Overview and Roadmap of Team Automata: from Synchronous to Asynchronous Communication

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joint work with Rolf Hennicker (LMU Munich, DE) and José Proença (University of Porto, PT)

T-LADIES 3rd year meeting, Genoa, Italy, July 22nd, 2025

Outline

- History of Team Automata
- Team Automata and other Coordination Models [anticipated at Catania meeting]
- Recent Results
  - **ICTAC'20** Compositionality of Safe Communication in Systems of Team Automata
    Extended Team Automata
  - **FM'21** Featured Team Automata
  - **FM'23** Can we Communicate? Using Dynamic Logic to Verify Team Automata
    Model Check Team Automata
  - **ICTAC'23** Realisability of Global Models of Interaction
    Realisable Team Automata [presented at Catania meeting]
- Ongoing Work: Asynchronous Team Automata [anticipated at APM in Turin]

History of Team Automata

Team Automata

A formalism for interacting component-based systems, whereby multiple sending and receiving actions from concurrent automata can synchronise on certain executions

First proposed at the 1997 ACM SIGGROUP Conference on Supporting Group Work for modelling components of groupware systems and their interconnections [GROUP'97]

Inspired by Input/Output (I/O) automata, inheriting the distinction between internal and external (input and output) actions used for communication with the environment

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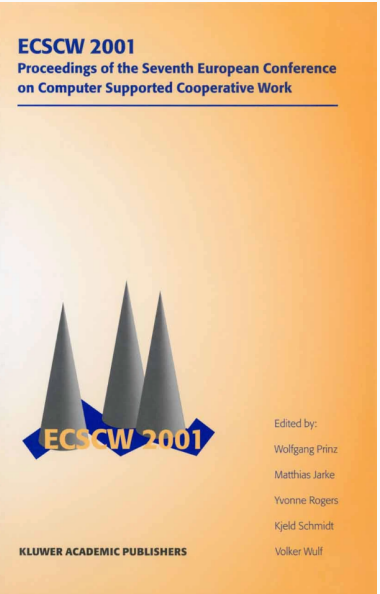
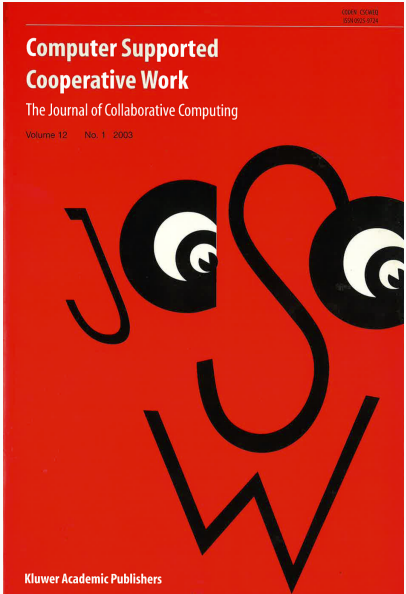
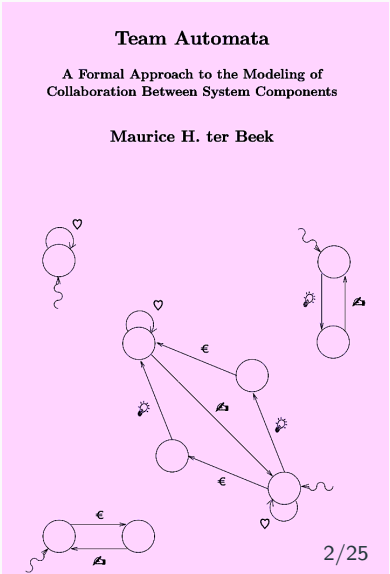
Formally defined in Computer Supported Cooperative Work (CSCW) — The Journal of Collaborative Computing, as composed by component automata that synchronise [CSCW'03]

Technically an extension of I/O automata, imposing hardly any restrictions on the role of actions in components, while composition is not limited to the synchronous product [IPL'05]

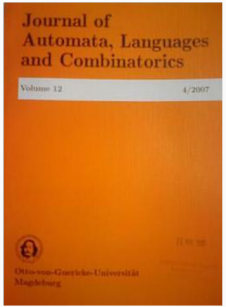
1997-2003: Team Automata and CSCW







post-2003: Team Automata and Formal Languages



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Vector team automata

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TEAMS OF PUSHDOWN AUTOMATA

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Associativity of Infinite Synchronized Shuffles and Team Automata

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A Calculus for Team Automata*

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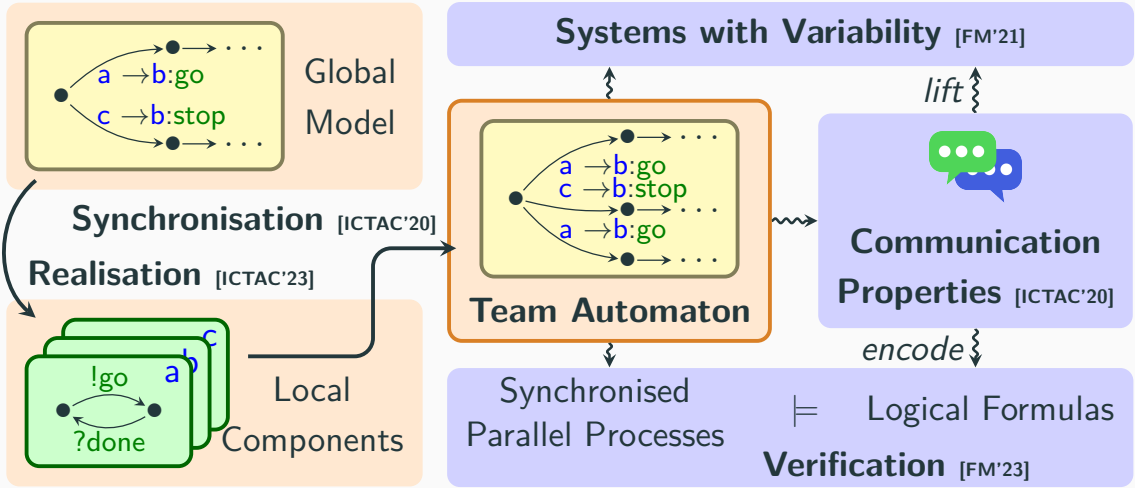
post-2003: Team Automata and Formal Methods



[COORDINATION'24]

25+ Years: Selected Publications

2024	Team Automata: Overview and Roadmap	COORDINATION'24
2023	Realisability of Global Models of Interaction	ICTAC'23
2023	Overview on Constrained Multiparty Synchronisation in Team Automata *	FACS'23
2023	Can we Communicate? Using Dynamic Logic to Verify Team Automata	FM'23
2021	Featured Team Automata	FM'21
2020	Compositionality of Safe Communication in Systems of Team Automata	ICTAC'20
2020	Team Automata@Work: On Safe Communication	COORDINATION'20
2017	Communication Requirements for Team Automata	COORDINATION'17
2016	Conditions for Compatibility of Components: The Case of Masters and Slaves	ISoLA'16
2014	On Distributed Cooperation and Synchronised Collaboration	JALC
2013	Compatibility in a multi-component environment *	TCS
2012	Vector Team Automata	TCS
2010	Team Automata Based Framework for Spatio-Temporal RBAC Model *	BAIP'10
2009	Associativity of Infinite Synchronized Shuffles and Team Automata	Fundam. Inform.
2008	Extending Team Automata to Evaluate Software Architectural Design *	COMPSAC'08
2008	A calculus for team automata	ENTCS
2007	A Review on Specifying Software Architectures Using Extended Automata-Based Models *	FSEN'07
2006	Modelling a Secure Agent with Team Automata *	ENTCS
2006	A Team Automaton Scenario for the Analysis of Security Properties in Communication Protocols	JALC
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2005	Modularity for Teams of I/O Automata	IPL
2004	Teams of Pushdown Automata	IJCM
2004	Interactive Behaviour of Multi-Component Systems *	ToBaCo'04
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Team Automata by Example

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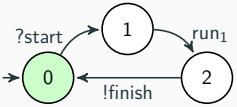

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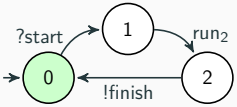

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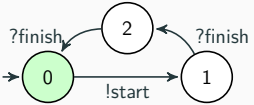

Controller

Team Automata

[CSCW'01'03] [FM'03,'21,'23] [TCS'12'13]

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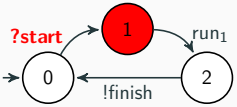

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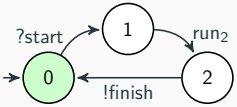

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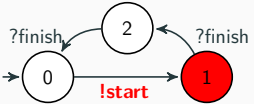

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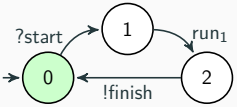

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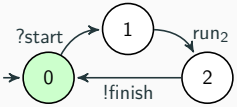

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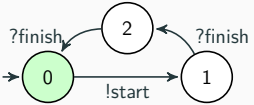

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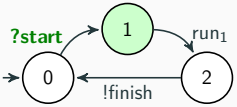

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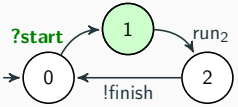

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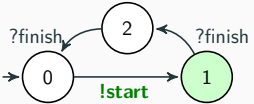

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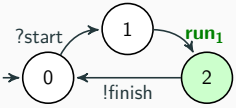

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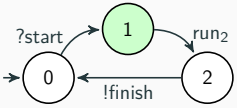

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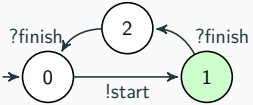

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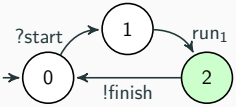

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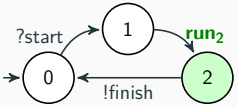

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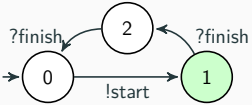

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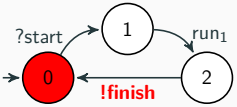

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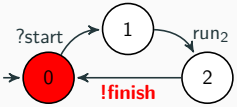

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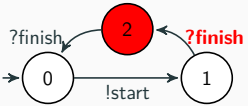

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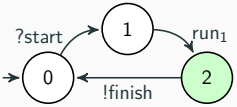

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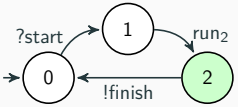

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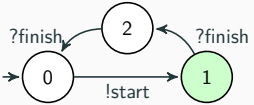

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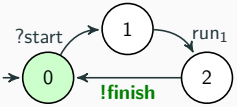

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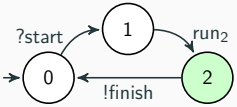

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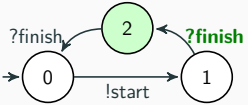

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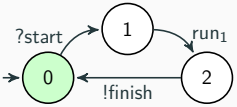
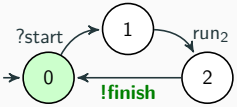
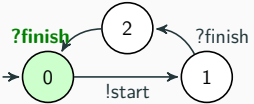


$\mathcal{R}unner_1$



$\mathcal{R}unner_2$



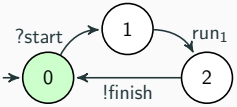
Controller

Team Automata

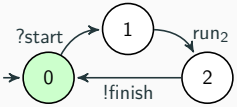
[CSCW'01'03] [FM'03,'21,'23] [TCS'12'13]

[COORDINATION'17,'20,'24] [ICTAC'20,'23]

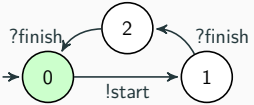
Extended Team Automata: Constrained Multiparty Synchronisations



$\mathcal{R}unner_1$



$\mathcal{R}unner_2$



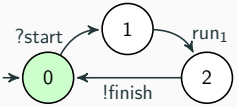
Controller

Extended TA synchronisations

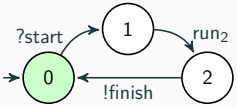
[CSCW'01'03] [FM'03,'21,'23] [TCS'12'13]

[COORDINATION'17,'20,'24] [ICTAC'20,'23]

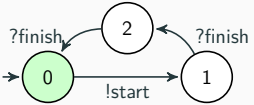
Extended Team Automata: Constrained Multiparty Synchronisations



$\mathcal{R}unner_1$



$\mathcal{R}unner_2$



Controller

Extended TA synchronisations

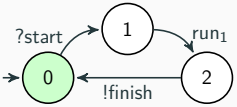
[CSCW'01'03] [FM'03,'21,'23] [TCS'12'13]

[COORDINATION'17,'20,'24] [ICTAC'20,'23]

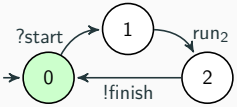
multiparty

$\text{Ctr} \rightarrow \{R1, R2\}$: start

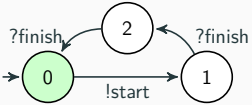
Extended Team Automata: Constrained Multiparty Synchronisations



$\mathcal{R}unner_1$



$\mathcal{R}unner_2$



Controller

Extended TA synchronisations

[CSCW'01'03] [FM'03,'21,'23] [TCS'12'13]

[COORDINATION'17,'20,'24] [ICTAC'20,'23]

multiparty

Ctr $\rightarrow \{R1, R2\}$: start

constrained

start: $1 \rightarrow 2$

finish: $1 \rightarrow 1$

Extended Team Automata and other Coordination Models

Overview on Constrained Multiparty Synchronisation in Team Automata

and other coordination models: [FACS'23] [COORDINATION'24]

Overview on Constrained Multiparty Synchronisation in Team Automata

and other coordination models: [FACS'23] [COORDINATION'24]

Runners with orchestrators

- Reo
- BIP

↳ S.-S.T.Q. Jongmans and F. Arbab, Overview of thirty semantic formalisms for Reo. *Scientific Annals of Computer Science* 22 (2012)

S. Bliudze and J. Sifakis, The algebra of connectors: structuring interaction in BIP. *IEEE Transactions on Computers* 57 (2008)

Overview on Constrained Multiparty Synchronisation in Team Automata

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Runners with choreographies

- Choreography Automata
- Multiparty Session Types

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Overview on Constrained Multiparty Synchronisation in Team Automata

and other coordination models: [FACS'23] [COORDINATION'24]

Runners with orchestrators
- Reo
- BIP

Runners with choreographies
- Choreography Automata
- Multiparty Session Types

. . . with both
- Contract Automata

S.-S.T.Q. Jongmans and F. Arbab, Overview of thirty semantic formalisms for Reo. *Scientific Annals of Computer Science* 22 (2012)

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D. Basile, P. Degano, G. Ferrari, and E. Tuosto, Relating two automata-based models of orchestration and choreography. *JLAMP* 85 (2016)

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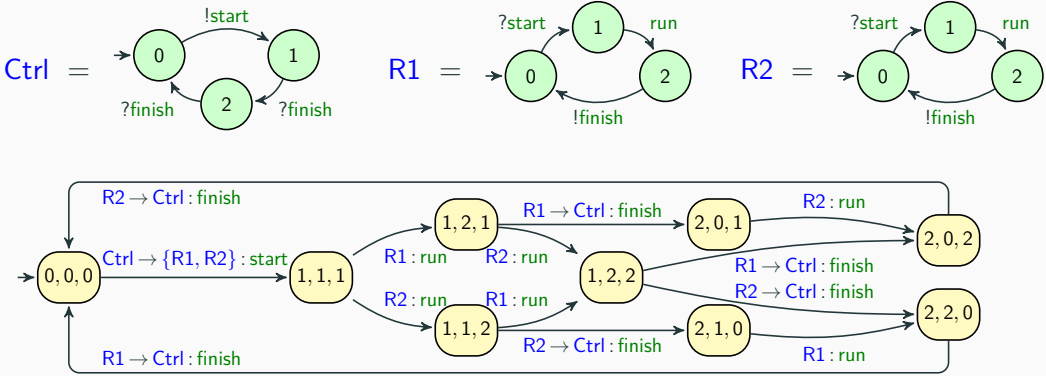
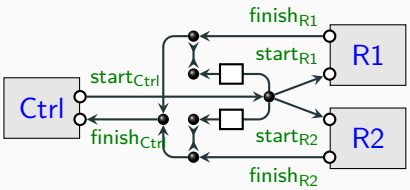
Team Automata

In [COORDINATION'24] we discuss for each formalism (1) the definition, (2) means of composition (via synchronisation), (3) a model of the Race example, (4) a brief relation with team automata, and (5) tool support

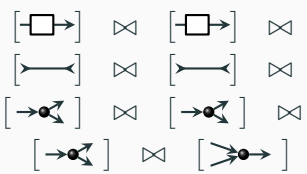
In [COORDINATION'24] we discuss for each formalism (1) the definition, (2) means of composition (via synchronisation), (3) a model of the Race example, (4) a brief relation with team automata, and (5) tool support



Reo via Port Automata



- Focus on connectors (not on components)
- Connectors built compositionally
- Components should be flexible/compatible



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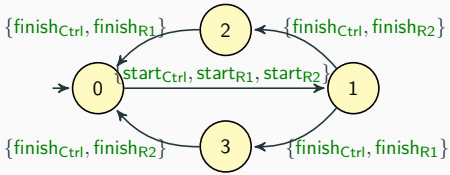
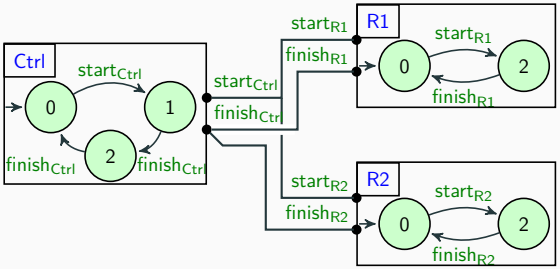


(semantics as a port automaton, after hiding internal ports shared among sub-connectors)

BIP without Priorities



$$\mathbb{N} = \{\mathsf{Ctrl}, \mathsf{R1}, \mathsf{R2}\}$$

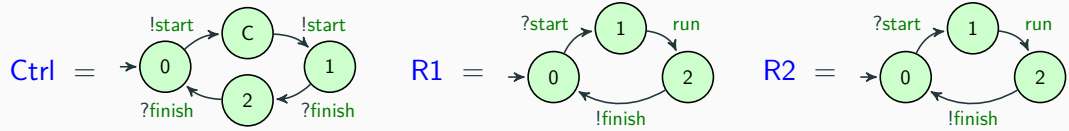
$$BP = (\{B_{\mathsf{Ctrl}}, B_{\mathsf{R1}}, B_{\mathsf{R2}}\}\ ,\ I)$$

$$I = \left\{ \begin{array}{l} \{\mathsf{start}_{\mathsf{Ctrl}}, \mathsf{start}_{\mathsf{R1}}, \mathsf{start}_{\mathsf{R2}}\}, \\ \{\mathsf{finish}_{\mathsf{Ctrl}}, \mathsf{finish}_{\mathsf{R1}}\}, \\ \{\mathsf{finish}_{\mathsf{Ctrl}}, \mathsf{finish}_{\mathsf{R2}}\} \end{array} \right\}$$

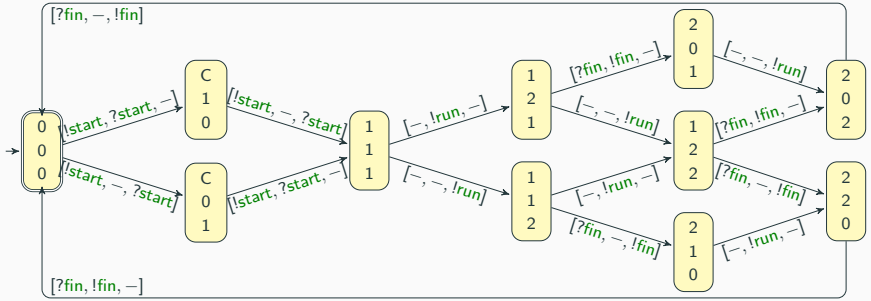
- Components expose ports
- Interactions restrict which ports can fire
- Constructors using unicast (●) and broadcast (▲) can be used to restrict interactions
- Dataflow can be added

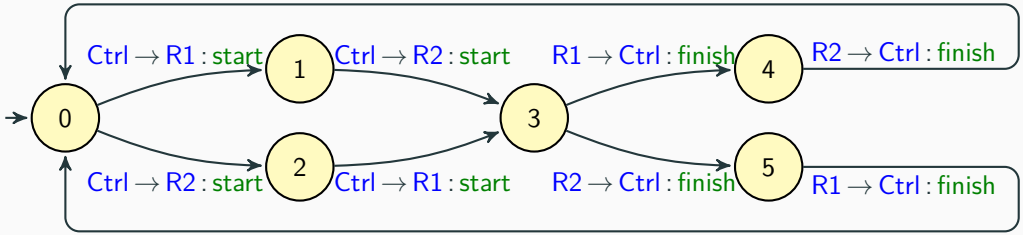
(individual components labelled by actions, restricted to the interactions allowed by I)

Contract Automata



(**C**ommitted states: whenever the intermediate state of two concatenated transitions is committed, the two transitions are executed atomically)





(without internal run actions)

- Similar to contract automata
- Several results over the language of CA
- Realising = Projecting the language of CA

Synchronous Multi-Party Session Types

$$\mathcal{G} = \mathsf{Ctrl} \to \mathsf{R1} : \mathsf{start}.\mathsf{Ctrl} \to \mathsf{R2} : \left\{ \begin{array}{l} \mathsf{start}_1.(\mathsf{R1} \to \mathsf{Ctrl} : \mathsf{finish}.\mathsf{R2} \to \mathsf{Ctrl} : \mathsf{finish}.\mathcal{G}), \\ \mathsf{start}_2.(\mathsf{R2} \to \mathsf{Ctrl} : \mathsf{finish}.\mathsf{R1} \to \mathsf{Ctrl} : \mathsf{finish}.\mathcal{G}) \end{array} \right\}$$

$$\mathcal{S} = \mathsf{Ctrl} \rhd \mathcal{L}_{\mathsf{Ctrl}} \parallel \mathsf{R1} \rhd \mathcal{L}_{\mathsf{R1}} \parallel \mathsf{R2} \rhd \mathcal{L}_{\mathsf{R2}}$$

$$\mathcal{L}_{\mathsf{Ctrl}} = \mathsf{R1}!\mathsf{start}.\mathsf{R2}!\left\{\mathsf{start}_1.(\mathsf{R1}?\mathsf{finish}.\mathsf{R2}?\mathsf{finish}.\mathcal{L}_{\mathsf{Ctrl}})\,,\ \mathsf{start}_2.(\mathsf{R2}?\mathsf{finish}.\mathsf{R1}?\mathsf{finish}.\mathcal{L}_{\mathsf{Ctrl}})\right\}$$

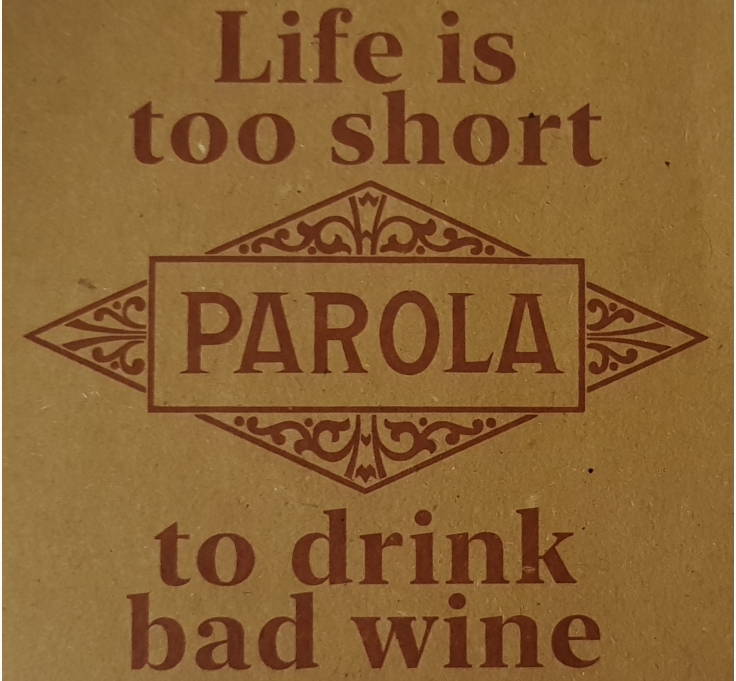
$$\mathcal{L}_{\mathsf{R1}} = \mathsf{Ctrl}?\mathsf{start}.\mathsf{Ctrl}!\mathsf{finish}.\mathcal{L}_{\mathsf{R1}}$$

$$\mathcal{L}_{\mathsf{R2}} = \mathsf{Ctrl}?\left\{\mathsf{start}_1.\mathsf{Ctrl}!\mathsf{finish}.\mathcal{L}_{\mathsf{R2}}\,,\ \mathsf{start}_2.\mathsf{Ctrl}!\mathsf{finish}.\mathcal{L}_{\mathsf{R2}}\right\}$$

(using only binary synchronisation and
using distinct start_1 and start_2 to differentiate the choice in the branch)

- Use projections for realisation
- Often impose syntactic restrictions on global types

Recent Results


Life is
too short
PAROLA
to drink
bad wine

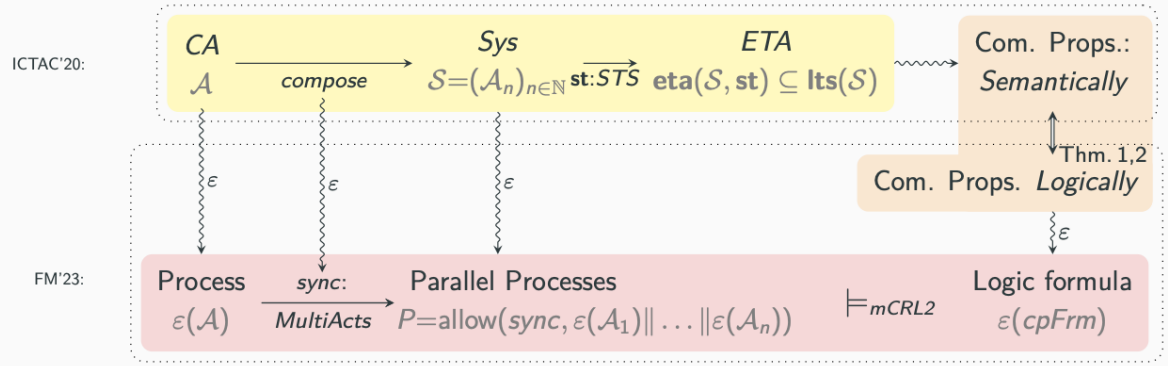
Model Check Team Automata

Safe Communication

Com. Props.: receptiveness (*no message loss*) & responsiveness (*no indefinite waiting*)

Using Dynamic Logic to Verify (Extended) Team Automata

Com. Props.: receptiveness (*no message loss*) & responsiveness (*no indefinite waiting*)



mCRL2 analysing system behaviour

Online Prototype: `https://github.com/arcalab/team-a`

ETA Specification

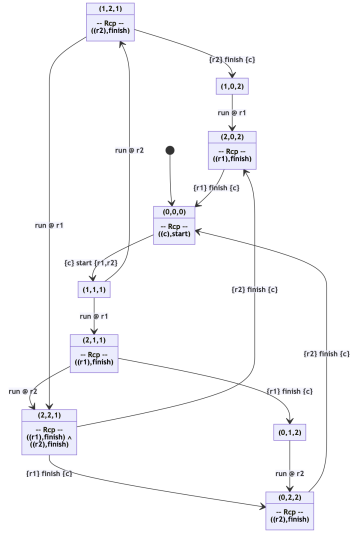
```
1  //Race example
2  CA runner (start)
3          (finish) = {
4   start 0
5   0 --> 1 by start
6   1 --> 2 by run
7   2 --> 0 by finish
8  }
9  CA controller (finish)
10          (start) = {
11  start 0
12  0 --> 1 by start
13  1 --> 2 by finish
14  2 --> 0 by finish
15 }
16 S = (r1:runner, r2:runner,
17      c:controller)
18 STS = {
19  default = 1 to 1
20  start = 1 to 2
21 }
```

Race example

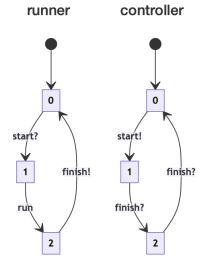
ETA Examples

Simple | Race | Chat

ETA diagram



CA



Online Prototype: `https://github.com/arcalab/team-a`

Communication Properties' Characterisation in mCRL2

Receptiveness:

```
[ (r1_finish|c_finish + r2_run + c_start|r1_start|r2_start + r2_finish|c_finish + r1_run)* ](
  ((<c_start> true)  =>  (<c_start|r1_start|r2_start> true)) &&
  ((<r1_finish> true)  =>  (<r1_finish|c_finish> true)) &&
  ((<r2_finish> true)  =>  (<r2_finish|c_finish> true))
)
```

Responsiveness:

```
[ (r1_finish|c_finish + r2_run + c_start|r1_start|r2_start + r2_finish|c_finish + r1_run)* ](
   (<c_finish +
     r1_start|r2_start> true)
   =>
   (<r1_finish|c_finish +
     c_start|r1_start|r2_start +
     r2_finish|c_finish> true)
)
```

Weak Receptiveness:

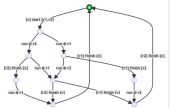
```
[ (r1_finish|c_finish + r2_run + c_start|r1_start|r2_start + r2_finish|c_finish + r1_run)* ](
  ((<r1_finish> true)  =>  (<(r2_run+r2_finish|c_finish)* . r1_finish|c_finish> true)) &&
  ((<r2_finish> true)  =>  (<(r1_finish|c_finish+r1_run)* . r2_finish|c_finish> true)) &&
  ((<c_start> true)  =>  (<(r2_run+r1_run)* . c_start|r1_start|r2_start> true))
)
```

Weak Responsiveness:

```
[ (r1_finish|c_finish + r2_run + c_start|r1_start|r2_start + r2_finish|c_finish + r1_run)* ](
   (<c_finish +
     r1_start|r2_start> true)
   =>
   (<(r2_run+r1_run)* . r1_finish|c_finish +
     c_start|r1_start|r2_start +
     (r2_run+r1_run)* . r2_finish|c_finish> true)
)
```

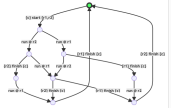
View mCRL2 evidence

Receptiveness: true

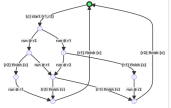


Responsiveness: false

Weak Receptiveness: true



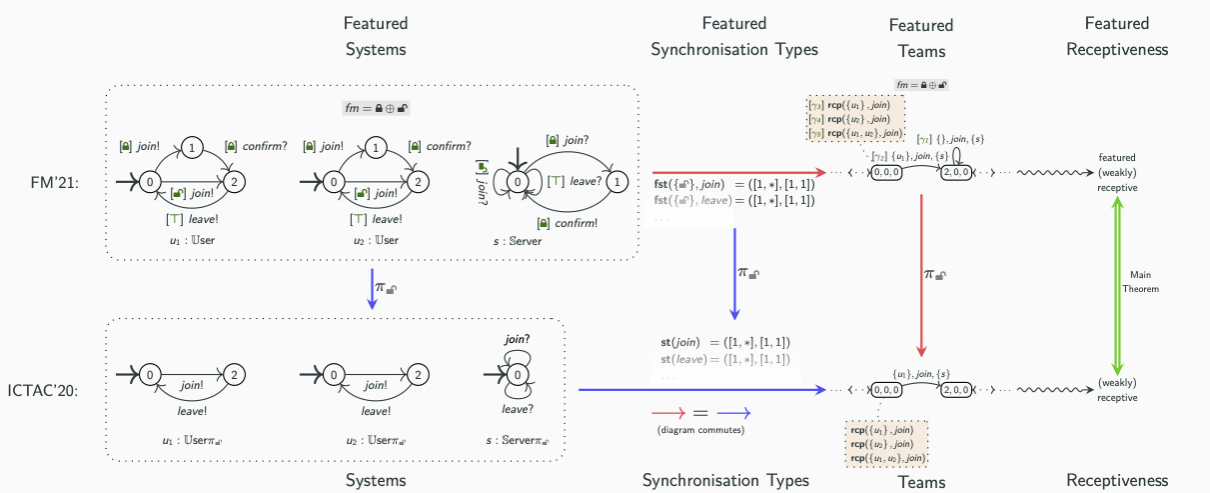
Weak Responsiveness: true



Featured Team Automata

Featured Extended Team Automata (fETA)

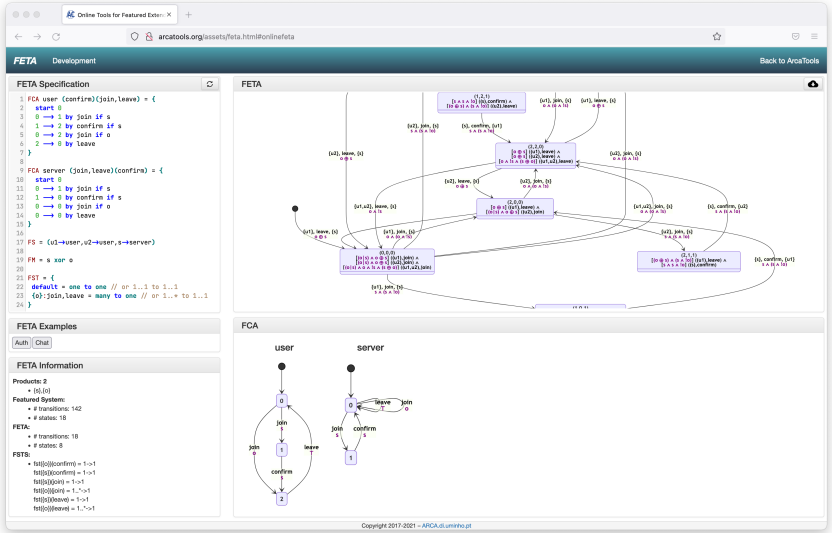
Recall from safe communication: receptiveness (*no message loss*)



Online Prototype: `http://arcatools.org/feta`

- Specify
- Generate*
- Visualise
- Statistics

*SAT solver to solve *fm*



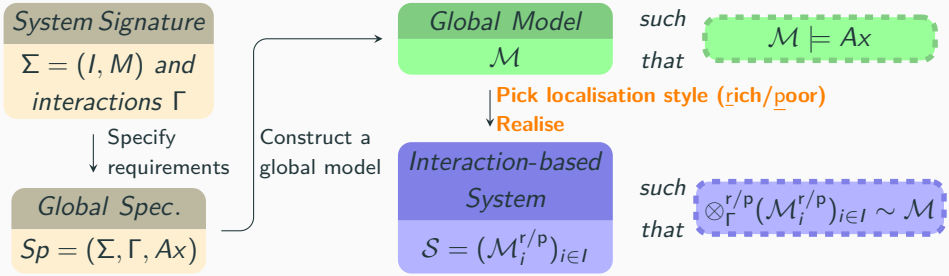
Team Automata as Realisations of Global Interaction Models [skip]

Challenge

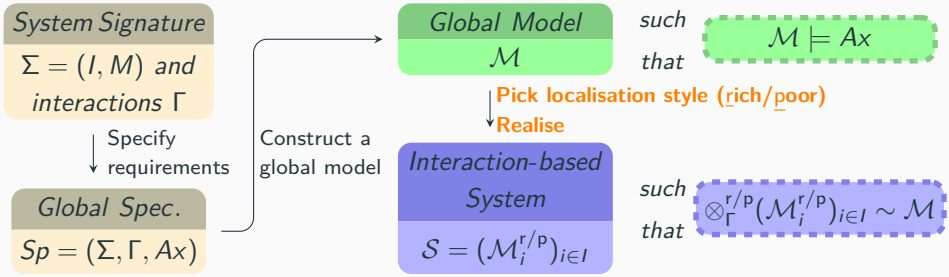
How to check if a global model is realisable and, if it is, how to synthesise a realisation?

Realisability of Global Models of Interaction

How to check if a global model is realisable and, if it is, how to synthesise a realisation?



How to check if a global model is realisable and, if it is, how to synthesise a realisation?



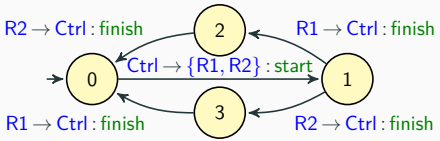
Multi-interactions

rich (à la multi-party session types, choreography languages) $i \to j : m \Rightarrow$ local output action $ij!m$ for i and local input action $ij?m$ for j

poor (à la component-based I/O development, loose coupling) $i \to j : m \Rightarrow$ local output action $!m$ for i and local input action $?m$ for j

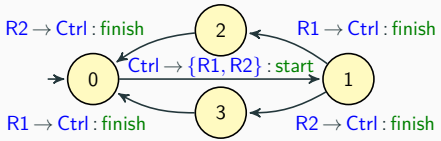
Example

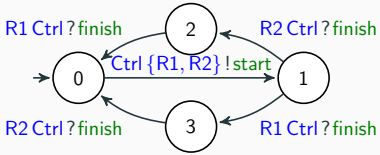
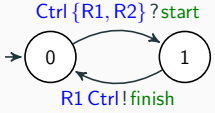
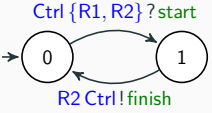
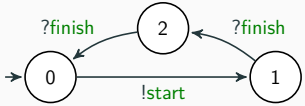
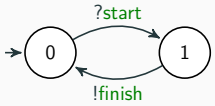
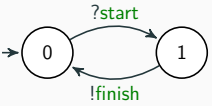
$$\Gamma_{\text{Race}} = \left\{ \begin{array}{l} \text{Ctrl} \to \{\text{R1}, \text{R2}\} : \text{start}\,, \\ \text{R1} \to \text{Ctrl} : \text{finish}\,, \\ \text{R2} \to \text{Ctrl} : \text{finish} \end{array} \right\}$$



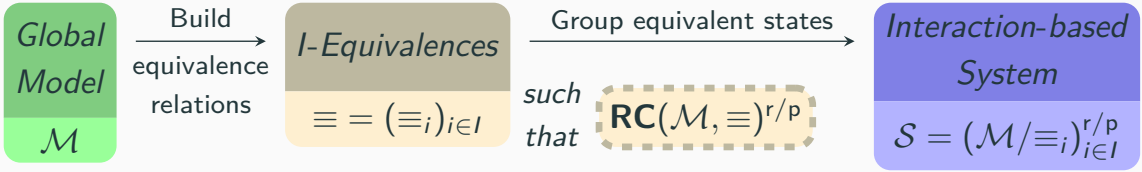
Example

$$\Gamma_{\text{Race}} = \left\{ \begin{array}{l} \text{Ctrl} \to \{\text{R1}, \text{R2}\} : \text{start}\,, \\ \text{R1} \to \text{Ctrl} : \text{finish}\,, \\ \text{R2} \to \text{Ctrl} : \text{finish} \end{array} \right\}$$



Localisation	Local Ctrl	Local R1	Local R2
Rich			
Poor			

Check Realisability and System Synthesis



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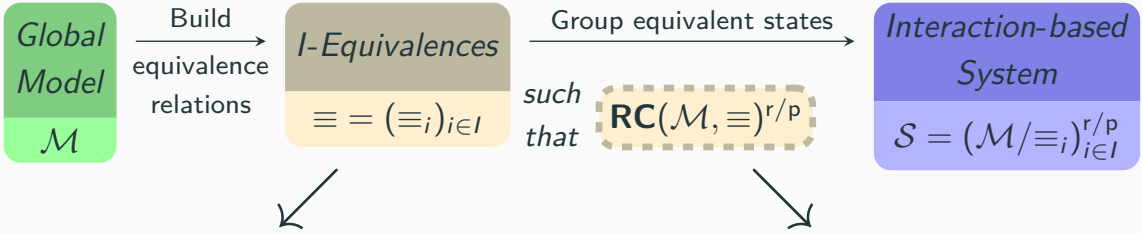

I. Castellani, M. Mukund, and P.S. Thiagarajan,
Synthesizing Distributed Transition Systems
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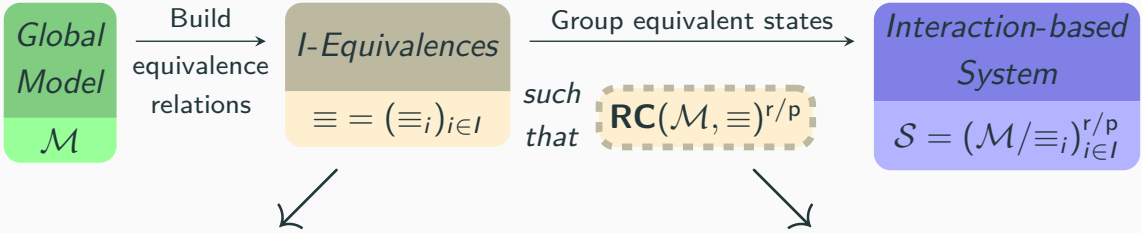

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Theorems 2/3

If $RC(\mathcal{M}, \equiv)^{r/p}$ holds, then $\mathcal{M} \sim \otimes_{\Gamma}^{r/p}((\mathcal{M}/\equiv_i)^{r/p})_{i \in I}$

Novelty

1. Realisations of global models with arbitrary multi-interactions supporting any kind of synchronous communication between multiple senders and multiple receivers
2. Correctness notion for realisation based on bisimulation rather than isomorhism, so allowing to deal with non-determinism
3. To construct realisations we consider, and analyse, two different localisation styles: rich and poor local actions
4. A prototypical tool Ceta checks the realisability conditions and, if they are satisfied, generates local quotients and hence realisations

`https://github.com/arcalab/choreo/tree/ceta`

`https://lmf.di.uminho.pt/ceta`

Online Prototype: `https://lmf.di.uminho.pt/ceta`

Choreographic Extended Team Automata

Choreography

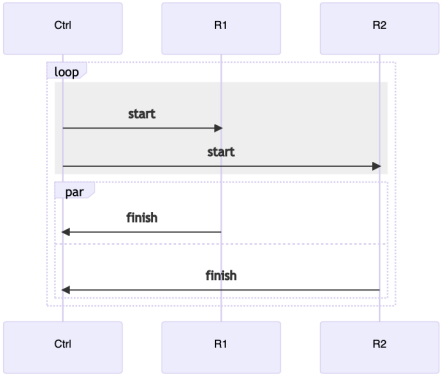
```
1 // Race example
2 (
3  (Ctrl->R1,R2: start);
4  (R1->Ctrl:finish ||
5   R2->Ctrl:finish)
6 )*
```

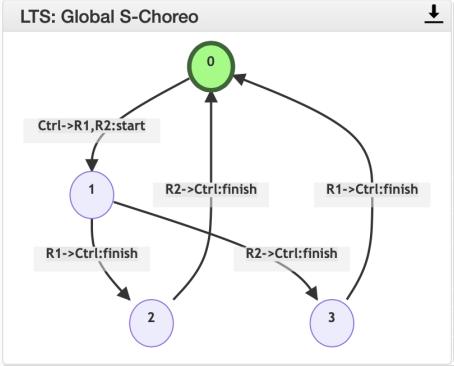
A controller starts 2 runners at the same time, and receives a finish message from each runner at a time.

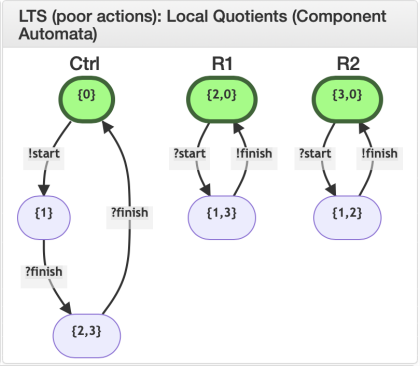
Examples

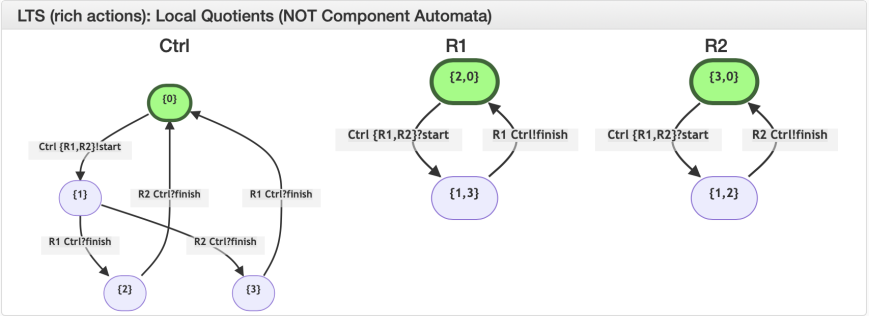
Race (simple) | Race (R1-first) | Race (once, simple) | Toss | Gossip (bad) | Gossip (good) | Cast-v1 | Cast-v2 | ab+cb+ca | ab;ac | ab|ac | ab;cd | ab|cd

Sequence Diagram




LTS: Global S-Choreo
0
Ctrl->R1,R2:start
1
R2->Ctrl:finish
R1->Ctrl:finish
R1->Ctrl:finish
R2->Ctrl:finish
2
3


LTS (poor actions): Local Quotients (Component Automata)
Ctrl
{0}
!start
{1}
?finish
?finish
{2,3}
R1
{2,0}
?start
!finish
{1,3}
R2
{3,0}
?start
!finish
{1,2}


LTS (rich actions): Local Quotients (NOT Component Automata)
Ctrl
{0}
Ctrl {R1,R2}!start
{1}
R2 Ctrl?finish
R1 Ctrl?finish
R1 Ctrl?finish
R2 Ctrl?finish
{2}
{3}
R1
{2,0}
Ctrl {R1,R2}?start
R1 Ctrl!finish
{1,3}
R2
{3,0}
Ctrl {R1,R2}?start
R2 Ctrl!finish
{1,2}

Ongoing Work

Roadmap: Team Automata with asynchronous communication?

Inspiration from multi-composition of asynchronous systems of CFSMs

D. Brand and P. Zafiropulo, On Communicating Finite-State Machines. *Journal of the ACM* 30 (1983)

F. Barbanera and R. Hennicker, Safe Composition of Systems of Communicating Finite State Machines @ ICE'24

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Basically finite-state I/O-automata that communicate by asynchronous exchanges of messages via buffered FIFO channels, but

- CFSM, like MPST, use potentially infinite FIFO buffers as message channels
- CFSM systems use binary peer-to-peer communication with rich local actions

Behaviour of CFSM systems formalised as a transition relation on configurations (which are pairs of a tuple of component states and a tuple of channel buffers)

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⇒ Need to generalise to asynchronous multi-party communication for team automata

? Alternative with multisets as channels L. Clemente, F. Herbreteau, and G. Sutre, Decidable topologies for communicating automata with FIFO and bag channels @ CONCUR'14

Roadmap Work: Safety Properties of Asynchronous Team Automata?

Consider safe communication as well as safe composition, "guaranteeing the composition not to 'break' any relevant property of the single systems"

F. Barbanera, M. Dezani-Ciancaglini, I. Lanese, and E. Tuosto, Composition and decomposition of multiparty sessions. *JLAMP* 119 (2021)

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- Avoid orphan message configurations (in which each component is in a final state, but there is still at least one non-empty buffer) P.-M. Deniélou and N. Yoshida, Multiparty Session Types Meet Communicating Automata @ ESOP'12

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However, unlike team automata, they consider only binary peer-to-peer communication

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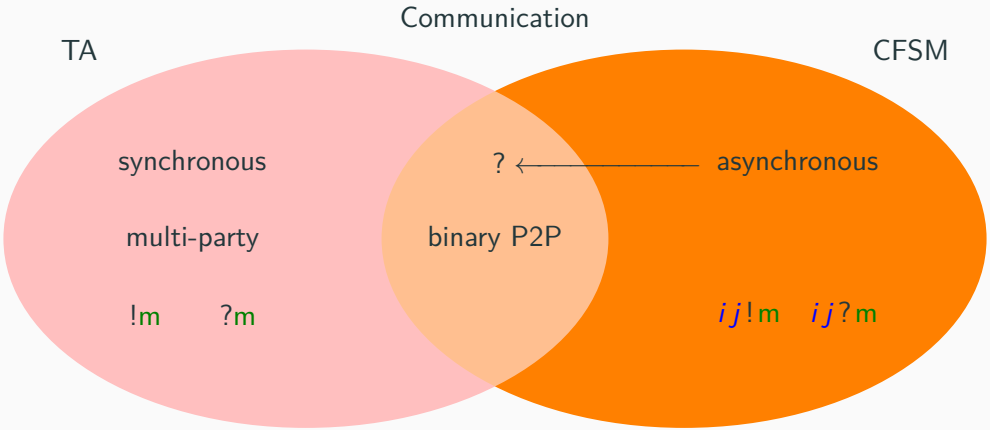
However, unlike team automata, asynchronous communication between CFSMs uses rich local actions

Conclusion



"Every good talk should include a Venn diagram" – Einar (Lima, Peru, 2023)

Publicity

Thanks for your attention! Questions?

I would be glad to see some of you in Turin, 11–16 April 2026

General Chairs: Maurice ter Beek, CNR–ISTI, Pisa, Italy
Ferruccio Damiani, Università di Torino, Italy

MARS 2026: 7th Workshop on Models for Formal Analysis of Real Systems

PC Chairs: Gregor Gössler, Université Grenoble Alpes, France
Maurice ter Beek, CNR–ISTI, Pisa, Italy

https://www.mars-workshop.org/mars2026/