A Choreographic View of Smart Contracts

Elvis Gerardin Konjoh Selabi
@GSSI & UniCam

Maurizio Murgia
@GSSI

António Ravara
@NOVA

Emilio Tuosto
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A tutorial @ FORTE 2025, Lille

Work partly supported by the PRIN 2022 PNRR project DeLiCE (F53D23009130001)

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What's up doc?

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Prologue . . . . An inspiring initiative

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Act I . . . . A coordination framework

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Epilogue . . . . Work in progress

– Prologue –

[An inspiring initiative]

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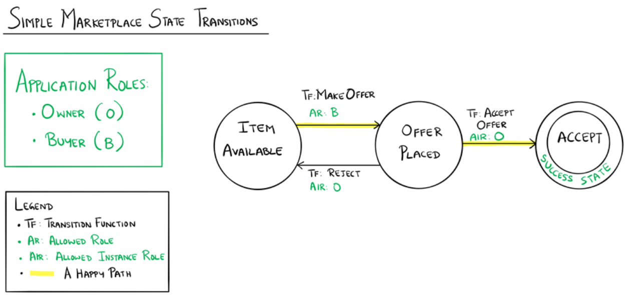
A smart contract among Owners and Buyers



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

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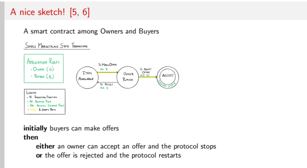
└A nice sketch! [5, 6]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A smart contract looks like

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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So, we saw an interesting model where

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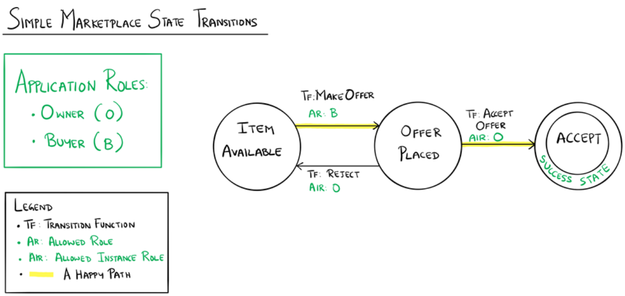

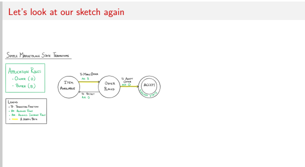

The diagram specifies a lot...

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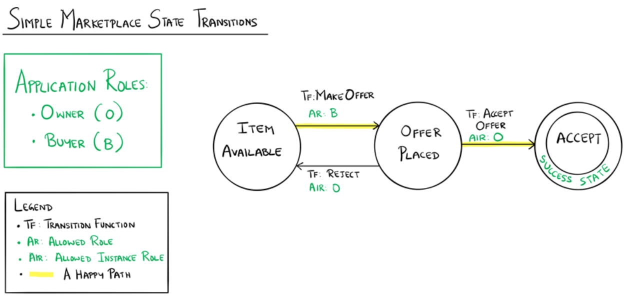
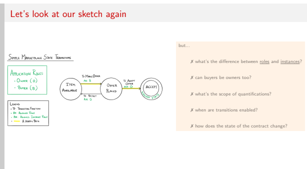


but...

- ✗ what's the difference between <u>roles</u> and <u>instances</u>?
- ✗ can buyers be owners too?
- ✗ what's the scope of quantifications?
- ✗ when are transitions enabled?
- ✗ how does the state of the contract change?



The diagram specifies a lot...

1. is the sketch giving semantics to roles and instances?
2. not forbidden...however what if we wanted to separate the roles?
3. 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?
4. ok
5. should the price of the item remain unchanged when the owner rejects offers?

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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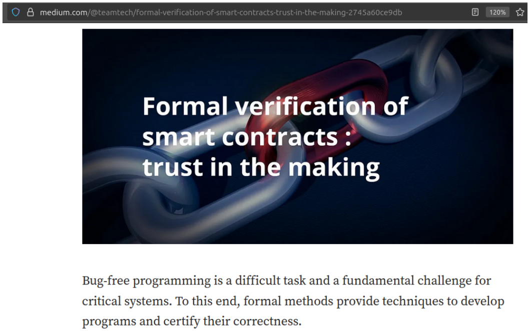
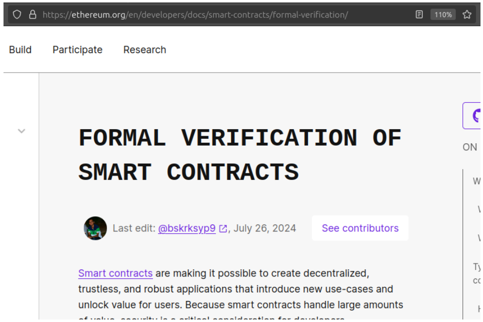
...and by the way



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



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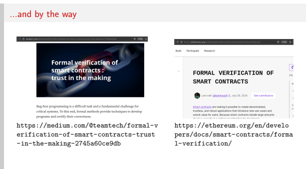

– Act I –

[A coordination framework]

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Basic concepts and notation

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

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states of the coordinator determine which operations each roles is entitled to invoke

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We assume that sorts can be inferred; **TRAC** instead requires to assign sorts explicitly

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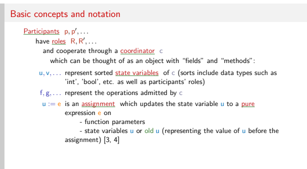
- state variables u or old u (representing the value of u before the assignment) [3, 4]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Expressions are standard but for state variables occurring in rhs e must have the old $\_$ qualifier; this concept will be used in the definition of (progress for) well-formedness

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., $x = x+1 \iff$ False.

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Data-Aware FSMs

A DAFSMs c on state variables $u_1, \ldots, u_n$ is a finite-state machine "instantiated" by a participant p whose transitions are decorated with specific labels as follows[1]

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

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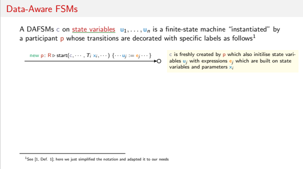

start is a "built-in" (and pleonastic) function name

each state variable is declared and initialises with type-consistent expressions on state variables and parameters x_i

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$$\circ \xrightarrow{\{\gamma\}\ \pi \triangleright \mathsf{f}(\cdots, T_i\ \mathsf{x}_i, \cdots)\ A} \circ$$

where γ is a guard (ie a boolean expression) and
$$\pi \ ::= \ \mathsf{new}\ \mathsf{p} \colon \mathsf{R} \ \big|\ \mathsf{any}\ \mathsf{p} \colon \mathsf{R} \ \big|\ \mathsf{p}$$
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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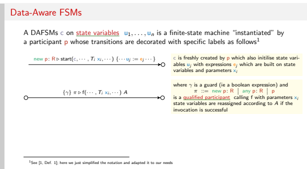

γ predicates over state variables and formal parameters of its transition; guards have to be satisfied for the invocation to succeed: an invocation that makes the guard false is rejected

- $\mathsf{new}\ \mathsf{p} \colon \mathsf{R}$ specifies that p must be a fresh participant with role R
- $\mathsf{any}\ \mathsf{p} \colon \mathsf{R}$ qualifies p as an existing participant with role R
- p refers 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 A are either state variables or parameters of the invocation

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

accepting states are denoted as usual

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└─Data-Aware FSMs

Exercise: modelling

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

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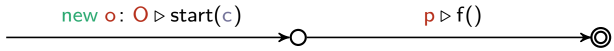
let them play with qualified participants

Not all DAFSMs “make sense”



names’ freeness

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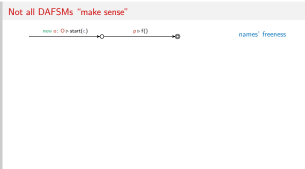

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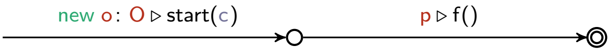

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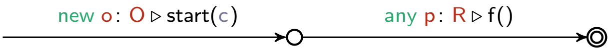
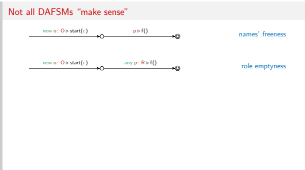


role emptyness



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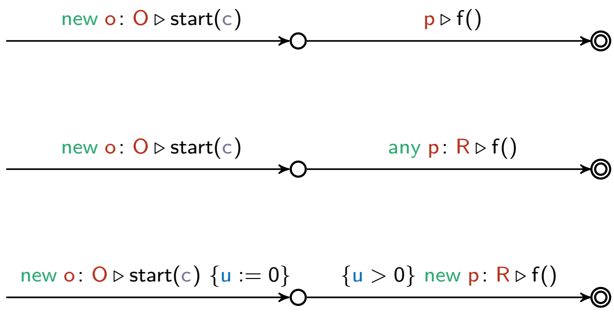

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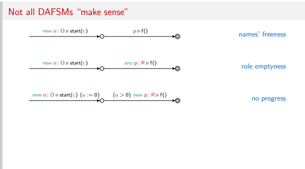

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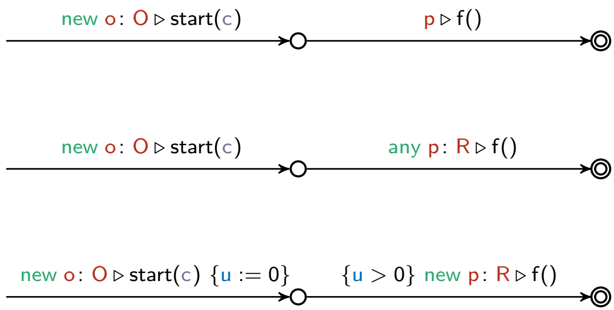

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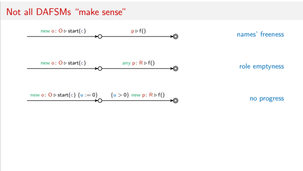

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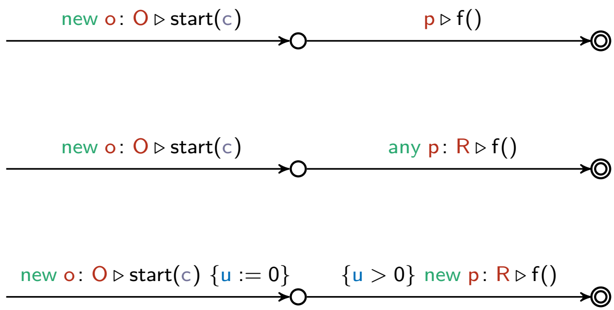

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Save names’ freeness, the other properties are undecidable in general, so we’ll look for sufficient conditions to rule out nonsensical DAFSMs

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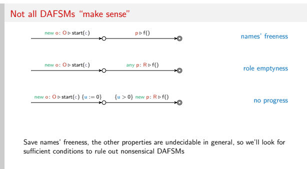

Closed DAFSMs

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

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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

Closed DAFSMs

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

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

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

The occurrence of p is bound in a path

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

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

Roles non-emptyness

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

Role R is expanded in a path

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

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

2025-05-22

A Choreographic View of Smart Contracts

└─Roles non-emptyness

Roles non-emptyness

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todo

Exercise: Role emptyness

todo

Progress

A DAFSM with state variables $u_1, \ldots, u_n$ is consistent if it is closed and the following implication holds for each transition $\circ \xrightarrow{\{\gamma\}\ \pi \triangleright \mathsf{f}(\cdots,\, T_i\ x_i, \cdots)\ A} \text{(s)}$

$$\mathbb{V}_U\, \mathbb{E}_X \left(\gamma\{\text{old } u_1, \ldots, \text{old } u_n / u_1, \ldots, u_n\} \;\wedge\; \gamma_A \implies \gamma_s\right)$$

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for a finite set of symbols Z, $\mathbb{V}_Z\left(\_\right)$ and $\mathbb{E}_Z\left(\_\right)$ are the universal and existential closures of a logical formula on the symbols in Z

Progress

A DAFSM with state variables $u_1, \ldots, u_n$ is consistent if it is closed and the following implication holds for each transition $\circ \xrightarrow{\{\gamma\}\ \pi \triangleright \mathsf{f}(\cdots,\ T_i\ x_i, \cdots)\ A} \text{(s)}$

$$\forall_U \exists_X \left(\gamma\{\text{old } u_1, \ldots, \text{old } u_n / u_1, \ldots, u_n\} \ \wedge\ \gamma_A \implies \gamma_s\right)$$

where

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

$$X = \{x \mid \exists i\ :\ x = x_i \text{ or } x \text{ is a parameter of an outgoing transition of s}\}$$

$$\gamma_s = \begin{cases} \text{the disjunction of guards of the outgoing transitions of s} & \text{is not accepting} \\ \text{True} & \text{otw} \end{cases}$$

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

for a finite set of symbols Z, $\forall_Z\,(\_)$ and $\exists_Z\,(\_)$ are the universal and existential closures of a logical formula on the symbols in Z

$u \notin A$
iff
for all $v := e \in A$, $u \neq v$ and old u does not occur in e

Exercise: Consistency

todo

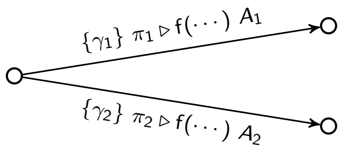
Exercise: Consistency
todo

Determinism

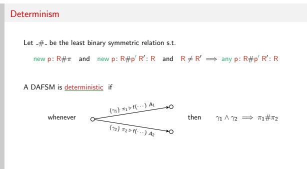
Let $\_\#\_$ be the least binary symmetric relation s.t.

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

A DAFSM is deterministic if

whenever 

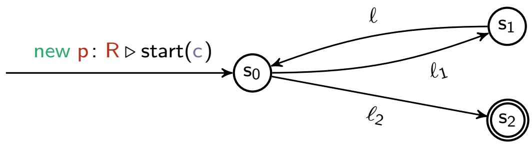
then $\gamma_1 \wedge \gamma_2 \implies \pi_1 \# \pi_2$



transitions from the same source state and calling the same function

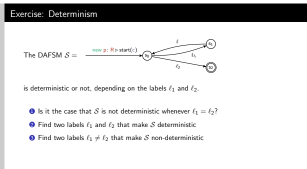
Exercise: Determinism

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 $\ell_1 = \ell_2 =$ new p: R $\mathcal{S}$ is deterministic
2. $\ell_1 = \ell_2 =$ new p: R ▷ f($\cdots$, T_i x_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 ▷ f(x : Int) and $\ell_2 = \{x \geq -1\}$ 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

Well-formedness

A DAFSM is well-formed when it is

empty-role free

consistent, and

deterministic

Well-formedness

A DAFSM is well-formed when it is

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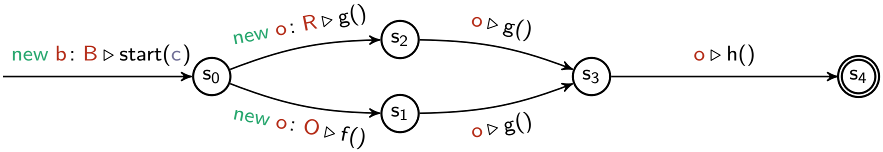
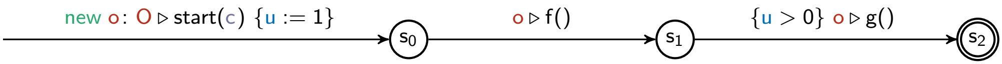
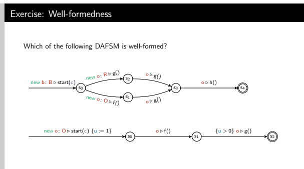
Exercise: Well-formedness

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 consistency since True does not imply $u > 0$ hinting that the protocol could get stuck in state s_1. However, this never happens because u 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 (and boring)

So we implemented **TRAC**, which

✓ transforms DAFSMs in a DSL to specify DAFSMs

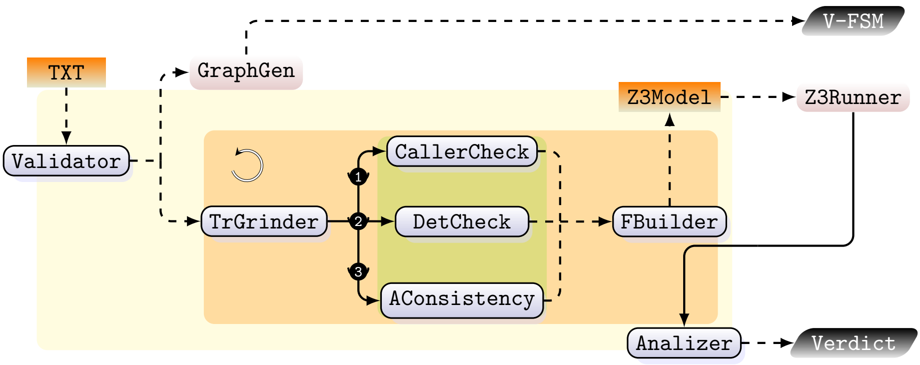
✓ verifies well-formedness condition relying on the SMT solver Z3

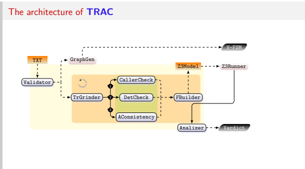
✓ it's efficient enough

✗ but cannot handle roles and inter-contract interactions

Verification
Checking well-formedness by hand is laborious and cumbersome (and boring)
So we implemented TRAC, which
✓ transforms DAFSMs in a DSL to specify DAFSMs
✓ verifies well-formedness condition relying on the SMT solver Z3
✓ it's efficient enough
✗ but cannot handle roles and inter-contract interactions

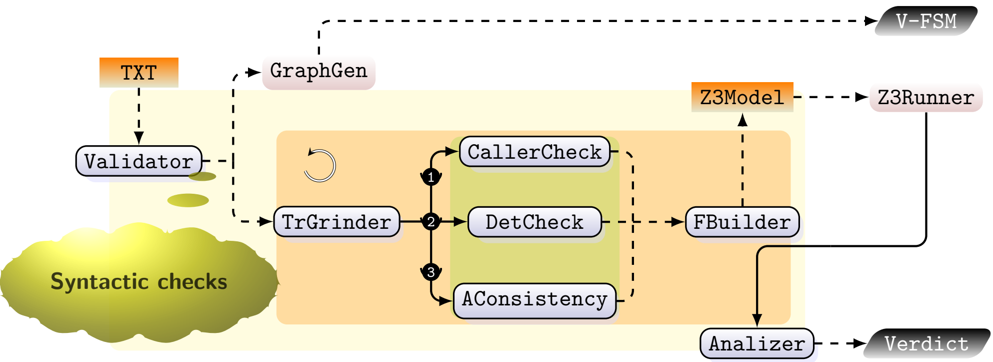
The architecture of **TRAC**

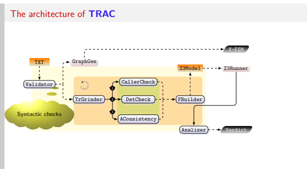




the architecture of **TRAC** is compartmentalised into two principal modules:
parsing and visualisation (yellow box) and
TRAC's core (orange box). The latter module implements well-formedness check (green box).
Solid arrows represent calls between components while dashed arrows data IO.

The architecture of **TRAC**

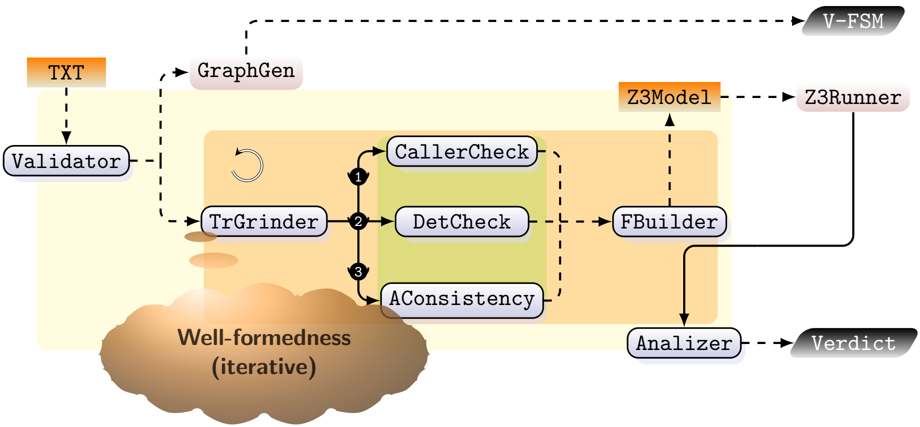


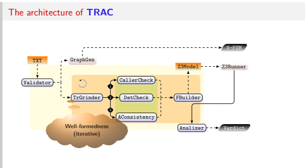


basic syntactic checks on a DSL representation of DAFSMs and transforming the input in a format that simplifies the analysis of the following phases:

- 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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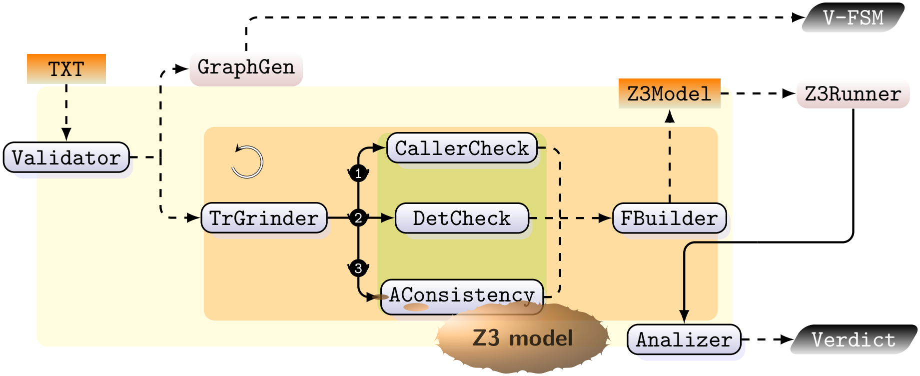
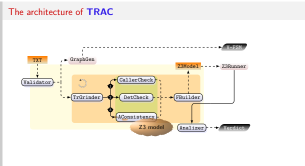
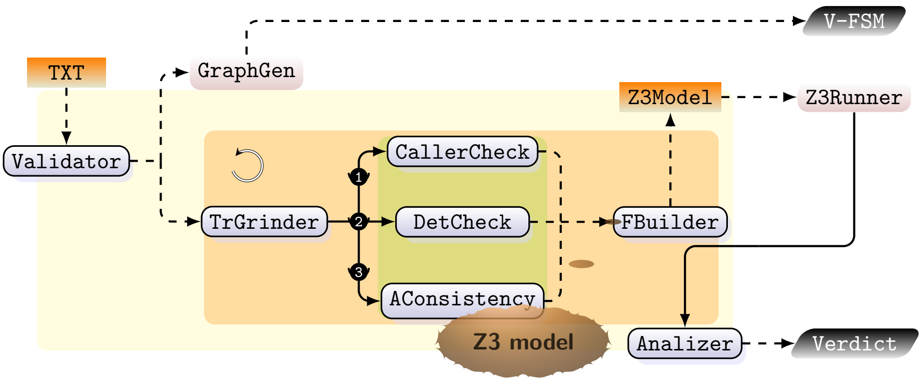




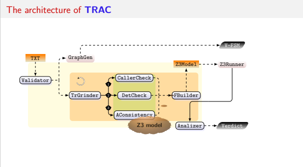
`AConsistency` (arrow ❸) to generate a Z3 formula which holds if, and only if, the transtion is consistent.



2025-05-22

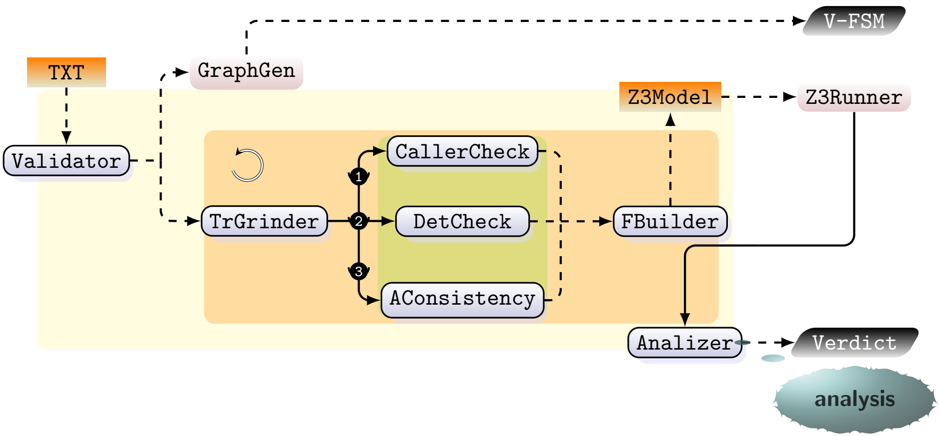
A Choreographic View of Smart Contracts

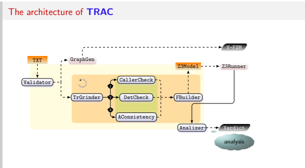
└The architecture of TRAC



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 networkx
```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Concrete syntax (I)

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

roles $\langle \texttt{str} \rangle^+$ . . . . role declaration
dafsm $\langle \texttt{str} \rangle$ ($\langle \texttt{pars} \rangle$) by $\langle \texttt{dcl} \rangle$ { $\qquad$ # $\langle \texttt{dcl} \rangle$ declares the participant creating the contract

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$\quad\langle \texttt{dcl} \rangle$ = e ; $\qquad$ # state variables with initial assignment (if any)

$\quad\vdots$

A Choreographic View of Smart Contracts

2025-05-22

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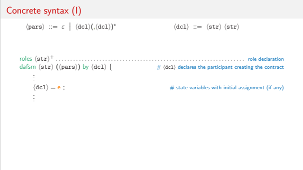

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recall that e and γ are SMT-Lib2 syntax for expressions and boolean expressions respectively

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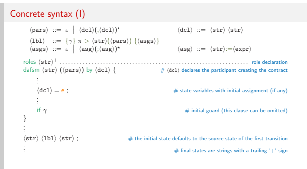
⋮
$\langle\texttt{str}\rangle$ $\langle\texttt{lbl}\rangle$ $\langle\texttt{str}\rangle$; # the initial state defaults to the source state of the first transition
⋮ # final states are strings with a trailing '+' sign



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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`

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roles Owner Conterparty {}
dafsm basicProvenance(Owner o) by cp : Conterparty {}
q0 cp > c.TransferResponsibility(Conterparty cp) {} q1
q1 any *cp*: *Conterparty* > c.TransferResponsibility(Conterparty cp) {} q1
q1 o > c.Complete() {} q2+

Concrete syntax (II)

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

```
⟨spec_constant⟩    ::= ⟨numeral⟩ | ⟨decimal⟩ | ⟨hexadecimal⟩ | ⟨binary⟩ | ⟨string⟩
⟨s_expr⟩           ::= ⟨spec_constant⟩ | ⟨symbol⟩ | ⟨reserved⟩ | ⟨keyword⟩
                     | ( ⟨s_expr⟩* )
⟨qual_identifier⟩  ::= ⟨identifier⟩ | ( as ⟨identifier⟩ ⟨sort⟩ )
⟨var_binding⟩      ::= ( ⟨symbol⟩ ⟨term⟩ )
⟨sorted_var⟩       ::= ( ⟨symbol⟩ ⟨sort⟩ )
⟨pattern⟩          ::= ⟨symbol⟩ | ( ⟨symbol⟩ ⟨symbol⟩+ )
⟨match_case⟩       ::= ( ⟨pattern⟩ ⟨term⟩ )
⟨term⟩             ::= ⟨spec_constant⟩
                     | ⟨qual_identifier⟩
                     | ( ⟨qual_identifier⟩ ⟨term⟩+ )
                     | ( let ( ⟨var_binding⟩+ ) ⟨term⟩ )
                     | ( lambda ( ⟨sorted_var⟩+ ) ⟨term⟩ )
                     | ( forall ( ⟨sorted_var⟩+ ) ⟨term⟩ )
                     | ( exists ( ⟨sorted_var⟩+ ) ⟨term⟩ )
                     | ( match ⟨term⟩ ( ⟨match_case⟩+ ) )
                     | ( ! ⟨term⟩ ⟨attribute⟩+ )
```

(borrowed from [?])

https://smt-lib.org/papers/smt-lib-reference-v2.6-r2021-05-12.pdf
http://smtlib.github.io/jSMTLIB/SMTLIBTutorial.pdf

Exercise: TRAC syntax (II)

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

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– Act III –

[A little exercise]

– Act III –
[A little exercise]

A Choreographic View of Smart Contracts

2025-05-22

https://github.com/blockchain-unica/rosetta-smart-contracts/tree/main/contracts/vesting

– Epilogue –

[Work in progress]

– Epilogue –

[Work in progress]

Work in progress

Work in progress

Thank you

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

[3] B. Meyer. *Introduction to the Theory of Programming Languages*.
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