Automata for smart contracts...and more

Emilio Tuosto @ GSSI

joint work with

Maurizio Murgia @GSSI
Elvis Gerardin Konjoh Selabi @GSSI & UniCam
Antonio Ravara @NOVA

A tutorial @ FORTE 2025, Lille

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What’s up doc?

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Epilogue . . . . Work in progress

– Prologue –

[An inspiring initiative]

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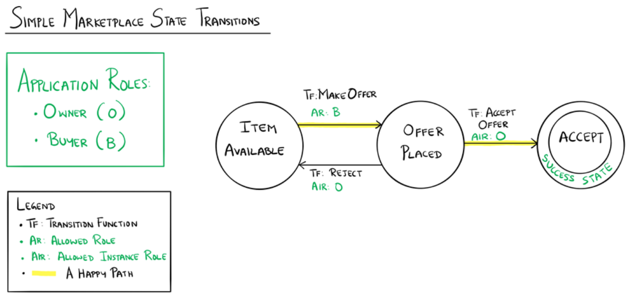
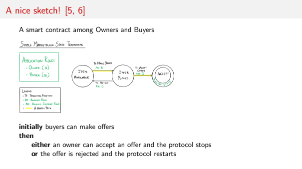
A nice sketch! [5, 6]

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." [2]

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A new coordination model

So, we saw an interesting model where

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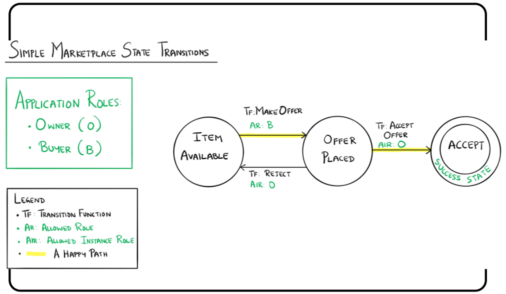
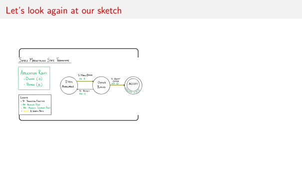
Let's look again at our sketch





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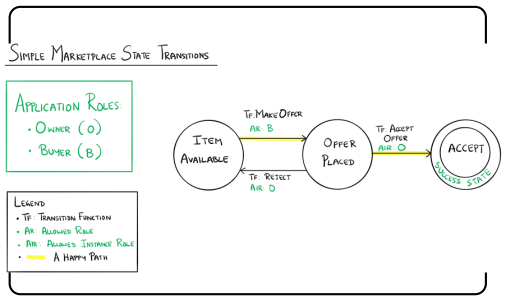


but...

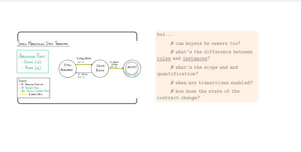
✗ can buyers be owners too?

✗ what’s the difference between roles and instances?

✗ what’s the scope and and quantification?

✗ when are transitions enabled?

✗ how does the state of the contract change?



ok

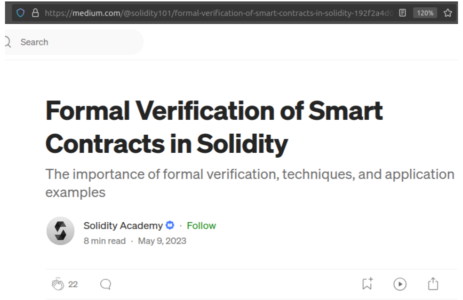
ok

from [6]: “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?

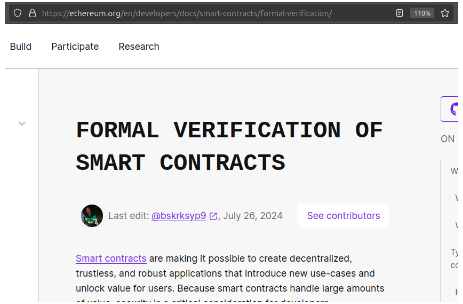
ok

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

...and by the way



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



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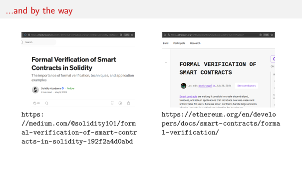

Let's go formal!

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

- ✗ roles with multiple instances
- ✗ instances with many roles
- ✗ are the known notions of well-formedness suitable?
- ✗ data-awareness is crucial

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– Act I –

[A coordination framework]

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Basic concepts and notation

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We adapt the mechanism based on the old keyword from the Eiffel language [4] which, as explained in [3] 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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<u>Assignment</u> $\mathsf{c}.\mathsf{x} := \mathsf{e}$ where e is a standard syntax of <u>pure</u> expressions[1]; let $B, B', \ldots$ range over finite sets of assignments where each variable can be assigned at most once

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Data-Aware FSMs

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

Here are possible transitions of DAFSMs[2]

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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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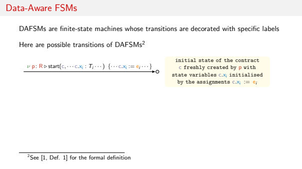

each state variable is declared and initialises with type-consistent expressions

start is a “build-in” function name

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

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$\nu\ \mathsf{p} \colon \mathsf{R} \triangleright \mathsf{start}(\mathsf{c}, \cdots \mathsf{c.x_i} : T_i \cdots)\ \{\cdots \mathsf{c.x_i} := \mathsf{e}_i \cdots\}$

```
initial state of the contract
c freshly created by p with
state variables c.xi initialised
by the assignments c.xi := ei
```

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

```
where g (ie a boolean
expression) is a guard and
π ::= ν p: R | any p: R | p
is a qualified participant
invoking operation f
with parameters c.yi
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

ν p: R specifies that p must be a fresh participant with role R
any p: 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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$$\circ \xrightarrow{\ell} \circledcirc$$

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

Give a DAFSM for the following contract protocol:

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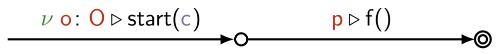
let them play with qualified participants

Not all DAFSMs “make sense”



free names

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

free names

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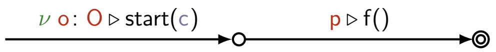

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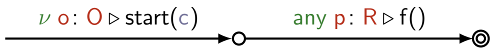

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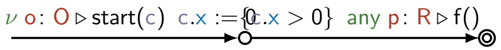
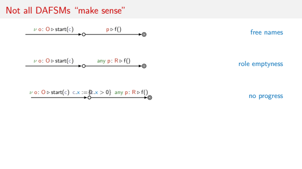


no progress



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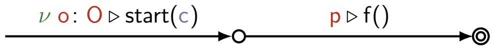

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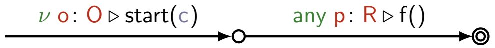

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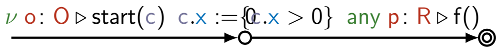

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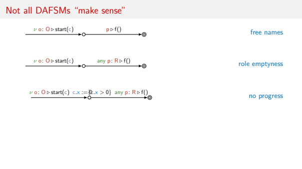

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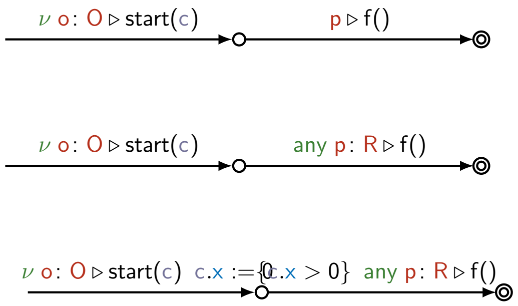

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Save name freeness, the other properties are undecidable in general, so we'll look for sufficient conditions on DAFSMs ensuring role non-emptyness and progress.

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Binders: parameter declarations in function call, ν p: R, and any p: R

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

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The occurrence of p is bound in a path $\sigma \circ \xrightarrow{\{g\}\ \mathsf{p} \triangleright \mathsf{f}(\cdots \mathsf{y}_i : T_i \cdots)\ B} \circ\ \sigma'$ 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

Closed DAFSMs

Binders: parameter declarations in function call, $\nu\ \mathsf{p} \colon \mathsf{R}$, and $\mathsf{any}\ \mathsf{p} \colon \mathsf{R}$

p is bound in $\circ \xrightarrow{\{g\}\ \pi \triangleright \mathsf{f}(\cdots \mathsf{y}_i : T_i \cdots)\ B} \circ$ if, for some role R,

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

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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 σ $\circ \xrightarrow{\{g\}\ \text{any p: R} \triangleright f(\cdots y_i : T_i \cdots)\ B} \circ$ σ' 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

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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 $X = \{\mathrm{c.x_1}, \ldots, \mathrm{c.x_n}\}$ is <u>consistent</u> if it is closed and the following implication holds for each transition $\circ \xrightarrow{\{\mathrm{g}\}\ \pi \triangleright \mathrm{f}(\cdots \mathrm{y}_i : T_i \cdots)\ B} \mathrm{(s)}$

$$\forall(\mathrm{c.x}, \mathrm{old\ c.x})_{\mathrm{c.x} \in X}\ \exists(y)_{y \in Y}\ :\ (\mathrm{g}\{\mathrm{old\ c.x}/\mathrm{c.x}\}_{\mathrm{c.x} \in X}\ \wedge\ \mathrm{g}_B) \implies \mathrm{g_s} \qquad \text{where}$$

$$Y = \{y \mid \exists i\ :\ y = y_i \text{ or } y \text{ is a parameter of an outgoing transition of s}\}$$

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

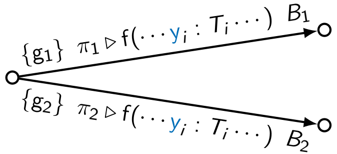
$$\mathrm{g}_B = \bigwedge_{(\mathrm{c.x} := \mathrm{e}) \in B} \mathrm{c.x} = \mathrm{e}\ \wedge \bigwedge_{\mathrm{c.x} \notin B} \mathrm{c.x} = \mathrm{old\ c.x}$$

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

Determinism

A DAFSM is deterministic if

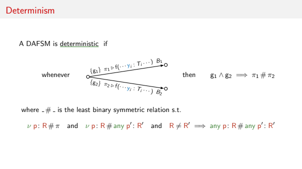
whenever



then $g_1 \wedge g_2 \implies \pi_1 \# \pi_2$

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

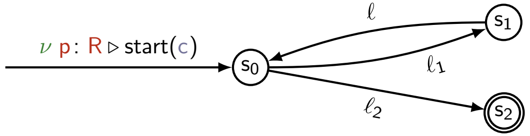
$\nu\, p\colon R \# \pi$ and $\nu\, p\colon R \# \text{any } p'\colon R'$ and $R \neq R' \implies \text{any } p\colon R \# \text{any } p'\colon R'$



transitions from the same source state and calling the same function

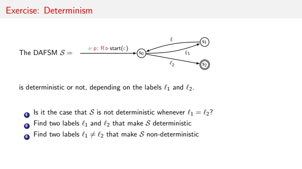
Exercise: Determinism

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 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



1. no: eg for $\ell_1 = \ell_2 = \nu$ p: R $\mathcal{S}$ is deterministic
2. $\ell_1 = \ell_2 =$ ν p: R $\triangleright$ 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. $\ell_1 = \{x \leq 0\}$ p $\triangleright$ f(x : Int) and $\ell_2 = \{x \geq -1\}$ p $\triangleright$ 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

Well-formedness

A DAFSM is well-formed when it is

empty-role free

consistent, and

deterministic

Well-formedness

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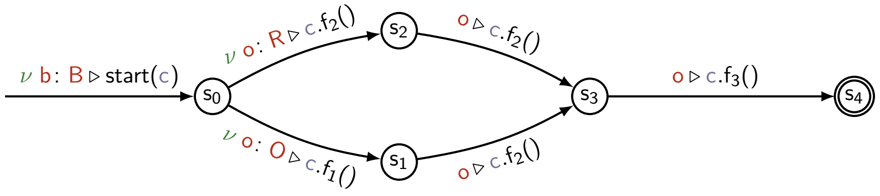
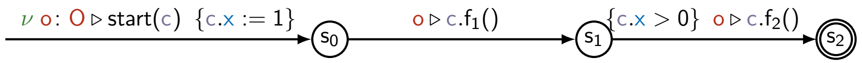
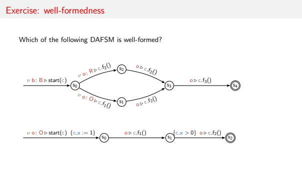
Exercise: well-formedness

Which of the following DAFSM is well-formed?







yes: o is defined on paths it occurs on and the DAFSM is deterministic.

no: the transition from s_0 violates **??** since True does not imply $c.x > 0$ hinting that the protocol could get stuck in state s_1. However, this never happens because $c.x$ is initially set to 1 and never changed, hence the transition from s_1 would be enabled when the protocol lands in s_1.

– Act II –

[A tool]

– Act II –
[A tool]

Verification

Checking well-formedness by hand is laborious and cumbersome

So we implemented **TRAC**, which
- transforms DAFSMs in a DSL to specify DAFSMs
- verifies well-formedness condition relying on the SMT solver Z3

Verification

Checking well-formedness by hand is laborious and cumbersome

So we implemented **TRAC**, which
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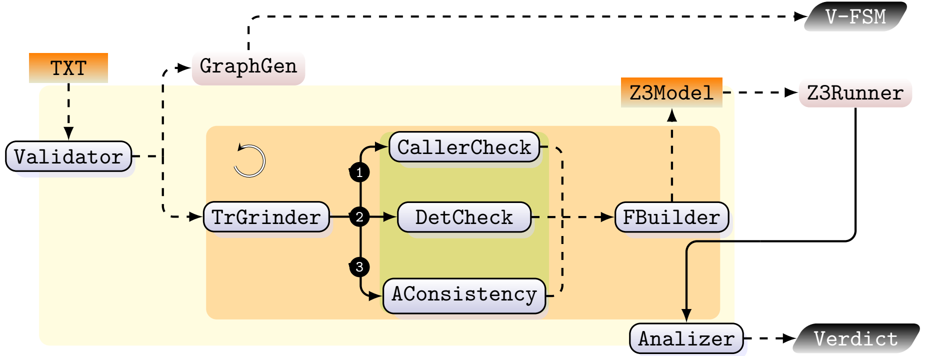
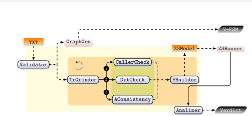
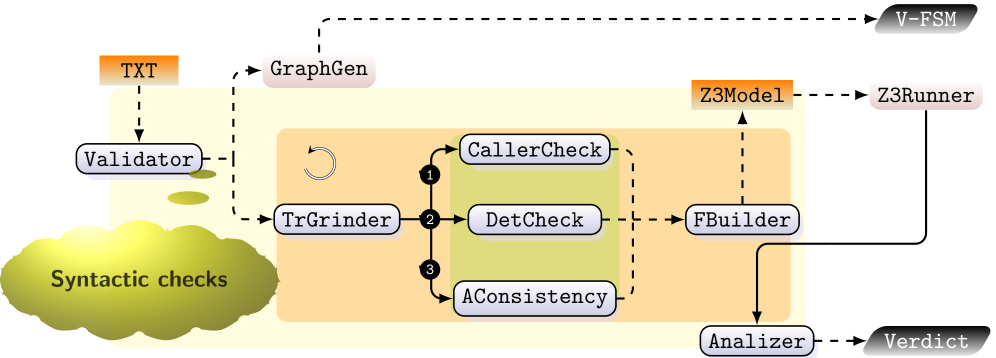
The architecture of **TRAC**





the architecture of **TRAC** is compartmentalised into two principal modules:
parsing and visualisation (yellow box) and
TRAC's core (orange box). The latter module implements well-formedness check (green box).
Solid arrows represent calls between components while dashed arrows data IO.

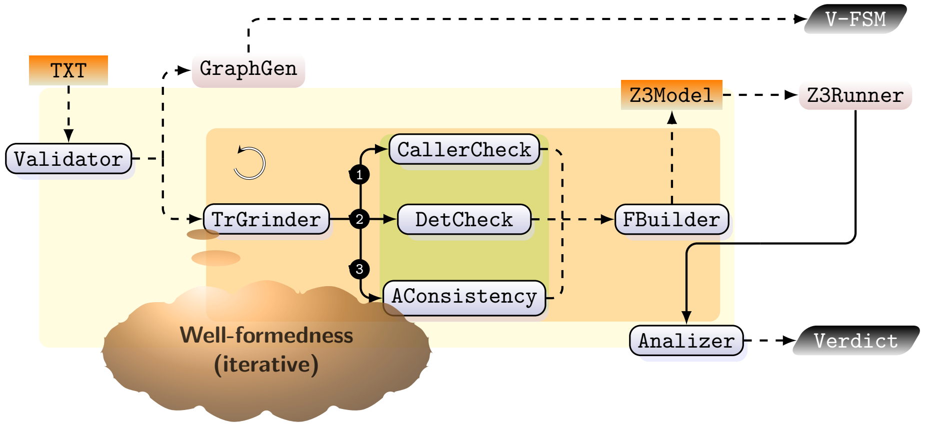
The architecture of **TRAC**



basic syntactic checks on a DSL representation of DAFSMs and transforming the input in a format that simplifies the analysis of the following phases:

- passed to `GraphGen` for visual representation of DAFSMs (`V-FSM` output)
- passed to the `TrGrinder` component (orange box) for well-formedness checking.

The architecture of **TRAC**



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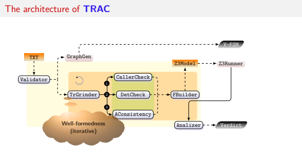
└─The architecture of **TRAC**



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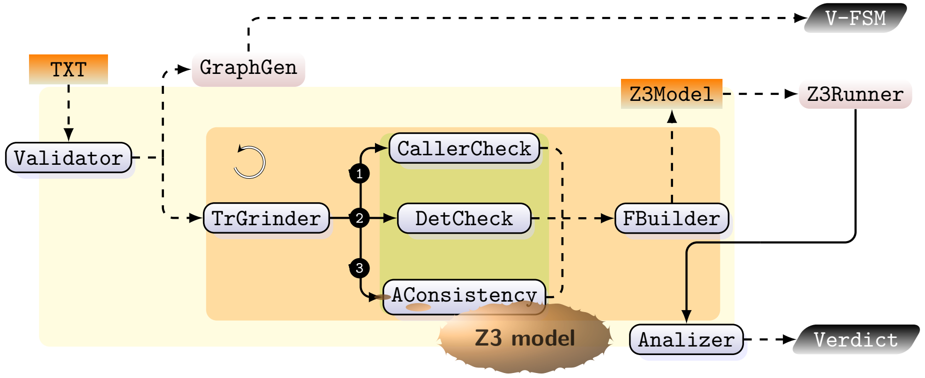
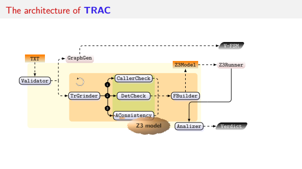
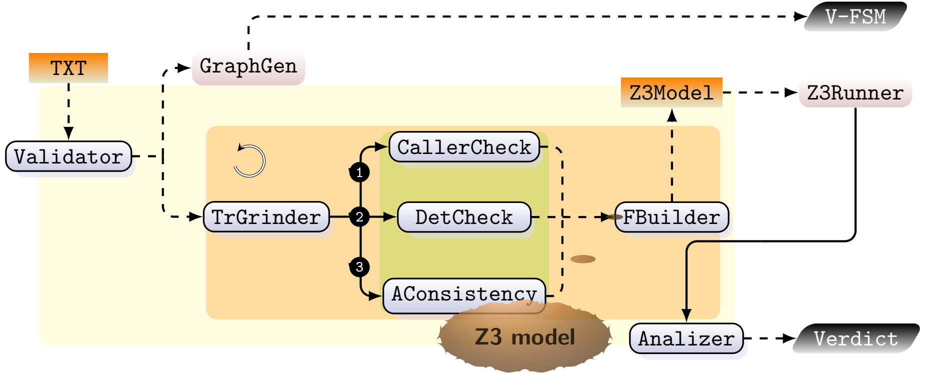
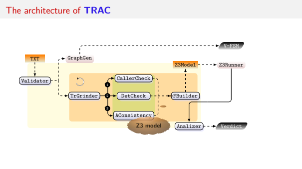




AConsistency (arrow 3) to generate a Z3 formula which holds if, and only if, the transtion is consistent.

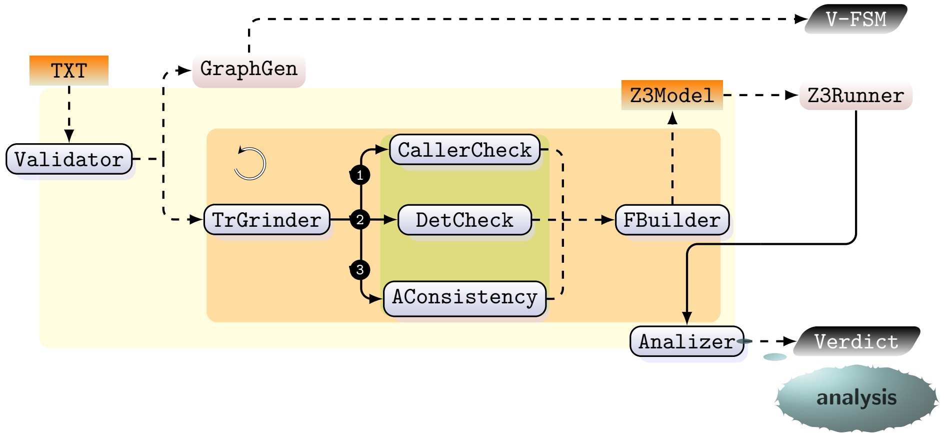
The architecture of **TRAC**

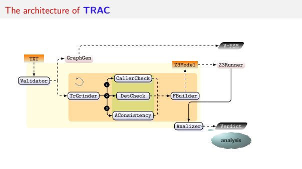




computes the z3 f.la equivalent to the conjunction of the outputs which is then passed to a Z3 engine to check its satisfiability

The architecture of **TRAC**





Finally, the `Analizer` component that diagnoses the output of Z3 and produces a `Verdict` which reports (if any) the violations of well-formedness of the DAFSM in input.

Installation

Detailed instructions at `https://github.com/loctet/TRAC`

Dependencies: Java RE (to render DAFSM graphically) & Python 3.6 or later

```
pip install z3-solver matplotlib numpy plotly pandas networkx
```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forse servono solo solo z3-solver e networkx

https://doi.org/10.5281/zenodo.10996456

– Act III –

[A little exercise]

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– Act III –

[A little exercise]

– Epilogue –

[Work in progress]

Thank you

Thank you

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[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.
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[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.

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