A Choreographic View of Smart Contracts

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joint work with

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A tutorial @ FORTE 2025, Lille

What's up doc?

Prologue . . . . . An inspiring initiative

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Act I . . . . . A coordination framework

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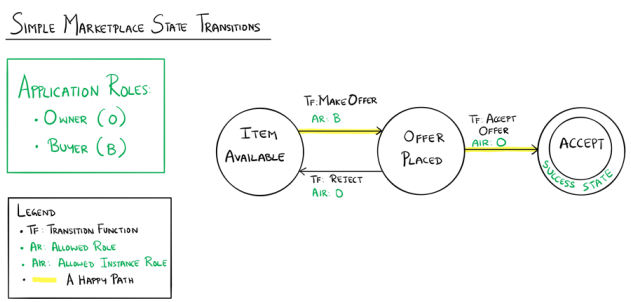
Epilogue . . . . . Work in progress

– Prologue –

[An inspiring initiative]

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

A nice sketch! [5, 6]
A smart contract among Owners and Buyers
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What did we just see?

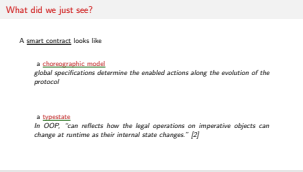
A smart contract looks like

a choreographic model

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

a typestate

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



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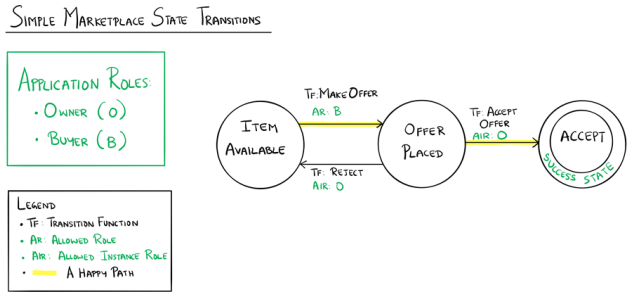

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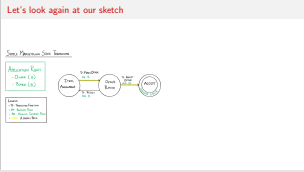

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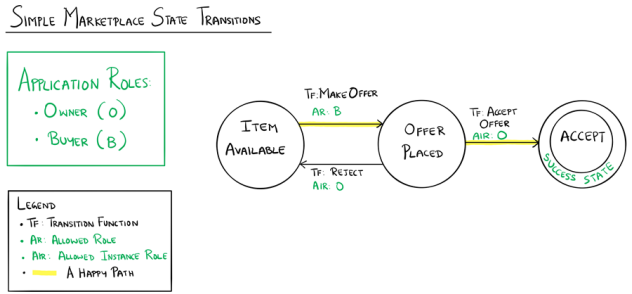
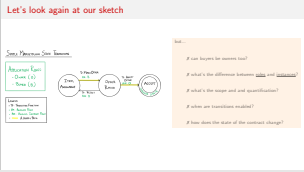


but...

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



ok

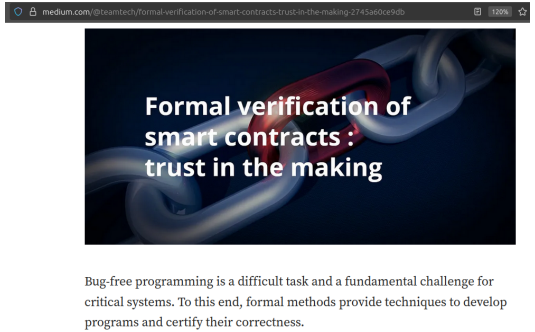
ok

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?

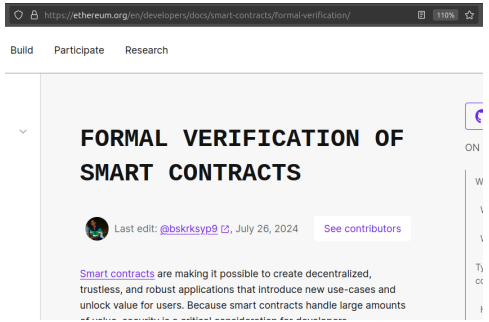
ok

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

...and by the way



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



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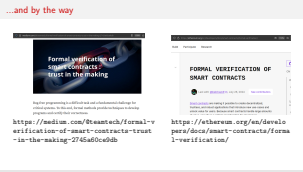
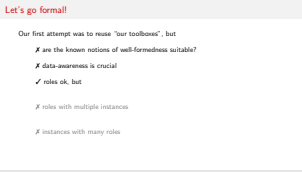


Let's go formal!

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

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



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– Act I –

[A coordination framework]

Basic concepts and notation

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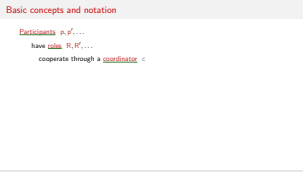

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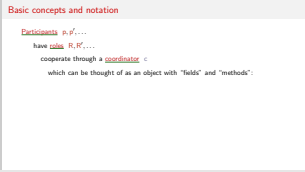

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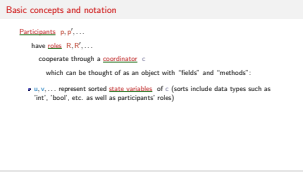

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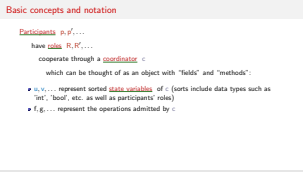

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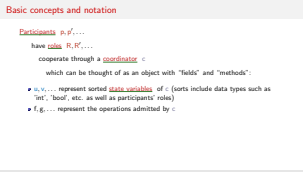

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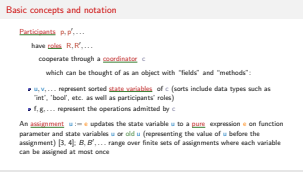
An assignment $u := e$ updates the state variable u to a pure expression e on function parameter and state variables u or old u (representing the value of u before the assignment) [3, 4]; $B, B', \ldots$ range over finite sets of assignments where each variable can be assigned at most once



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

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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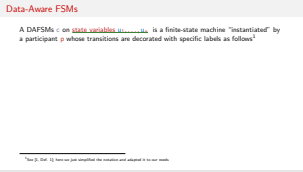

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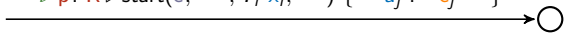
$\nu\ p\colon R \triangleright \mathsf{start}(c, \cdots, T_i\ x_i, \cdots)\ \{\cdots u_j := e_j \cdots\}$



the DAFSM c is freshly created by p instantiating state variables u_j with expressions e_j on state variables and the parameters x_i

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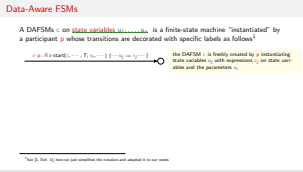

each state variable is declared and initialises with type-consistent expressions on state variables and parameters u_j

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

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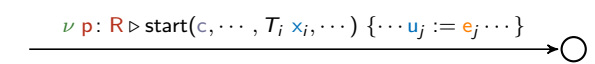

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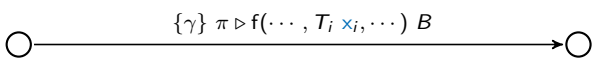

where γ is a guard (ie a boolean expression) and

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

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

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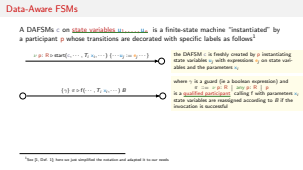

γ predicates over state variables and formal parameters of its transition; guards have to be satisfied for the invocation to succeed: an invocation that makes the guard false is rejected

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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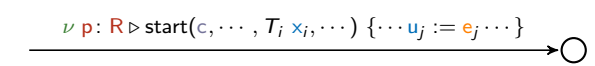

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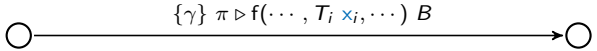

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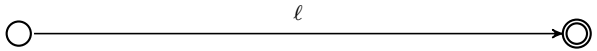

accepting states are denoted as usual

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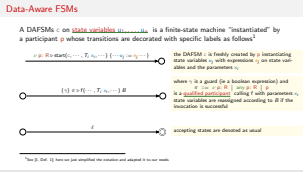

Exercise: modelling

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

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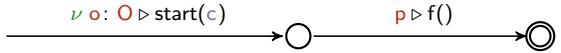
let them play with qualified participants

Not all DAFSMs “make sense”



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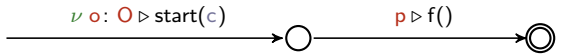

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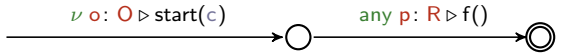
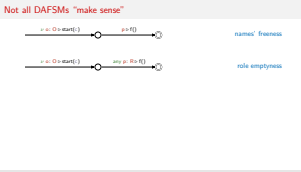


role emptyness



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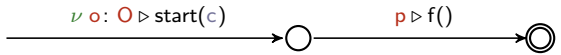

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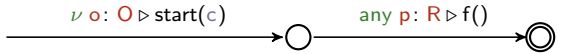

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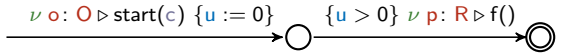
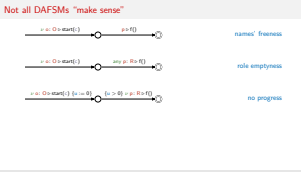


no progress



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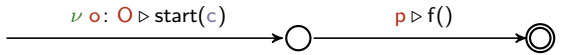

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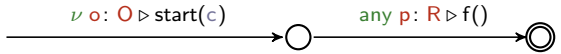

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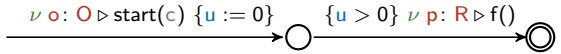

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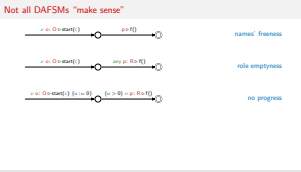

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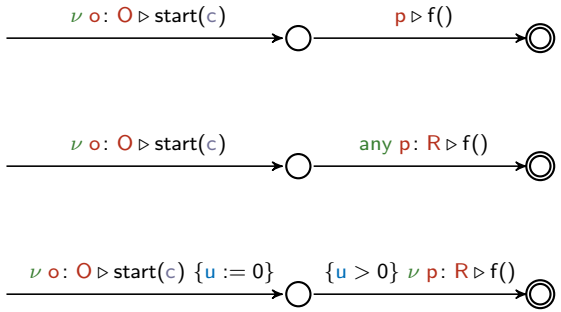
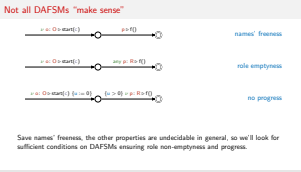


Save names' freeness, the other properties are undecidable in general, so we'll look for sufficient conditions on DAFSMs ensuring role non-emptyness and progress.



Closed DAFSMs

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

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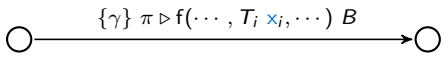
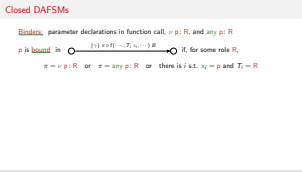
p is bound in 

if, for some role R,

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



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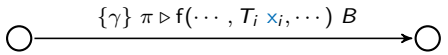
p is bound in 

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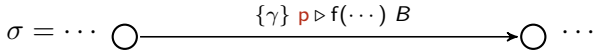
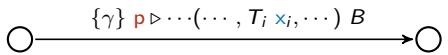
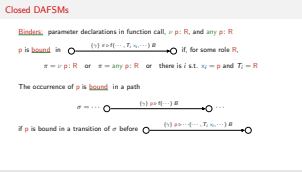
The occurrence of p is bound in a path



if p is bound in a transition of σ before 



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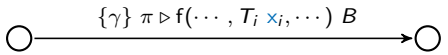
p is bound in 

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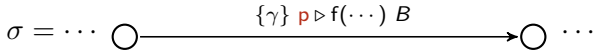
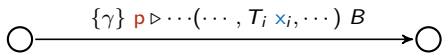
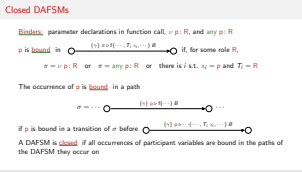


if p is bound in a transition of σ before 

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



Roles non-emptyness

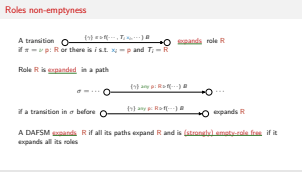
A transition $\bigcirc \xrightarrow{\{\gamma\}\ \pi \triangleright \mathsf{f}(\cdots, T_i\ \mathsf{x}_i, \cdots)\ B} \bigcirc$ expands role R
if $\pi = \nu\ \mathsf{p}\colon \mathsf{R}$ or there is i s.t. $\mathsf{x}_i = \mathsf{p}$ and $T_i = \mathsf{R}$

Role R is expanded in a path

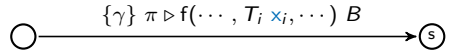
$$\sigma = \cdots \bigcirc \xrightarrow{\{\gamma\}\ \text{any p}\colon \mathsf{R} \triangleright \mathsf{f}(\cdots)\ B} \bigcirc \cdots$$

if a transition in σ before $\bigcirc \xrightarrow{\{\gamma\}\ \text{any p}\colon \mathsf{R} \triangleright \mathsf{f}(\cdots)\ B} \bigcirc$ expands R

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



Progress

A DAFSM with state variables $U = \{u_1, \ldots, u_n\}$ is consistent if it is closed and the following implication holds for each transition 

$$\forall(u, \text{old } u)_{u \in U}\ \exists(x)_{x \in X} :\ (\gamma\{\text{old } u/u\}_{u \in U}\ \wedge\ \gamma_B) \implies \gamma_s$$

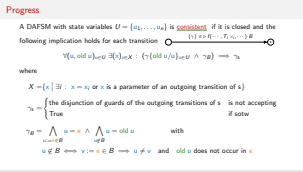
where

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

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

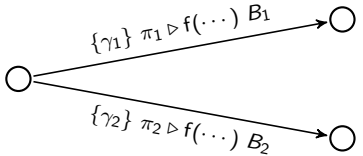
$$\gamma_B = \bigwedge_{u := e \in B} u = e\ \wedge\ \bigwedge_{u \notin B} u = \text{old } u \qquad \text{with}$$

$$u \notin B \iff v := e \in B \implies u \neq v \quad \text{and} \quad \text{old } u \text{ does not occur in } e$$



Determinism

A DAFSM is deterministic if

whenever 

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

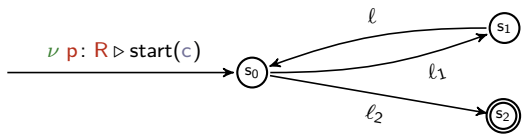
where $\_ \# \_$ is the least binary symmetric relation s.t.

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

Determinism
A DAFSM is deterministic if
whenever
then
where $\_ \# \_$ is the least binary symmetric relation s.t.

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

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1. no: eg for $\ell_1 = \ell_2 = \nu$ p: R $\mathcal{S}$ is deterministic
2. $\ell_1 = \ell_2 = \ \nu$ p: R ▷ f($\cdots$, 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

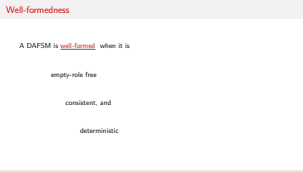
Well-formedness

A DAFSM is well-formed when it is

empty-role free

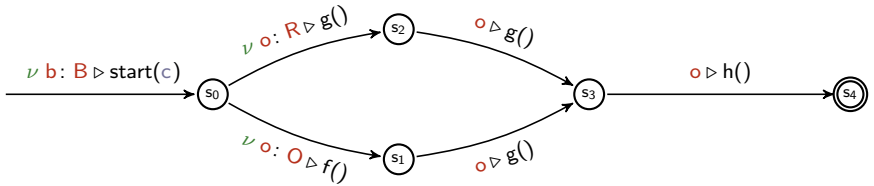
consistent, and

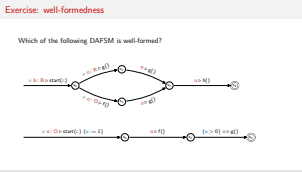
deterministic



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]

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
- ✓ it's efficient enough
- ✗ but cannot handle roles and inter-contract interactions

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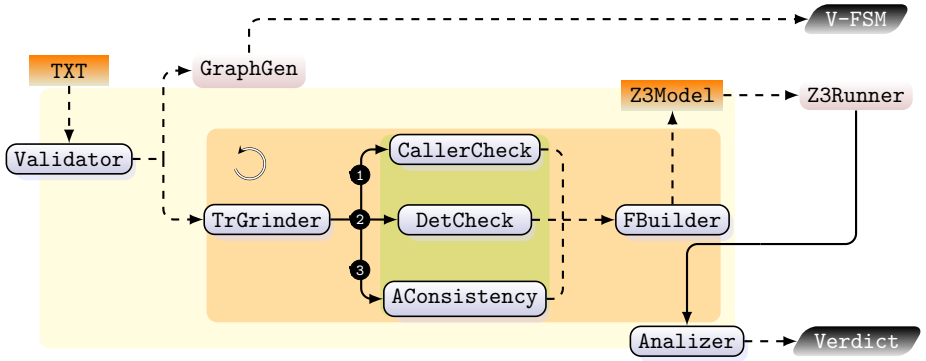
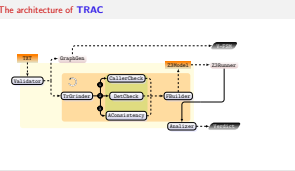
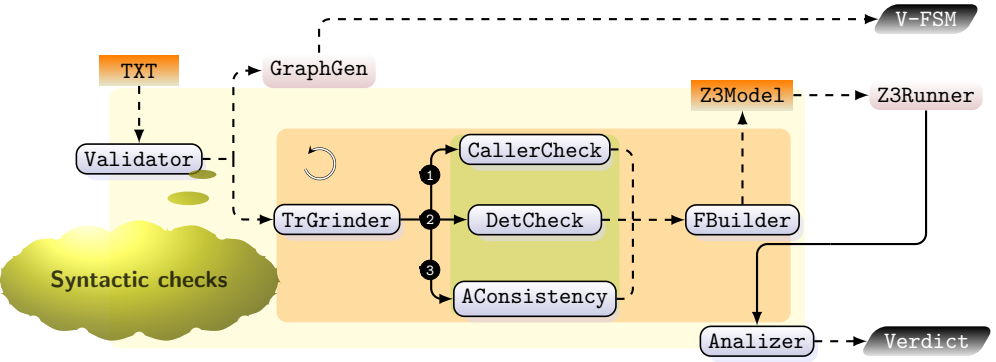
The architecture of **TRAC**

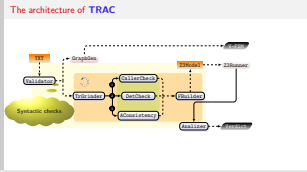




the architecture of **TRAC** is compartmentalised into two principal modules: parsing and visualisation (yellow box) and **TRAC**'s core (orange box). The latter module implements well-formedness check (green box). Solid arrows represent calls between components while dashed arrows data IO.

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.

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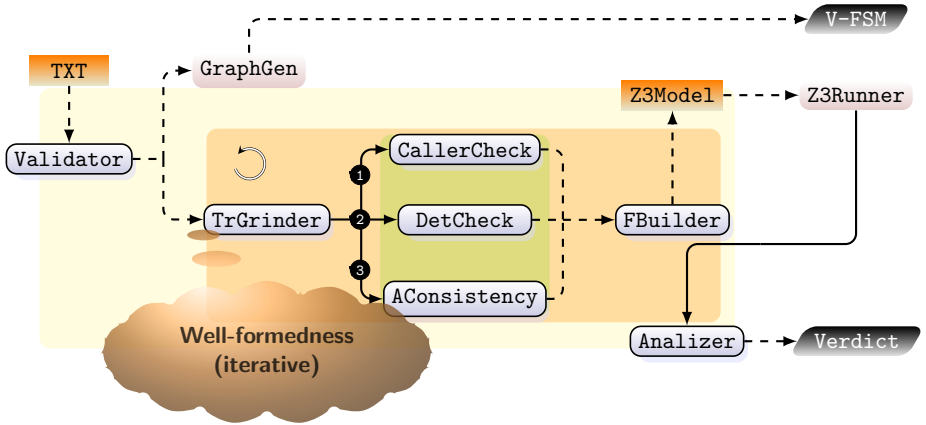

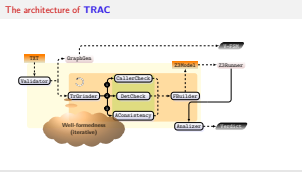

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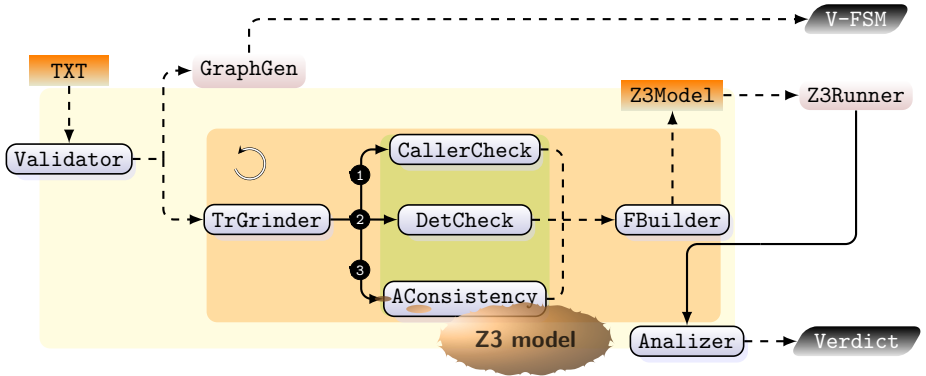
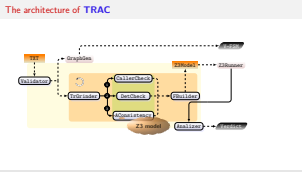
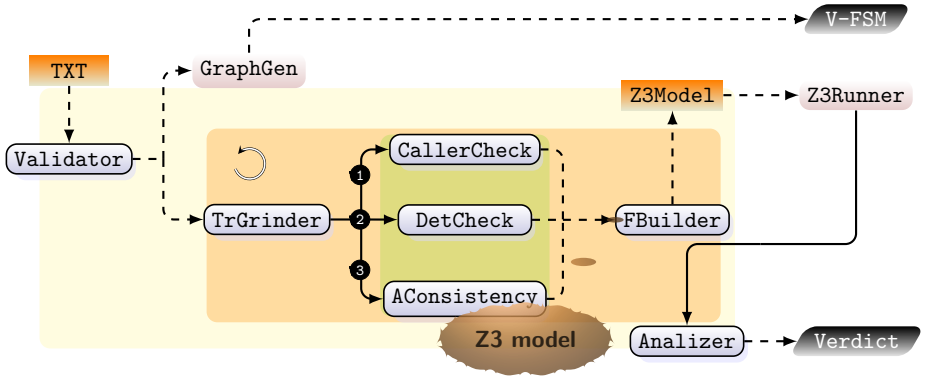
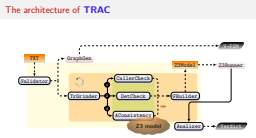




`AConsistency` (arrow ❸ to generate a Z3 formula which holds if, and only if, the transtion is consistent.

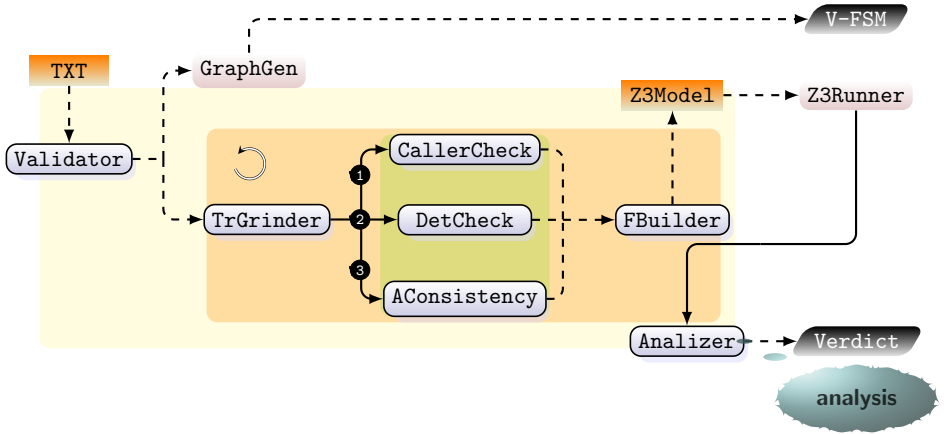
The architecture of **TRAC**

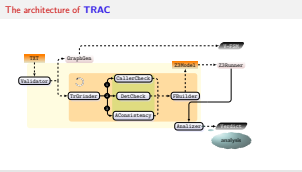




computes the z3 f.la equivalent to the conjunction of the outputs which is then passed to a Z3 engine to check its satisfiability

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

```
$ pip install z3-solver matplotlib networkx
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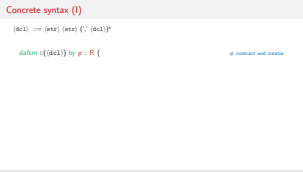
Concrete syntax (I)

⟨dcl⟩ ::= ⟨str⟩ ⟨str⟩ (',' ⟨dcl⟩)*

dafsm c(⟨dcl⟩) by p : R { # contract and creator



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

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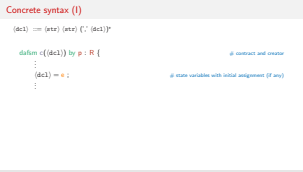
⋮

⟨dcl⟩ = e ; # state variables with initial assignment (if any)

⋮



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⟨lbl⟩ ::= {γ} ⟨qlf⟩ '>' f(···) {⟨asg⟩}

⟨asg⟩ ::= ⟨str⟩ ':=' e (';' ⟨asg⟩)*

⟨qlf⟩ ::= new p ':' R | any p ':' R | p

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⟨str⟩ ⟨lbl⟩ ⟨str⟩ ;                                # the initial state defaults to the source state of the first transition
⋮                                                  # final states are strings with a trailing '+' sign
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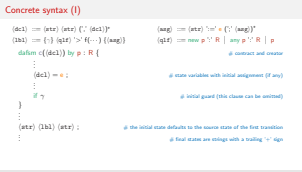

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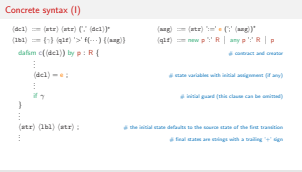

recall that e and γ are SMT-Lib2 syntax for expressions and boolean expressions respectively
in gray optional lexemes

Exercise: **TRAC** syntax (I)

Edit a `.trac` file for the DAFSM on slide **??**.

use basic_provenance.txt ?

Exercise: **TRAC** syntax (I)
Edit a `.trac` file for the DAFSM on slide **??**.

Concrete syntax (II)

The syntax of expressions (and hence of guards) follows the z3py API (at ??)

Concrete syntax (II)
The syntax of expressions (and hence of guards) follows the z3py API (at ??)

Exercise: **TRAC** syntax (II)

Edit a `.trac` file for the DAFSM on slide **??**.

Exercise: **TRAC** syntax (II)
Edit a `.trac` file for the DAFSM on slide **??**.

– Act III –

[A little exercise]

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

– Epilogue –

[Work in progress]

Thank you

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