triangleright \mathsf{f}(\cdots)\ \{A_1\}"] \arrow[dr, "\{\gamma_2\}\ \pi_2 \triangleright \mathsf{f}(\cdots)\ \{A_2\}"'] & \\ & \circ \end{tikzcd} \quad \text{then} \quad \gamma_1 \wedge \gamma_2 \implies \pi_1 \# \pi_2$$

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 whenever $\ell_1 = \ell_2$?
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

Well-formedness

A DAFSM is well-formed when it is

closed,

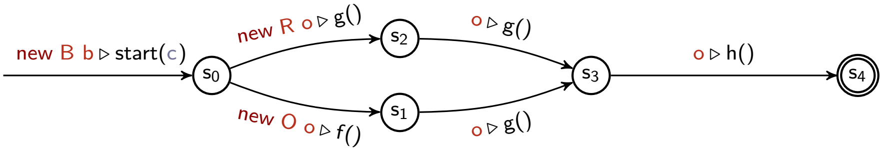
empty-role free,

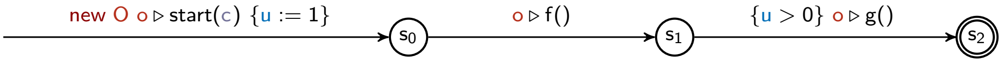
consistent, and

deterministic

Exercise: Well-formedness

Which of the following DAFSM is well-formed?





– Act II –

[A tool]

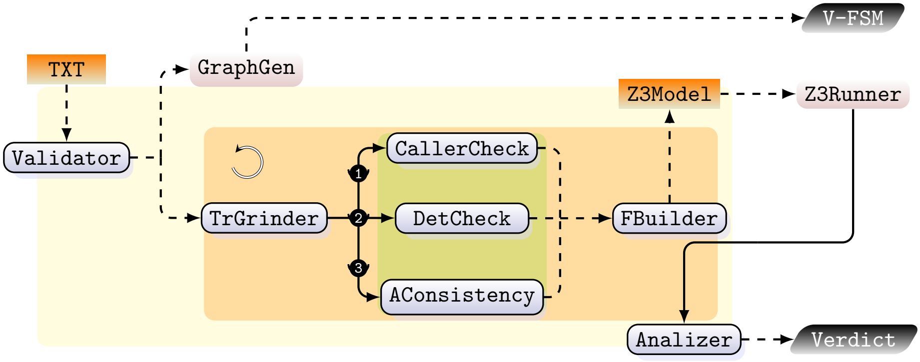
Verification

Checking well-formedness by hand is laborious and cumbersome (and boring)

So we implemented **TRAC**, which

- ✓ features a DSL to specify DAFSMs
- ✓ verifies well-formedness (relying on the SMT solver Z3)
- ✓ it's efficient enough
- ✗ but cannot handle roles and inter-contract interactions

The architecture of **TRAC**



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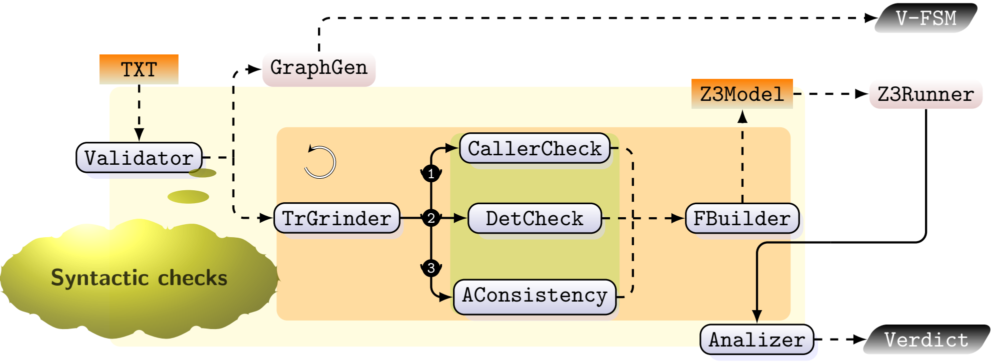

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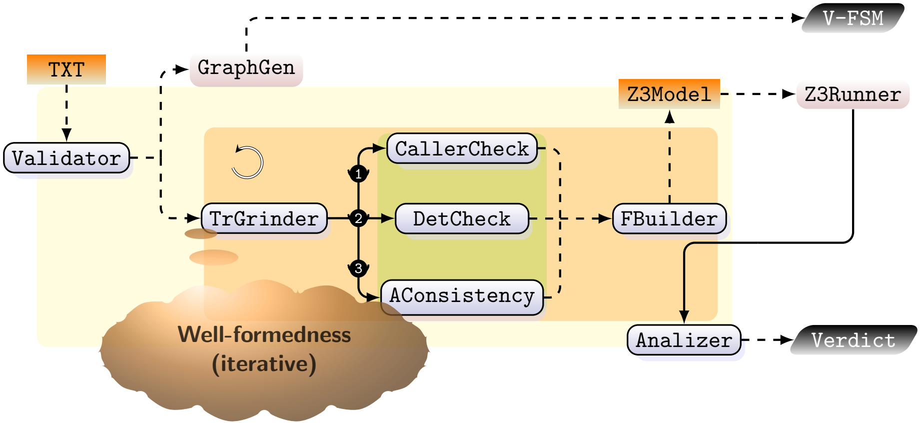

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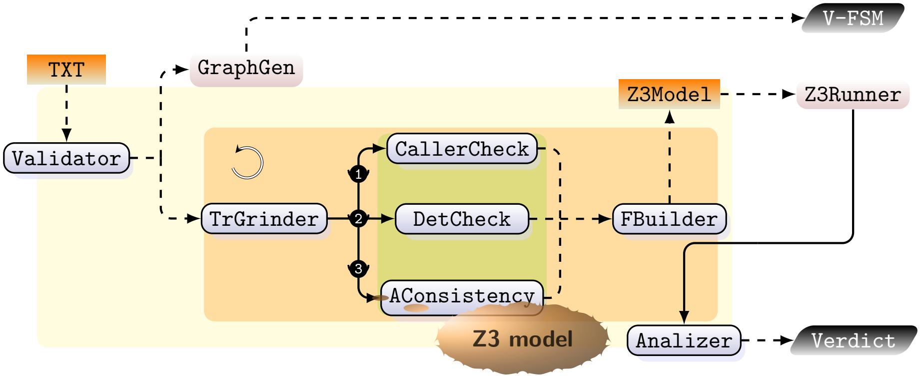

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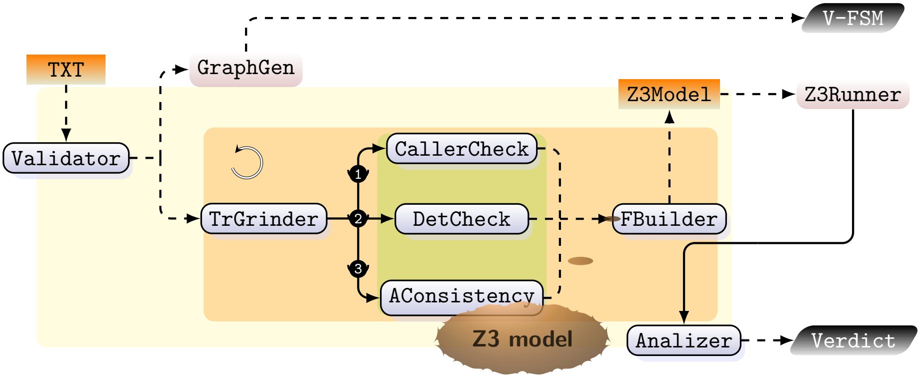

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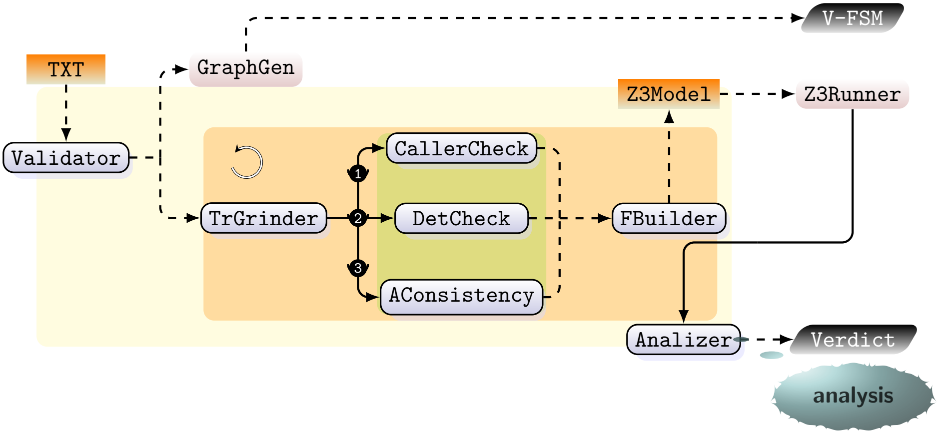

Installation

Dependencies: GraphViz and Python 3.6 or later

Detailed instructions in the `README.md` file at
`https://github.com/loctet/TRAC/tree/TRAC_v1/`

Concrete syntax (I)

$\langle pars \rangle \ ::= \ \varepsilon \ \mid \ \langle dcl \rangle (, \langle dcl \rangle)^\star$ $\qquad\qquad$ $\langle dcl \rangle \ ::= \ \langle str \rangle \ \langle str \rangle$

roles $\langle str \rangle^+$ // set the roles
dafsm $\langle str \rangle (\langle pars \rangle)$ by $\langle dcl \rangle$ { // $\langle dcl \rangle$ declares the participant creating the contract

Concrete syntax (I)

$\langle \mathit{pars} \rangle ::= \varepsilon \mid \langle \mathit{dcl} \rangle (,\langle \mathit{dcl} \rangle)^\star$ $\qquad$ $\langle \mathit{dcl} \rangle ::= \langle \mathit{str} \rangle \ \langle \mathit{str} \rangle$

roles $\langle \mathit{str} \rangle^+$ // set the roles

dafsm $\langle \mathit{str} \rangle (\langle \mathit{pars} \rangle)$ by $\langle \mathit{dcl} \rangle$ { // $\langle \mathit{dcl} \rangle$ declares the participant creating the contract

$\vdots$

$\langle \mathit{dcl} \rangle$:= e ; // state variables with initial assignment (if any)

Concrete syntax (I)

$$\langle \mathit{pars} \rangle \ ::= \ \varepsilon \ \big| \ \langle \mathit{dcl} \rangle (,\langle \mathit{dcl} \rangle)^{\star} \qquad\qquad \langle \mathit{dcl} \rangle \ ::= \ \langle \mathit{str} \rangle \ \langle \mathit{str} \rangle$$

roles $\langle \mathit{str} \rangle^{+}$ // set the roles
dafsm $\langle \mathit{str} \rangle(\langle \mathit{pars} \rangle)$ by $\langle \mathit{dcl} \rangle$ { // $\langle \mathit{dcl} \rangle$ declares the participant creating the contract
$\vdots$
$\langle \mathit{dcl} \rangle$:= e ; // state variables with initial assignment (if any)
$\vdots$
if γ // initial guard (this clause can be omitted)
}

Concrete syntax (I)

$$\langle \mathit{pars} \rangle ::= \varepsilon \mid \langle \mathit{dcl} \rangle (,\langle \mathit{dcl} \rangle)^\star \qquad \langle \mathit{dcl} \rangle ::= \langle \mathit{str} \rangle\ \langle \mathit{str} \rangle$$

$$\langle \mathit{lbl} \rangle ::= \{\gamma\}\ \pi > \langle \mathit{str} \rangle(\langle \mathit{pars} \rangle)\ \{\langle \mathit{asgs} \rangle\}$$

$$\langle \mathit{asgs} \rangle ::= \varepsilon \mid \langle \mathit{asg} \rangle (;\langle \mathit{asg} \rangle)^\star \qquad \langle \mathit{asg} \rangle ::= \langle \mathit{str} \rangle{:=}\langle \mathit{expr} \rangle$$

roles $\langle \mathit{str} \rangle^+$ // set the roles

dafsm $\langle \mathit{str} \rangle(\langle \mathit{pars} \rangle)$ by $\langle \mathit{dcl} \rangle$ { // $\langle \mathit{dcl} \rangle$ declares the participant creating the contract

$\vdots$

$\langle \mathit{dcl} \rangle$:=e ; // state variables with initial assignment (if any)

$\vdots$

if γ // initial guard (this clause can be omitted)

}

$\vdots$

[$\langle \mathit{str} \rangle$] $\langle \mathit{lbl} \rangle$ [$\langle \mathit{str} \rangle$] ; // the initial state defaults to the source state of the first transition

$\vdots$ // final states are strings with a trailing '+' sign

Exercise: **TRAC** usage (I)

Edit a `.trac` file for the contract specified at
`https://github.com/Azure-Samples/blockchain/blob/master/blockchain-workbench/application-and-smart-contract-samples/basic-provenance/readme.md`

Concrete syntax (II)

The syntax of expressions (and hence of guards) follows the SMT-lib standard:

$$
\begin{array}{lcl}
\langle \mathit{spec\_constant} \rangle & ::= & \langle \mathit{numeral} \rangle \mid \langle \mathit{decimal} \rangle \mid \langle \mathit{hexadecimal} \rangle \mid \langle \mathit{binary} \rangle \mid \langle \mathit{string} \rangle \\
\langle \mathit{s\_expr} \rangle & ::= & \langle \mathit{spec\_constant} \rangle \mid \langle \mathit{symbol} \rangle \mid \langle \mathit{reserved} \rangle \mid \langle \mathit{keyword} \rangle \\
 & \mid & (\ \langle \mathit{s\_expr} \rangle^{*}\ ) \\
\langle \mathit{qual\_identifier} \rangle & ::= & \langle \mathit{identifier} \rangle \mid (\ \mathtt{as}\ \langle \mathit{identifier} \rangle\ \langle \mathit{sort} \rangle\ ) \\
\langle \mathit{var\_binding} \rangle & ::= & (\ \langle \mathit{symbol} \rangle\ \langle \mathit{term} \rangle\ ) \\
\langle \mathit{sorted\_var} \rangle & ::= & (\ \langle \mathit{symbol} \rangle\ \langle \mathit{sort} \rangle\ ) \\
\langle \mathit{pattern} \rangle & ::= & \langle \mathit{symbol} \rangle \mid (\ \langle \mathit{symbol} \rangle\ \langle \mathit{symbol} \rangle^{+}\ ) \\
\langle \mathit{match\_case} \rangle & ::= & (\ \langle \mathit{pattern} \rangle\ \langle \mathit{term} \rangle\ ) \\
\langle \mathit{term} \rangle & ::= & \langle \mathit{spec\_constant} \rangle \\
 & \mid & \langle \mathit{qual\_identifier} \rangle \\
 & \mid & (\ \langle \mathit{qual\_identifier} \rangle\ \langle \mathit{term} \rangle^{+}\ ) \\
 & \mid & (\ \mathtt{let}\ (\ \langle \mathit{var\_binding} \rangle^{+}\ )\ \langle \mathit{term} \rangle\ ) \\
 & \mid & (\ \mathtt{lambda}\ (\ \langle \mathit{sorted\_var} \rangle^{+}\ )\ \langle \mathit{term} \rangle\ ) \\
 & \mid & (\ \mathtt{forall}\ (\ \langle \mathit{sorted\_var} \rangle^{+}\ )\ \langle \mathit{term} \rangle\ ) \\
 & \mid & (\ \mathtt{exists}\ (\ \langle \mathit{sorted\_var} \rangle^{+}\ )\ \langle \mathit{term} \rangle\ ) \\
 & \mid & (\ \mathtt{match}\ \langle \mathit{term} \rangle\ (\ \langle \mathit{match\_case} \rangle^{+}\ )\ ) \\
 & \mid & (\ \mathtt{!}\ \langle \mathit{term} \rangle\ \langle \mathit{attribute} \rangle^{+}\ )
\end{array}
$$

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probably not needed

(borrowed from [2])

Exercise: **TRAC** syntax (II)

Edit a `.trac` file for the DAFSM on slide 13.

– Act III –

[A little exercise]

– Epilogue –

[Work in progress]

Work in progress

Thank you

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 *LNCS*, pages 239–257. Springer, 2024.

[2] C. Barrett, P. Fontaine, and C. Tinelli. *The SMT-LIB Standard*, version 2.7 edition, 2025.

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

References II

[4] B. Meyer. *Introduction to the Theory of Programming Languages*. Prentice-Hall, 1990.

[5] B. Meyer. *Eiffel: The Language*. Prentice-Hall, 1991.

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

[7] 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.