

# A Choreographic View of Smart Contracts

Elvis Gerardin Konjoh Selabi  
@GSSI & UniCam

Maurizio Murgia  
@GSSI

António Ravara  
@NOVA

Emilio Tuosto  
@ GSSI

A tutorial @ FORTE 2025, Lille

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

This slides



## What's up doc?

Prologue ..... An inspiring initiative

## What's up doc?

Prologue . . . . . An inspiring initiative

Act I . . . . . A coordination framework

## What's up doc?

Prologue . . . . . An inspiring initiative

Act I . . . . . A coordination framework

Act II . . . . . Some tool support

## What's up doc?

Prologue . . . . . An inspiring initiative

Act I . . . . . A coordination framework

Act II . . . . . Some tool support

Act III . . . . . A little exercise

## What's up doc?

Prologue . . . . . An inspiring initiative

Act I . . . . . A coordination framework

Act II . . . . . Some tool support

Act III . . . . . A little exercise

Epilogue . . . . . Work in progress

– Prologue –

[ An inspiring initiative ]



# A nice sketch! [5, 6]

## A smart contract among Owners and Buyers

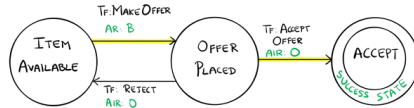
### SIMPLE MARKETPLACE STATE TRANSITIONS

#### APPLICATION ROLES:

- OWNER (O)
- BUYER (B)

#### LEGEND

- TF: TRANSITION FUNCTION
- AR: ALLOWED ROLE
- AIR: ALLOWED INSTANCE ROLE
- — A HAPPY PATH



**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]*

# A new coordination model

So, we saw an interesting model where

distributed components coordinate through a global specification

which specifies how actions are enabled along the computation

“without forcing” components to be cooperative!

# Let's look at our sketch again

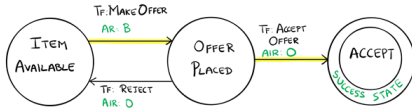
## SIMPLE MARKETPLACE STATE TRANSITIONS

### APPLICATION ROLES:

- OWNER (O)
- BUYER (B)

### LEGEND

- TF: TRANSITION FUNCTION
- AR: ALLOWED ROLE
- AIR: ALLOWED INSTANCE ROLE
- — A HAPPY PATH



# Let's look at our sketch again

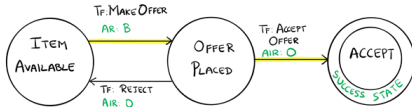
## SIMPLE MARKETPLACE STATE TRANSITIONS

### APPLICATION ROLES:

- OWNER (O)
- BUYER (B)

### LEGEND

- TF: TRANSITION FUNCTION
- AR: ALLOWED ROLE
- AIR: ALLOWED INSTANCE ROLE
- — A HAPPY PATH



but...

✗ what's the difference between roles and instances?

✗ can buyers be owners too?

✗ what's the scope of quantifications?

✗ when are transitions enabled?

✗ how does the state of the contract change?

## Let's go formal!

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

✗ are known notions of well-formedness suitable?

✗ data-awareness is crucial

✓ we got roles okay, but

✗ limitations on instances of roles

✗ instances can have one role only

## 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

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

...and by the way

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



Bug-free programming is a difficult task and a fundamental challenge for critical systems. To this end, formal methods provide techniques to develop programs and certify their correctness.

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

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

Buidl Participate Research

## FORMAL VERIFICATION OF SMART CONTRACTS



Last edit: @bskrksyp9, July 26, 2024

[See contributors](#)

[Smart contracts](#) are making it possible to create decentralized, trustless, and robust applications that introduce new use-cases and unlock value for users. Because smart contracts handle large amounts of value, security is a critical consideration for developers.

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



– Act I –

[ A coordination framework ]

# Basic concepts and notation

Participants  $p, p', \dots$

# Basic concepts and notation

Participants  $p, p', \dots$

have roles  $R, R', \dots$

# Basic concepts and notation

Participants  $p, p', \dots$

have roles  $R, R', \dots$

and cooperate through a coordinator  $c$

# Basic concepts and notation

Participants  $p, p', \dots$

have roles  $R, R', \dots$

and cooperate through a coordinator  $c$

which can be thought of as an object with “fields” and “methods”:

# Basic concepts and notation

Participants  $p, p', \dots$

have roles  $R, R', \dots$

and cooperate through a coordinator  $c$

which can be thought of as an object with “fields” and “methods”:

$u, v, \dots$  represent sorted state variables of  $c$  (sorts include data types such as 'int', 'bool', etc. as well as participants' roles)

# Basic concepts and notation

Participants  $p, p', \dots$

have roles  $R, R', \dots$

and cooperate through a coordinator  $c$

which can be thought of as an object with “fields” and “methods”:

$u, v, \dots$  represent sorted state variables of  $c$  (sorts include data types such as 'int', 'bool', etc. as well as participants' roles)

$f, g, \dots$  represent the operations admitted by  $c$

# Basic concepts and notation

Participants  $p, p', \dots$

have roles  $R, R', \dots$

and cooperate through a coordinator  $c$

which can be thought of as an object with “fields” and “methods”:

$u, v, \dots$  represent sorted state variables of  $c$  (sorts include data types such as 'int', 'bool', etc. as well as participants' roles)

$f, g, \dots$  represent the operations admitted by  $c$

$u := e$  is an assignment which updates the state variable  $u$  to a pure expression  $e$  on

- function parameters
- state variables  $u$  or  $\text{old } u$  (representing the value of  $u$  before the assignment) [3, 4]



# Basic concepts and notation

Participants  $p, p', \dots$

have roles  $R, R', \dots$

and cooperate through a coordinator  $c$

which can be thought of as an object with “fields” and “methods”:

$u, v, \dots$  represent sorted state variables of  $c$  (sorts include data types such as 'int', 'bool', etc. as well as participants' roles)

$f, g, \dots$  represent the operations admitted by  $c$

$u := e$  is an assignment which updates the state variable  $u$  to a pure expression  $e$  on

- function parameters

- state variables  $u$  or  $\text{old } u$  (representing the value of  $u$  before the assignment) [3, 4]

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

# Data-Aware FSMs

A DAFSM  $c$  on roles  $R_1, \dots, R_m$  and state variables  $u_1, \dots, u_n$  is a finite-state machine “instantiated” by a participant  $p$  whose transitions are decorated as follows<sup>1</sup>


---

<sup>1</sup>See [1, Def. 1]; here we just simplified the notation and adapted it to our needs

# Data-Aware FSMs

A DAFSM  $c$  on roles  $R_1, \dots, R_m$  and state variables  $u_1, \dots, u_n$  is a finite-state machine “instantiated” by a participant  $p$  whose transitions are decorated as follows<sup>1</sup>

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



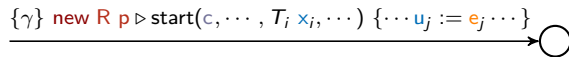
$c$  is freshly created by  $p$  which also initialises state variables  $u_j$  with expressions  $e_j$  which are built on state variables and parameters  $x_i$

---

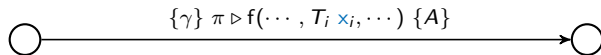
<sup>1</sup>See [1, Def. 1]; here we just simplified the notation and adapted it to our needs

# Data-Aware FSMs

A DAFSM  $c$  on roles  $R_1, \dots, R_m$  and state variables  $u_1, \dots, u_n$  is a finite-state machine “instantiated” by a participant  $p$  whose transitions are decorated as follows<sup>1</sup>



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

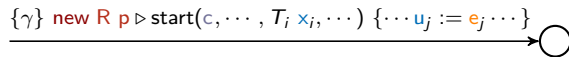


where  $\gamma$  is a guard (ie a boolean expression) and  $\pi ::= \text{new } R \ p \mid \text{any } R \ p \mid p$  is a qualified participant calling  $f$  with parameters  $x_i$ ; state variables are reassigned according to  $A$  if the invocation is successful

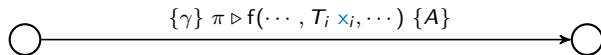
<sup>1</sup>See [1, Def. 1]; here we just simplified the notation and adapted it to our needs

# Data-Aware FSMs

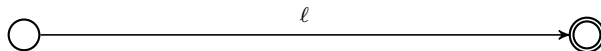
A DAFSM  $c$  on roles  $R_1, \dots, R_m$  and state variables  $u_1, \dots, u_n$  is a finite-state machine “instantiated” by a participant  $p$  whose transitions are decorated as follows<sup>1</sup>



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



where  $\gamma$  is a guard (ie a boolean expression) and  $\pi ::= \text{new } R \text{ } p \mid \text{any } R \text{ } p \mid p$  is a qualified participant calling  $f$  with parameters  $x_i$ ; state variables are reassigned according to  $A$  if the invocation is successful



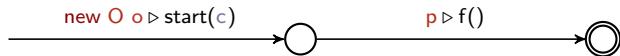
accepting states are denoted as usual

<sup>1</sup>See [1, Def. 1]; here we just simplified the notation and adapted it to our needs

## Exercise: modelling

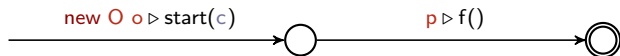
Give a DAFSM for the protocol on slide 8 resolving the ambiguities discussed there.

## Not all DAFSMs “make sense”

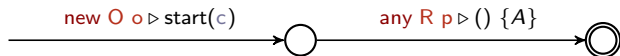


names' freeness

## Not all DAFSMs “make sense”



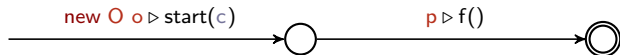
names' freeness



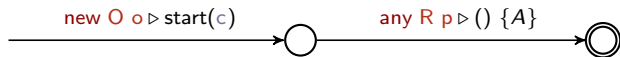
role emptiness



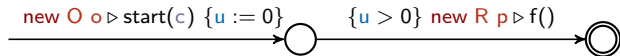
## Not all DAFSMs “make sense”



names' freeness

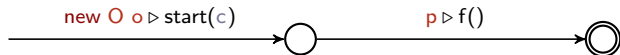


role emptiness

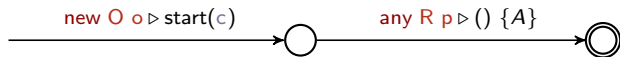


no progress

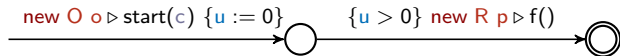
## Not all DAFSMs “make sense”



names' freeness



role emptiness



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 (with scope local to the transition),  
new  $R\ p$ , and any  $R\ p$  (with scope along paths)

# Closed DAFSMs

Binders: parameter declarations in function calls (with scope local to the transition),  
new  $R$   $p$ , and any  $R$   $p$  (with scope along paths)

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

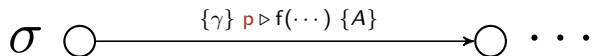
$\pi = \text{new } R \ p$  or  $\pi = \text{any } R \ p$  or there is  $i$  s.t.  $x_i = p$  and  $T = R_i$

# Closed DAFSMs

Binders: parameter declarations in function calls (with scope local to the transition),  
**new**  $R\ p$ , and **any**  $R\ p$  (with scope along paths)

$p$  is bound in  $\bigcirc \xrightarrow{\{\gamma\} \pi \triangleright f(\dots, T_i\ x_i, \dots) \{A\}} \bigcirc$  if, for some role  $R$ ,  
 $\pi = \text{new } R\ p$  or  $\pi = \text{any } R\ p$  or there is  $i$  s.t.  $x_i = p$  and  $T = R_i$

The occurrence of  $p$  is bound in a path



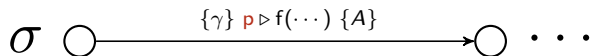
if  $p$  is bound in a transition of  $\sigma$

# Closed DAFSMs

Binders: parameter declarations in function calls (with scope local to the transition),  
**new**  $R\ p$ , and **any**  $R\ p$  (with scope along paths)

$p$  is bound in  $\bigcirc \xrightarrow{\{\gamma\} \pi \triangleright f(\dots, T_i\ x_i, \dots) \{A\}} \bigcirc$  if, for some role  $R$ ,  
 $\pi = \text{new } R\ p$  or  $\pi = \text{any } R\ p$  or there is  $i$  s.t.  $x_i = p$  and  $T = R_i$

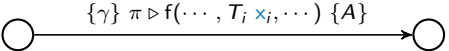
The occurrence of  $p$  is bound in a path



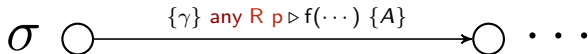
if  $p$  is bound in a transition of  $\sigma$

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

## Role emptiness

A transition  expands role  $R$  if  $\pi = \text{new } R \text{ } p$  or there is  $i$  s.t.  $x_i = p$  and  $T_i = R$

Role  $R$  is expanded in a path

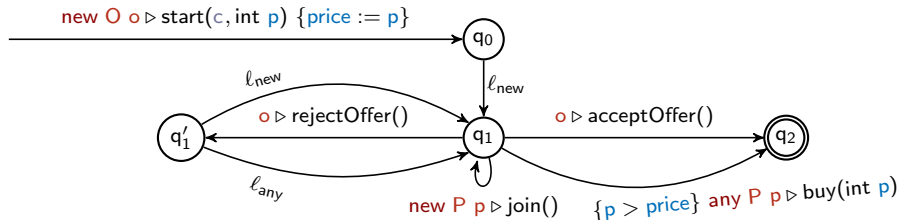


if a transition in  $\sigma$  expands  $R$

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

## Exercise: Role emptiness

Is the DAFSM below empty-role free?



where

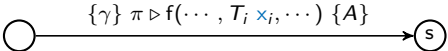
$\ell_{\text{new}} = \{ \text{newOffer} > 0 \} \text{ new } B \ b \triangleright \text{makeOffer}(\text{int } \text{newOffer}) \{ \text{offer} := \text{newOffer} \}$  and

$\ell_{\text{any}} = \{ \text{newOffer} > 0 \} \text{ any } B \ b \triangleright \text{makeOffer}(\text{int } \text{newOffer}) \{ \text{offer} := \text{newOffer} \}$



# Progress

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

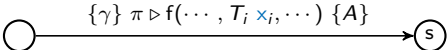
for each 

$\forall_U \mathbb{E}_X (\gamma\{\text{old } u_1, \dots, \text{old } u_n / u_1, \dots, u_n\} \wedge \gamma_A \implies \bigvee_{1 \leq j \leq m} \mathbb{E}_{\gamma_j} \gamma_j)$  is satisfiable

where

# Progress

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

for each 

$\forall_U \mathbb{E}_X (\gamma\{\text{old } u_1, \dots, \text{old } u_n / u_1, \dots, u_n\} \wedge \gamma_A \implies \bigvee_{1 \leq j \leq m} \mathbb{E}_{Y_j} \gamma_j)$  is satisfiable

where

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

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

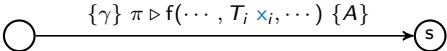
$$\gamma_A = \bigwedge_{u := e \in A} u = e \wedge \bigwedge_{u \notin A} u = \text{old } u$$

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

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

# Progress

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

for each 

$\forall_U \mathbb{E}_X (\gamma\{\text{old } u_1, \dots, \text{old } u_n / u_1, \dots, u_n\} \wedge \gamma_A \implies \bigvee_{1 \leq j \leq m} \mathbb{E}_{Y_j} \gamma_j)$  is satisfiable

and  is such that  $\mathbb{E}_X \gamma$  is satisfiable

where

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

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

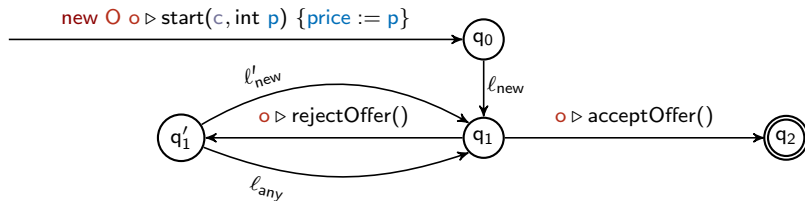
$$\gamma_A = \bigwedge_{u := e \in A} u = e \wedge \bigwedge_{u \notin A} u = \text{old } u$$

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

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

# Exercise: Consistency

Is the DAFSM below consistent?



where

$\ell_{\text{new}} = \{\text{newOffer} > 0\}$  **new**  $B$   $b \triangleright \text{makeOffer}(\text{int newOffer}) \{\text{offer} := \text{newOffer}\},$

$\ell'_{\text{new}} = \{\text{newOffer} \geq \text{price} * 1.05\}$  **new**  $B$   $b \triangleright \text{makeOffer}(\text{int newOffer}) \{\text{offer} := \text{newOffer}\},$  and

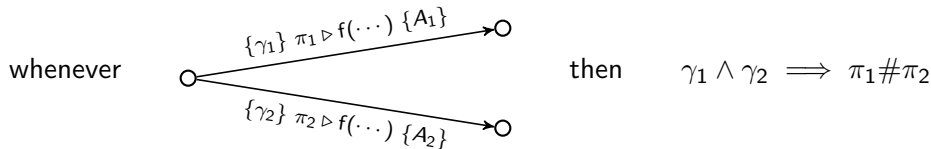
$\ell_{\text{any}} = \{\text{newOffer} \geq \text{price} * 1.05\}$  **any**  $B$   $b \triangleright \text{makeOffer}(\text{int newOffer}) \{\text{offer} := \text{newOffer}\}$

# Determinism

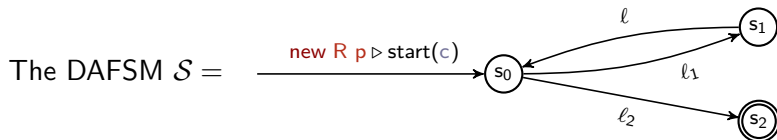
Let  $\#$  be the least binary symmetric relation s.t.

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

A DAFSM is deterministic if



## Exercise: Determinism



is deterministic or not, depending on the labels  $\ell_1$  and  $\ell_2$ .

- 1 Is it the case that  $\mathcal{S}$  is not deterministic whenever  $\ell_1 = \ell_2$ ?
- 2 Find two labels  $\ell_1$  and  $\ell_2$  that make  $\mathcal{S}$  deterministic
- 3 Find two labels  $\ell_1 \neq \ell_2$  that make  $\mathcal{S}$  non-deterministic

# Well-formedness

A DAFSM is well-formed when it is

closed,

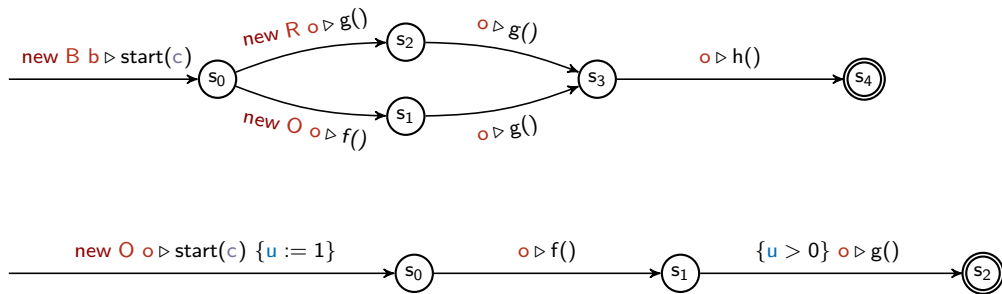
empty-role free,

consistent, and

deterministic

## Exercise: Well-formedness

Which of the following DAFSM is well-formed?





– Act II –

[ A tool ]

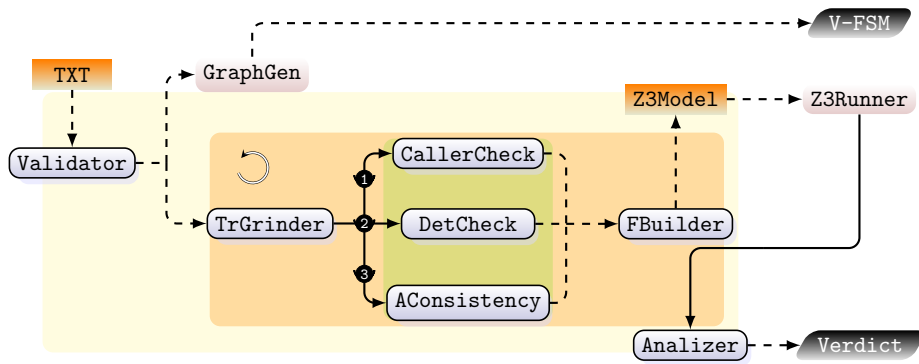
# Verification

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

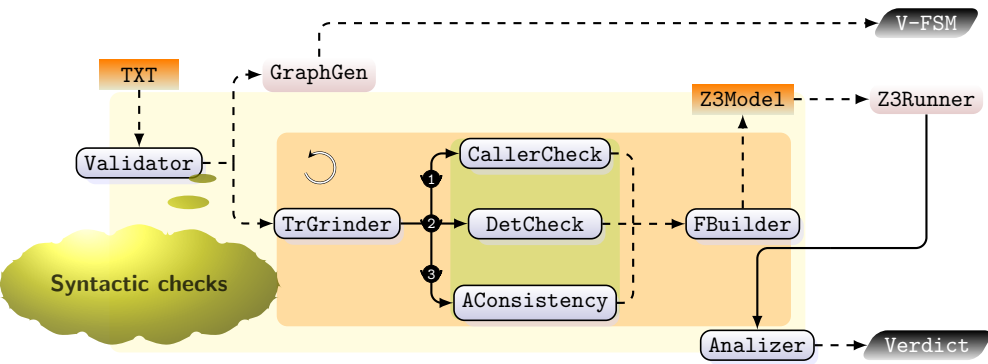
So we implemented a tool which

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

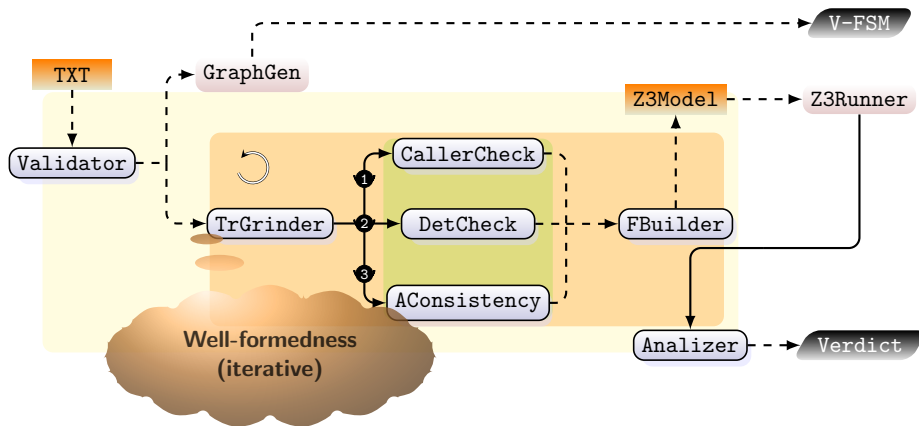
# The architecture of TRAC



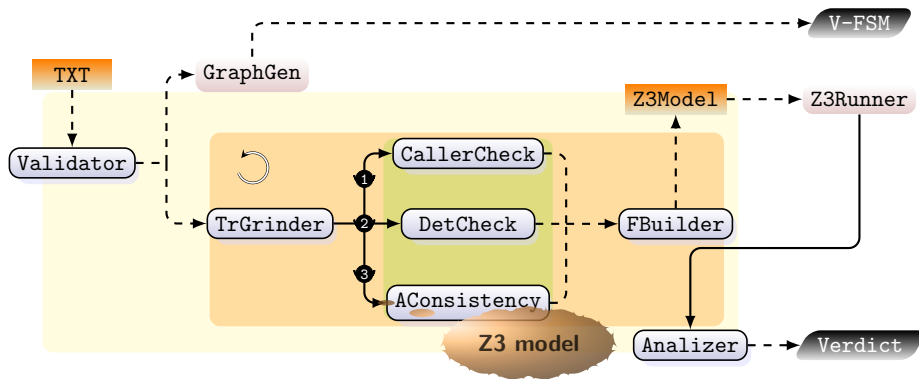
# The architecture of TRAC



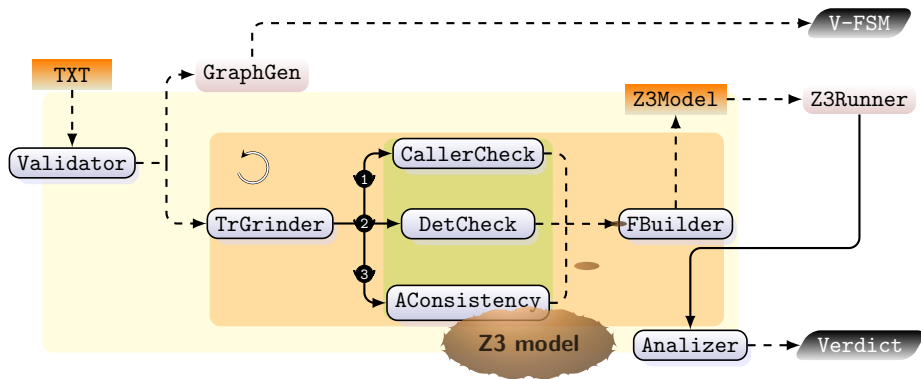
# The architecture of TRAC



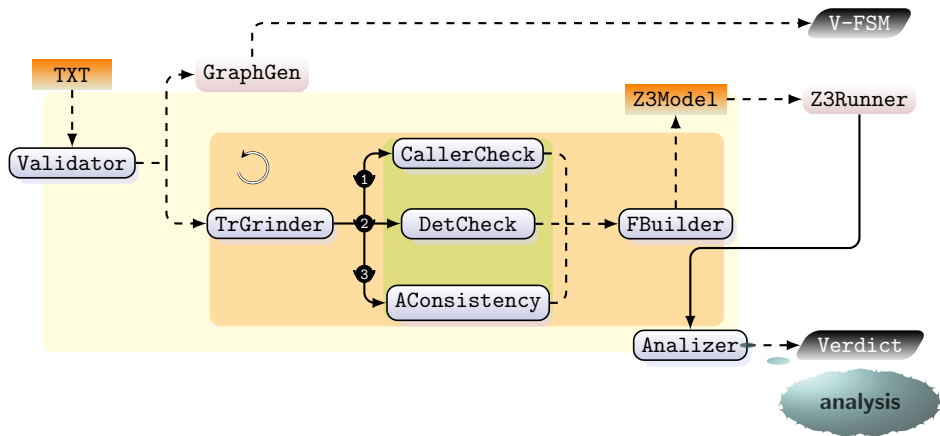
# The architecture of TRAC



# The architecture of TRAC



# The architecture of TRAC





## Getting TRAC

In the cloud: `https://trac-5sy1.onrender.com/`

or

In your hands: `https://github.com/loctet/TRAC/tree/TRAC\_v1/`

Dependencies: GraphViz and Python 3.7 or later

Installation instructions in the README.md

## Concrete syntax (I)

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

```
roles  $\langle str \rangle^+$   
dafsm  $\langle str \rangle (\langle pars \rangle)$  by  $\langle dcl \rangle$  {
```

```
// set the roles  
//  $\langle dcl \rangle$  declares the participant creating the contract
```

## Concrete syntax (I)

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

```
roles  $\langle str \rangle^+$  // set the roles
dafsm  $\langle str \rangle(\langle pars \rangle)$  by  $\langle dcl \rangle$  { //  $\langle dcl \rangle$  declares the participant creating the contract
:
 $\langle dcl \rangle := e$ ; // state variables (if any) with their initial assignment
```

## Concrete syntax (I)

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

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

## Concrete syntax (I)

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

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

$\langle asgs \rangle ::= \varepsilon \mid \langle asg \rangle (; \langle asg \rangle)^*$        $\langle asg \rangle ::= \langle str \rangle := e$

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

:
[ $\langle str \rangle$ ]  $\langle lbl \rangle$  [ $\langle str \rangle$ ] ;                 // the initial state defaults to the source state of the first transition
:
                                                    // final states are strings with a trailing '+' sign
```

## Exercise: **TRAC** usage (I)

Edit a `.trac` file for the contract specified at

`https:`

`//github.com/Azure-Samples/blockchain/blob/master/blockchain-workbench/application-and-smart-contract-samples/basic-provenance/readme.md`

## Concrete syntax (II)

The syntax of non-logical expressions is as in python while logical expressions are of the form

- `Not( $e$ )`
- `And( $e_1, \dots, e_n$ )`
- `Or( $e_1, \dots, e_n$ )`
- `Imply( $e_1, e_2$ )`

See <https://ericpony.github.io/z3py-tutorial/guide-examples.htm> for examples

## Exercise: **TRAC** syntax (II)

Edit a `.trac` file for the DAFSM on slide 14.



– Act III –

[ A little exercise ]

## A non-trivial contract

Use **TRAC** to specify a well-formed DAFSM for a contract that helps to raise funds.

The instantiating participant plays the role of the owner of the contract.

Once instantiated with a goal (the amount of money to raise), the contract handles a fundraising campaign whereby contributors can deposit funds if the campaign is active.

Once the goal is met, the owner triggers an inspection phase done by two agents.

At the end of the inspection one of the agents closes the campaign so that the owner can finally withdraw the funds.

– Epilogue –

[ Work in progress ]

### DAFSMs

Refine well-formedness

Extend the model

Projections & code generation

### TRAC

Other verification approaches (model checking)

Integration with other tools

Keep improving usability

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*. Prentice-Hall, 1990.

## References II

- [4] B. Meyer. *Eiffel: The Language*.  
Prentice-Hall, 1991.
- [5] Microsoft. The blockchain workbench.  
<https://github.com/Azure-Samples/blockchain/tree/master/blockchain-workbench>, 2019.
- [6] Microsoft. Simple marketplace sample application for azure blockchain workbench.  
<https://github.com/Azure-Samples/blockchain/tree/master/blockchain-workbench/application-and-smart-contract-samples/simple-marketplace>, 2019.