A Choreographic View of Smart Contracts

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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?

What's up doc?
Prologue . . . . An inspiring initiative

What's up doc?

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└What's up doc?

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Prologue . . . . An inspiring initiative

Act I . . . . A coordination framework

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Act II . . . . Some tool support

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Epilogue . . . . Work in progress

– Prologue –

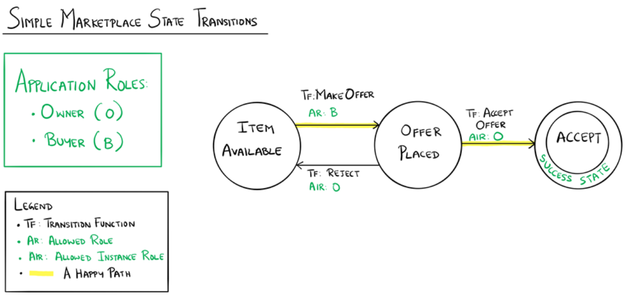
[An inspiring initiative]

– 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

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└─A nice sketch! [6, 7]

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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

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distributed components coordinate through a global specification

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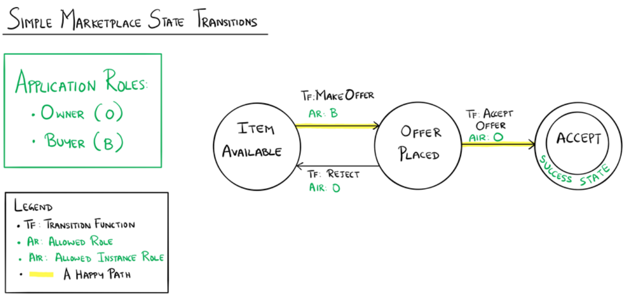
Let's look at our sketch again



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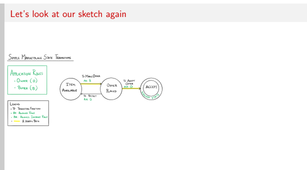

The diagram specifies a lot...

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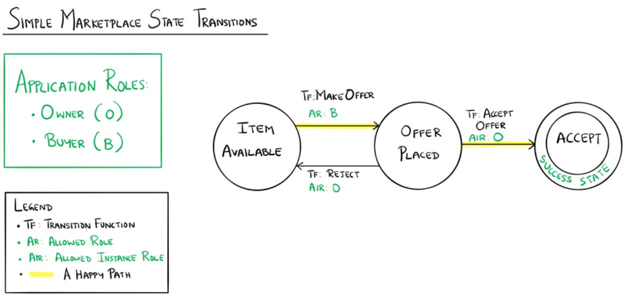


but...

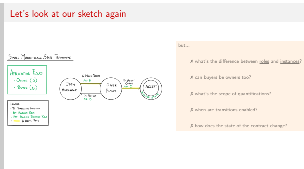
✗ what's the difference between roles and instances?

✗ can buyers be owners too?

✗ what's the scope of quantifications?

✗ when are transitions enabled?

✗ how does the state of the contract change?



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 [7]: "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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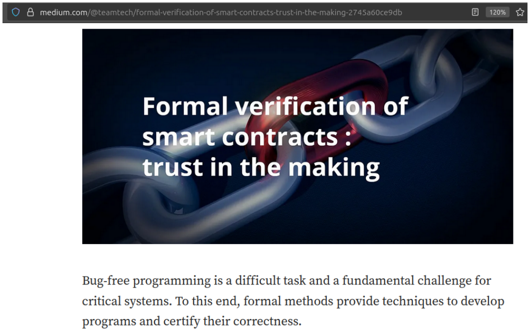

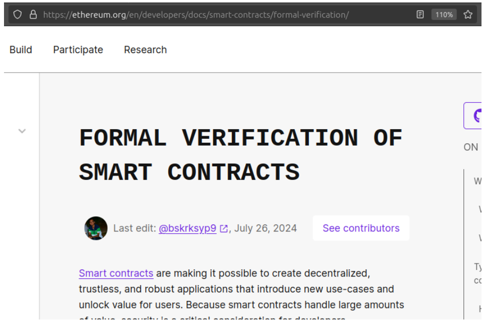

https://medium.com/@teamtech/formal-verification-of-smart-contracts-trust-in-the-making-2745a60ce9db

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

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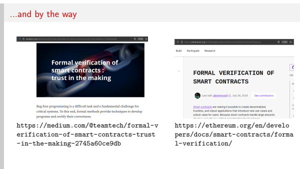

– Act I –

[A coordination framework]

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Basic concepts and notation

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Basic concepts and notation

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

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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 [5] which, as explained in [4] is necessary to render assignments into logical formulae since e.g., $x = x+1 \iff$ False.

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Data-Aware FSMs

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

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$$\xrightarrow{\ \mathsf{new}\ \mathsf{p}\colon \mathsf{R} \triangleright \mathsf{start}(\mathsf{c}, \cdots, T_i\ \mathsf{x}_i, \cdots)\ \{\cdots \mathsf{u}_j := \mathsf{e}_j \cdots\}\ } \bigcirc$$

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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$$\circ \xrightarrow{\ell} \circledcirc$$

accepting states are denoted as usual

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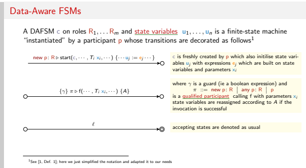

Exercise: modelling

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

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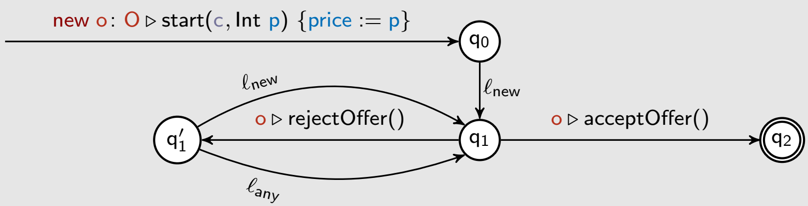
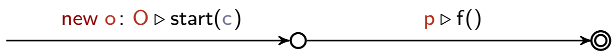
Let $\ell_{\mathsf{new}} = \{\mathsf{newOffer} > 0\}$ new $\mathsf{b}\colon \mathsf{B} \triangleright \mathsf{makeOffer}(\mathsf{Int\ newOffer})$ $\{\mathsf{offer} := \mathsf{newOffer}\}$
and $\ell_{\mathsf{any}} = \{\mathsf{newOffer} > 0\}$ any $\mathsf{b}\colon \mathsf{B} \triangleright \mathsf{makeOffer}(\mathsf{Int\ newOffer})$ $\{\mathsf{offer} := \mathsf{newOffer}\}$

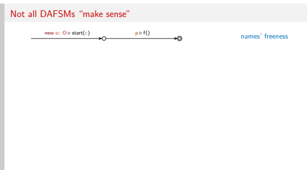


A new participant o acts as owner O for a coordinator c assigning an initial value p to the state variable price in the initial state q_0 where the only enabled function is makeOffer(Int offer). The first buyer b invoking this function with an actual parameter newOffer, satisfying the guard $\mathsf{newOffer} > 0$, moves the protocol to state q_1 while recording the new offer in the coordinator state with the assignment $\mathsf{offer} := \mathsf{newOffer}$. Contextually, the state of the coordinator records that the caller b plays role B.

Not all DAFSMs “make sense”



names’ freeness



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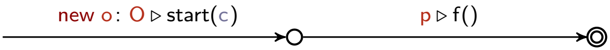

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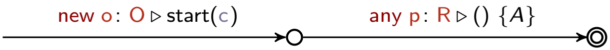
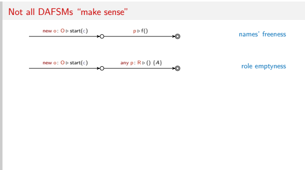


role emptyness



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

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$$\xrightarrow{\mathsf{new}\ \mathsf{o}\colon \mathsf{O} \triangleright \mathsf{start}(\mathsf{c})\ \{\mathsf{u} := 0\}} \bigcirc \xrightarrow{\{\mathsf{u} > 0\}\ \mathsf{new}\ \mathsf{p}\colon \mathsf{R} \triangleright \mathsf{f}()} \circledcirc$$

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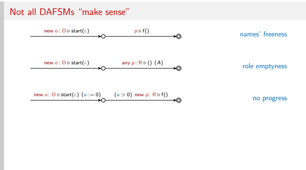

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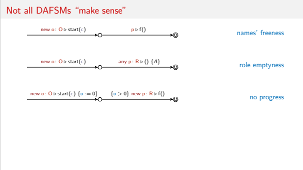

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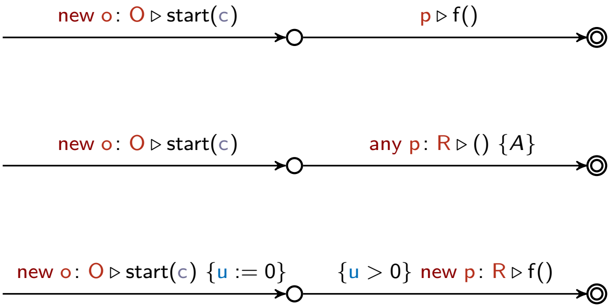
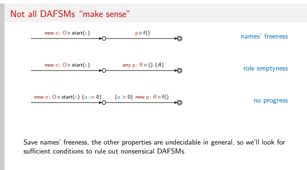


names’ freeness

role emptyness

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 p: R, and any p: R

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

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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,

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The occurrence of p is bound in a path

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

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Closed DAFSMs

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Role 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 $T_i = \mathsf{R}$

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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

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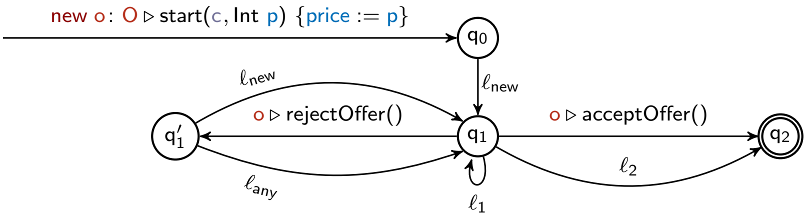
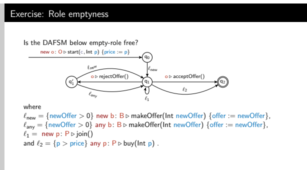
'expands' means register a new participant with that role in the protocol (the participant might already be registered with a different role)

Is the DAFSM below empty-role free?



where

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



No, because of the paths excluding the self-loop on the role P.
We can fix the problem by adding a parameter of type P to the start transition.

A DAFSM with state variables $\mathsf{u}_1, \dots, \mathsf{u}_n$ is consistent if it is closed and the following implication holds for each transition $\circ \xrightarrow{\{\gamma\}\ \pi \triangleright \mathsf{f}(\cdots,\ T_i\ \mathsf{x}_i, \cdots)\ \{A\}} \textcircled{s}$

$$\forall_X \left(\gamma\{\mathsf{old}\ \mathsf{u}_1, \dots, \mathsf{old}\ \mathsf{u}_n / \mathsf{u}_1, \dots, \mathsf{u}_n\} \ \wedge\ \gamma_A \implies \exists_{Y_1} \gamma_1 \vee \dots \vee \exists_{Y_m} \gamma_m\right)$$

where

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

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where

$$X = \{u_i, \text{old } u_i\}_{1 \le i \le n} \cup \{x \mid \exists i \ :\ x = x_i\}$$
$$Y_j = \{x \mid x \text{ is a parameter of the } j^{\text{th}} \text{ outgoing transition of s}\}$$

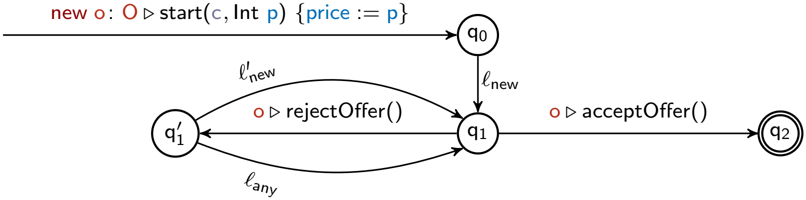
$$\gamma_j = \begin{cases} \text{the guard of the } j^{\text{th}} outgoing transition s of \text{s} & \text{if s not accepting} \\ \text{True} & \text{otw} \end{cases}$$

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

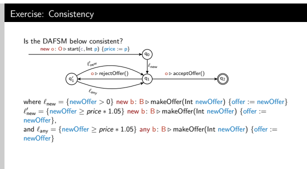
for a finite set of symbols Z, $\forall_Z\,(\_)$ and $\exists_Z\,(\_)$ are the universal and existential closures of a logical formula on the symbols in Z

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

Is the DAFSM below consistent?



where $\ell_{new} = \{\text{newOffer} > 0\}$ new b: B ▷ makeOffer(Int newOffer) {offer := newOffer}
$\ell'_{new} = \{\text{newOffer} \geq \mathit{price} * 1.05\}$ new b: B ▷ makeOffer(Int newOffer) {offer := newOffer},
and $\ell_{any} = \{\text{newOffer} \geq \mathit{price} * 1.05\}$ any b: B ▷ makeOffer(Int newOffer) {offer := newOffer}



It is not since the conditions in q_1 do not imply the disjuction of the conditions on the outgoing transitions from q'_1.

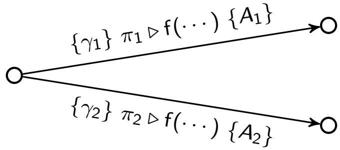
Determinism

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

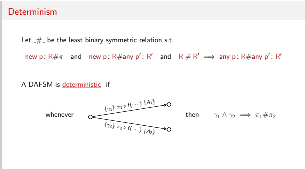
$$\text{new } p \colon R \# \pi \quad \text{and} \quad \text{new } p \colon R \# \text{any } p' \colon R' \quad \text{and} \quad R \neq R' \implies \text{any } p \colon R \# \text{any } p' \colon R'$$

A DAFSM is deterministic if

whenever

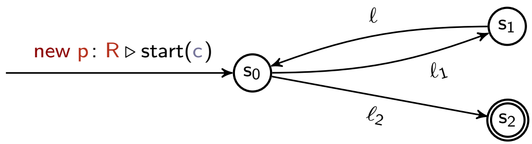


then $\quad \gamma_1 \wedge \gamma_2 \implies \pi_1 \# \pi_2$



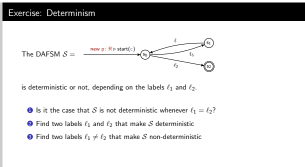
transitions from the same source state and calling the same function

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


Exercise: Determinism
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1. no: eg for $\ell_1 = \ell_2 = \text{new p: R}$ $\mathcal{S}$ is deterministic
2. $\ell_1 = \ell_2 = \text{new p: R} \triangleright f(\cdots, T_i\ x_i, \cdots)$ make $\mathcal{S}$ deterministic because the next state is unambiguously determined by the caller which is fresh on both transitions
3. $\ell_1 = \{x \leq 0\}\ p \triangleright f(\text{Int } x)$ and $\ell_2 = \{x \geq -1\}\ p \triangleright f(\text{Int } x)$ 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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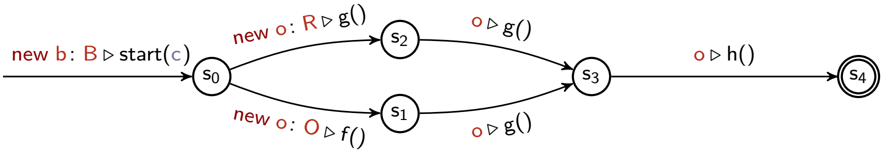
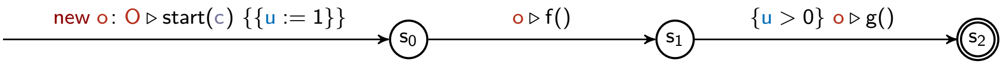
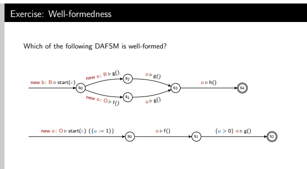
Exercise: Well-formedness

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 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]

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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 condition relying on the SMT solver Z3

✓ it's efficient enough

✗ but cannot handle roles and inter-contract interactions

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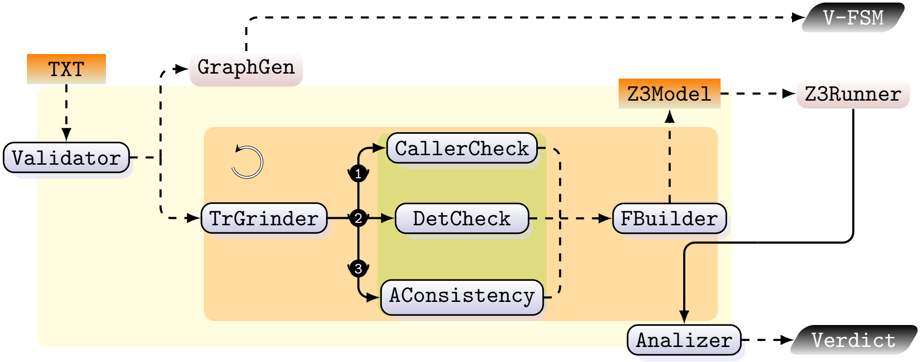
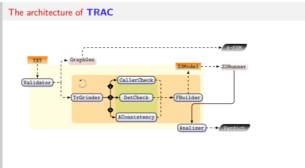
The architecture of **TRAC**





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.

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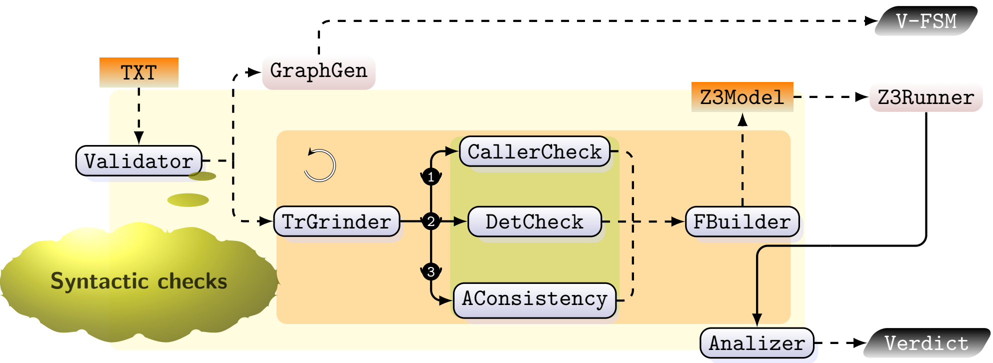

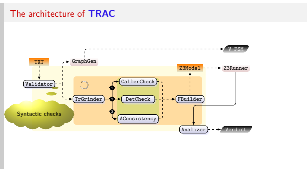

basic syntactic checks on a DSL representation of DAFSMs and transforming the input in a format that simplifies the analysis of the following phases:

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

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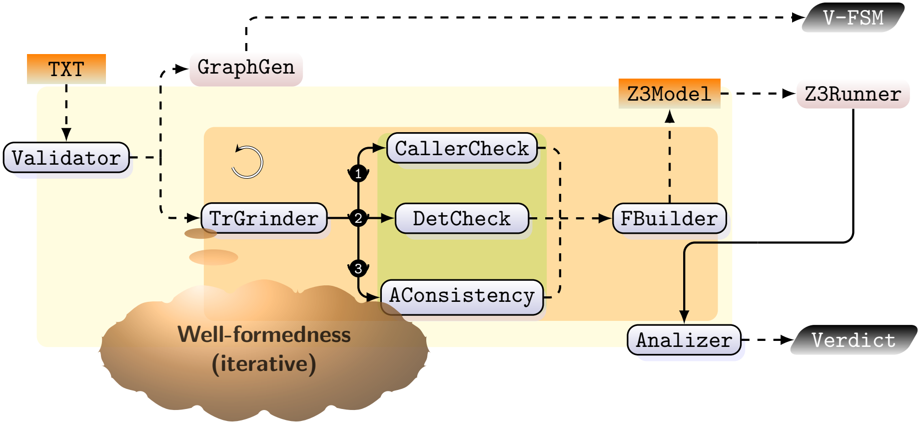

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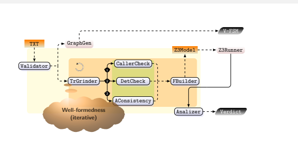
└─The architecture of **TRAC**



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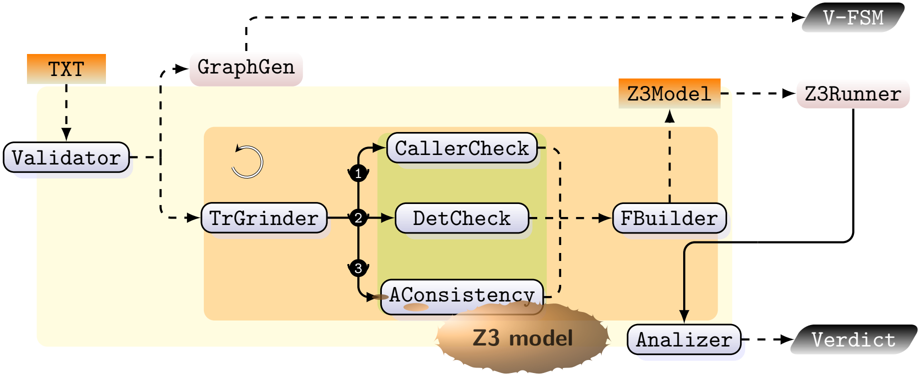
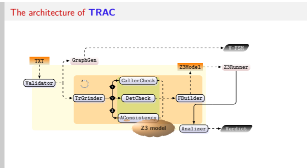
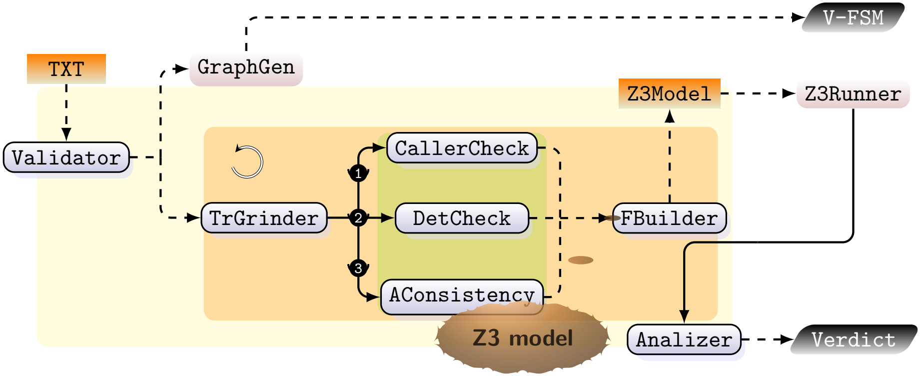
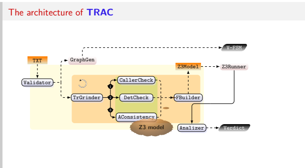




`AConsistency` (arrow ❸) to generate a Z3 formula which holds if, and only if, the transtion is consistent.

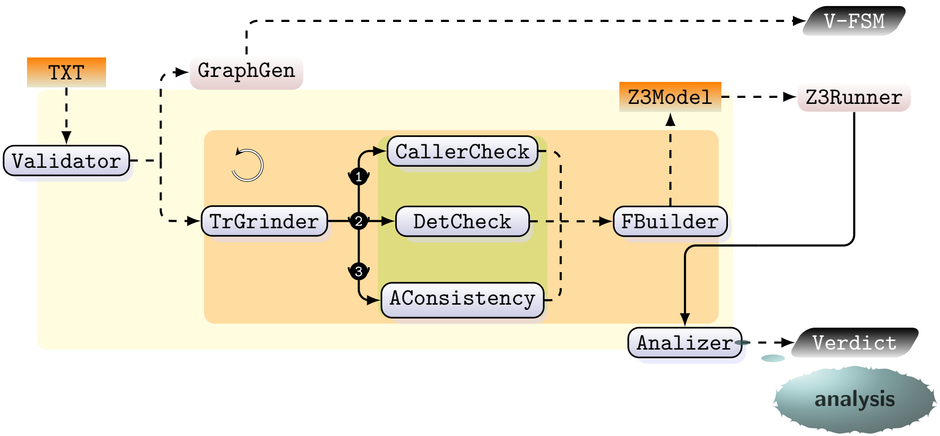
The architecture of **TRAC**

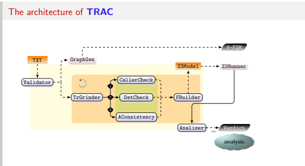




computes the z3 f.la equivalent to the conjunction of the outputs which is then passed to a Z3 engine to check its satisfiability

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

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$ pip install z3-solver matplotlib networkx
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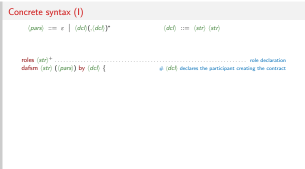
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$\quad\langle \mathit{dcl} \rangle = e$; $\qquad$ # state variables with initial assignment (if any)

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

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

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$\}$

$\vdots$

$\langle str \rangle$ $\langle lbl \rangle$ $\langle str \rangle$; # the initial state defaults to the source state of the first transition

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

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

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

$\quad\vdots$

$\quad$if γ # initial guard (this clause can be omitted)

}

$\vdots$

$\langle str \rangle\ \langle lbl \rangle\ \langle str \rangle$; # the initial state defaults to the source state of the first transition

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

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

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`

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

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

Concrete syntax (II)

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

```
⟨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⟩+ )
```

probably not needed

(borrowed from [2])

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.

Exercise: TRAC syntax (II)

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

TODO

– Act III –

[A little exercise]

– Act III –

[A little exercise]

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

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