Tuple-based Coordination of Distributed Systems

Distributed Systems

Sistemi Distribuiti

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Outline

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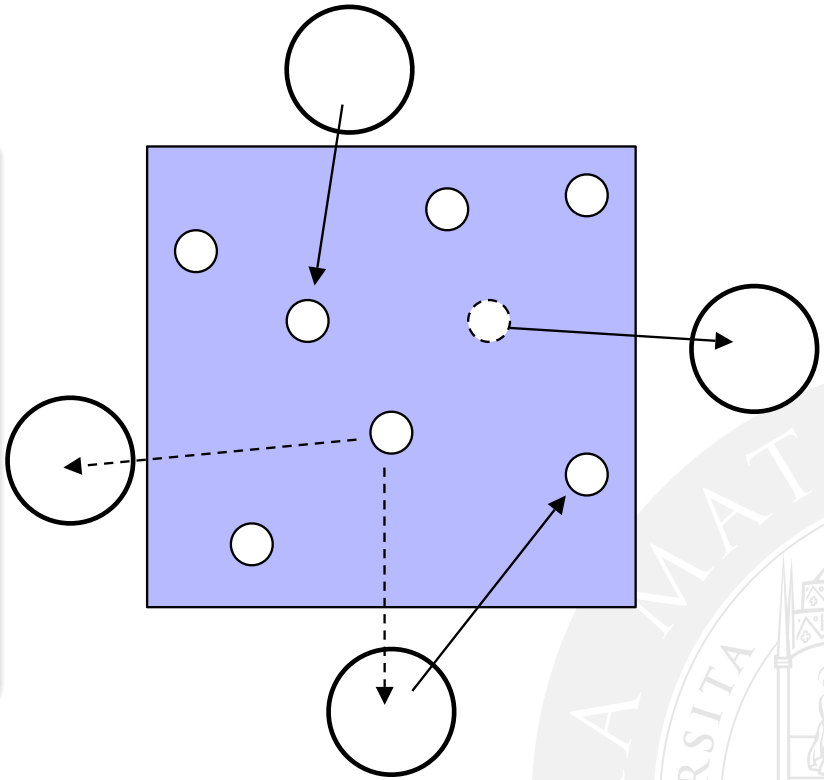
The Tuple-space Meta-model

The basics

- *Coordinables* synchronise, cooperate, compete
  - based on *tuples*
  - available in the *tuple space*
  - by *associatively* accessing, consuming and producing tuples



Tuple-based / Space-based Coordination Systems

Adopting the constructive coordination meta-model [Ciancarini, 1996]

coordination media tuple spaces

- as multiset / bag of data objects / structures called *tuples*

communication language tuples

- as ordered collections of (possibly heterogeneous) information items

coordination language tuple space primitives

- as a set of operations to put, browse and retrieve tuples to/from the space

Linda: The Communication Language [Gelernter, 1985]

Communication Language

tuples ordered collections of possibly heterogeneous information chunks

- examples: p(1), printer('HP',dpi(300)), [0,0.5], matrix(m0,3,3,0.5), tree_node(node00,value(13),left(_),right(node01)), ...

templates / anti-tuples specifications of set / classes of tuples

- examples: p(X), [?int,?int], tree_node(N), ...

tuple matching mechanism the mechanism that matches tuples and templates

- examples: pattern matching, unification, ...

Linda: The Coordination Language [Gelernter, 1985] I

out(T)

- out(T) puts tuple T in to the tuple space

  examples `out(p(1))`, `out(0,0.5)`, `out(course('Antonio Natali','Poetry',hours(150)))` ...

Linda: The Coordination Language [Gelernter, 1985] II

in(TT)

- `in(TT)` retrieves a tuple matching template `TT` from to the tuple space

  destructive reading the tuple retrieved is removed from the tuple centre

  non-determinism if more than one tuple matches the template, one is chosen non-deterministically

  suspensive semantics if no matching tuples are found in the tuple space, operation execution is suspended, and woken when a matching tuple is finally found

  examples `in(p(X))`, `in(0,0.5)`, `in(course('Antonio Natali',Title,hours(X))` ...

Linda: The Coordination Language [Gelernter, 1985] III

`rd(TT)`

- `rd(TT)` retrieves a tuple matching template `TT` from to the tuple space

  non-destructive reading the tuple retrieved is left untouched in the tuple centre

  non-determinism if more than one tuple matches the template, one is chosen non-deterministically

  suspensive semantics if no matching tuples are found in the tuple space, operation execution is suspended, and awakened when a matching tuple is finally found

  examples `rd(p(X))`, `rd(0,0.5)`, `rd(course('Alessandro Ricci','Operating Systems',hours(X)) ...`

Linda Extensions: Predicative Primitives

`inp(TT)`, `rdp(TT)`

- both `inp(TT)` and `rdp(TT)` retrieve tuple `T` matching template `TT` from the tuple space

  = `in(TT)`, `rd(TT)` (non-)destructive reading, non-determinism, and syntax structure is maintained

  ≠`in(TT)`, `rd(TT)` suspensive semantics is lost: this *predicative* versions primitives just fail when no tuple matching `TT` is found in the tuple space

  success / failure predicative primitives introduce *success / failure semantics*: when a matching tuple is found, it is returned with a success result; when it is not, a failure is reported

Linda Extensions: Bulk Primitives I

`in_all(TT)`, `rd_all(TT)`

- Linda primitives deal with one tuple at a time
  - some coordination problems require more than one tuple to be handled by a single primitive
- `rd_all(TT)`, `in_all(TT)` get all tuples in the tuple space matching with `TT`, and returns them all
  - no suspensive semantics: if no matching tuple is found, an empty collection is returned
  - no success / failure semantics: a collection of tuple is always successfully returned—possibly, an empty one
  - in case of logic-based primitives / tuples, the form of the primitive are `rd_all(TT,LT)`, `in_all(TT,LT)` (or equivalent), where the (possibly empty) list of tuples unifying with `TT` is unified with `LT`
  - (non-)destructive reading: `in_all(TT)` consumes all matching tuples in the tuple space; `rd_all(TT)` leaves the tuple space untouched

Linda Extensions: Bulk Primitives II

Other bulk primitives

- Many other bulk primitives have been proposed and implemented to address particular classes of problems
- Most of them too specific to be considered as a general extension to LINDA, and for inclusion in tuple-based models in general

Linda Extensions: Multiple Tuple Spaces

`ts ? out(T)`

- Linda tuple space might be a bottleneck for coordination
- Many extensions have focussed on making a multiplicity of tuple spaces available to processes
  - each of them encapsulating a portion of the coordination load
  - either hosted by a single machine, or distributed across the network
- Syntax required, and dependent on particular models and implementations
  - a space for tuple space names, possibly including network location
  - operators to associate Linda operators to tuple spaces
- For instance, `ts @ node ? out(p)` may denote the invocation of operation `out(p)` over tuple space `ts` on node `node`

Main Features of Tuple-based Coordination

Main features of the Linda model

tuples A tuple is an ordered collection of knowledge chunks, possibly heterogeneous in sort

generative communication until explicitly withdrawn, the tuples generated by coordinables have an independent existence in the tuple space; a tuple is equally accessible to all the coordinables, but is bound to none

associative access tuples in the tuple space are accessed through their content & structure, rather than by name, address, or location

suspensive semantics operations may be suspended based on unavailability of matching tuples, and be woken up when such tuples become available

Features of Linda: Tuples

- A tuple is an ordered collection of knowledge chunks, possibly heterogeneous in sort
  - a record-like structure
  - with no need of field names
  - easy aggregation of knowledge
  - raw semantic interpretation: a tuple contains all information concerning an given item
- Tuple structure based on
  - arity
  - type
  - position
  - information content
- Anti-tuples / Tuple templates
  - to describe / define sets of tuples
- Matching mechanism
  - to define belongingness to a set

Features of Linda: Generative Communication

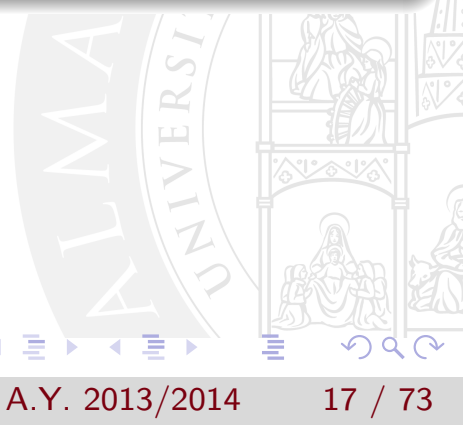
Communication orthogonality

- Both senders and the receivers can interact even without having prior knowledge about each others

  space uncoupling no need to coexist in space for two processes to interact

  time uncoupling no need for simultaneity for two processes to interact

  name uncoupling no need for names for processes to interact



Features of Linda: Associative Access

Content-based coordination

- Synchronisation based on tuple content & structure
  - absence / presence of tuples with some content / structure determines the overall behaviour of the coordinables, and of the coordinated system in the overall
  - based on tuple templates & matching mechanism
- *Information-driven coordination*
  - patterns of coordination based on data / information availability
  - based on tuple templates & matching mechanism
- *Reification*
  - making events become tuples
  - grouping classes of events with tuple syntax, and accessing them via tuple templates

Features of Linda: Suspensive Semantics

Blocking primitives

- `in` & `rd` primitives in Linda have a suspensive semantics
  - the coordination medium makes the primitives waiting in case a matching tuple is not found, and wakes it up when such a tuple is found
  - the coordinable invoking the suspensive primitive is expected to wait for its successful completion
- Twofold wait

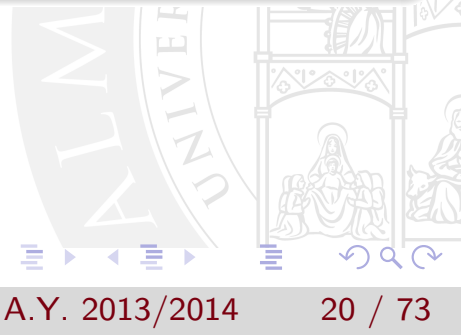
  in the coordination medium the operation is first (possibly) suspended, then (possibly) served: coordination based on absence / presence of tuples belonging to a given set

  in the coordination entity the invocation may cause a wait-state in the invoker: hypothesis on the internal behaviour of the coordinable

Our Running Example: The Dining Philosophers Problem

Dining Philosophers [Dijkstra, 2002]

- In the classical Dining Philosopher problem, N philosophers share N chopsticks and a spaghetti bowl
- Each philosopher either eats or thinks
- Each philosopher needs a pair of chopsticks to eat—and can access the two chopsticks on his left and on his right
- Each chopstick is shared by two adjacent philosophers
- When a philosopher needs to think, he gets rid of chopsticks



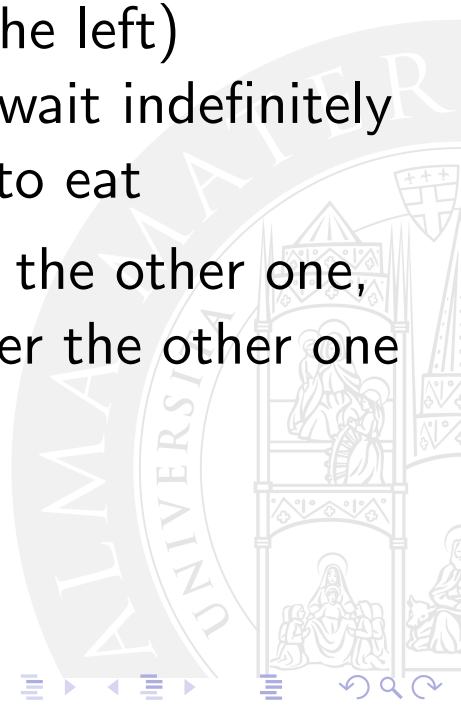
Concurrency issues in the Dining Philosophers Problem

shared resources Two adjacent philosophers cannot eat simultaneously

starvation If one philosopher eats all the time, the two adjacent philosophers will starve

deadlock If every philosopher picks up the same (say, the left) chopstick at the same time, all of them may wait indefinitely for the other (say, the right) chopstick so as to eat

fairness If a philosopher releases one chopstick before the other one, it favours one of his adjacent philosophers over the other one



Dining Philosophers in Linda

- The spaghetti bowl, or, more easily, the table where the bowl and the chopstick are, and the philosophers are seated, are represented by the tuple space
- Chopsticks are represented as tuples `chop(`i`)`, that represents the left chopstick for the $i-th$ philosopher
  - philosopher i needs chopsticks i (left) and $(i+1) mod N$ (right)
- Philosophers try to eat by getting their chopstick pairs from the tuple space as a pair of tuples `chop(`i`)` `chop(`i`+1 mod N)`
- Philosophers start to think by releasing their own chopstick pairs to the tuple space as a pair of tuples `chop(`i`)` `chop(`i`+1 mod N)`

! *In the following, we will use Prolog for philosopher agents*

Dining Philos in Linda: A Simple Philosopher Protocol

Philosopher using `ins` and `outs`

Dining Philos in Linda: A Simple Philosopher Protocol

Philosopher using ins and outs

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philosopher(I,J) :-




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+ shared resources handled correctly

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Issues

+ shared resources handled correctly
− starvation, deadlock and unfairness still possible

Dining Philos in Linda: Another Philosopher Protocol

Philosopher using `ins`, `inps` and `outs`

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+ shared resources handled correctly, deadlock possibly avoided

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- − starvation and unfairness still possible

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- − not-so-trivial philosopher's interaction protocol

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Issues

- \+ shared resources handled correctly, deadlock possibly avoided
- − starvation and unfairness still possible
- − not-so-trivial philosopher's interaction protocol
  - part of the coordination load is on the coordinables
  - rather than on the coordination medium

Dining Philos in Linda: Yet Another Philosopher Protocol

Philosopher using `ins` and `outs` with chopstick pairs `chops(I,J)`

Dining Philos in Linda: Yet Another Philosopher Protocol

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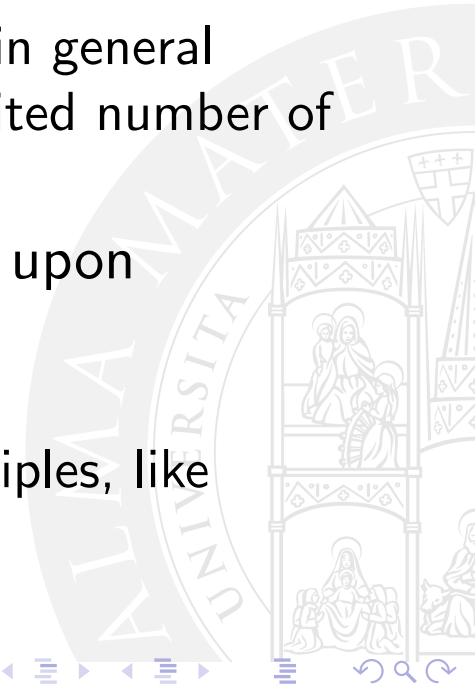
- \+ trivial philosopher's interaction protocol
- – shared resources not handled properly
- – starvation still possible

Dining Philosophers in Linda: Where is the Problem?

- Coordination is limited to writing, reading, consuming, suspending on one tuple at a time
  - the behaviour of the coordination medium is fixed once and for all
  - coordination problems that fits it are solved satisfactorily, those that do not fit are not
- Bulk primitives are not a general-purpose solution
  - adding ad hoc primitives does not solve the problem in general
  - and does not fit open scenarios—where instead a limited number of well-known primitives are the perfect solution
- As a result, the coordination load is typically charged upon coordination entities
  - this does not fit open scenarios
  - neither it does follow basic software engineering principles, like encapsulation and locality



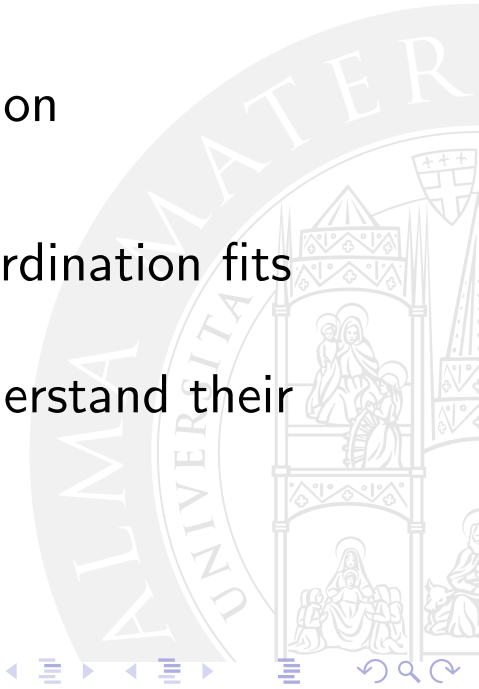
Dining Philosophers in Tuple-based Models: Solution?

- Making the behaviour of the coordination medium *adjustable* according to the coordination problem
  - if the behaviour of the coordination medium is *not* be fixed once and for all, and can be defined in accordance to the coordination needs
  - then, in principle all coordination problems may fit some admissible behaviour of the coordination medium
  - with no need to either add new *ad hoc* primitives, or change the semantics of the old ones
- In this way, coordination media could *encapsulate* solutions to coordination problems
  - represented in terms of *coordination policies*
  - enacted in terms of *coordinative behaviour* of the coordination media
- What is needed is a way to *define the behaviour* of a coordination medium according to the specific coordination issues
  - a general *computational model for coordination media*
  - along with a suitably expressive *programming language* to define the behaviour of coordination media

Outline

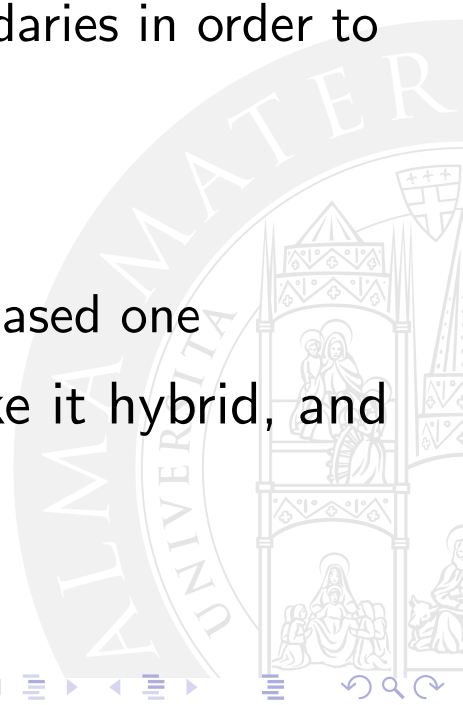
Data- vs. Control-driven Coordination

- What if we need to start an activity after, say, at least N processes have asked for a resource?
  - More generally, what if we need, in general, to coordinate based on the coordinable actions, rather than on the information available / exchanged?
- Classical distinction in the coordination community
  - data-driven coordination vs. control-driven coordination
- In more advanced scenario, these names do not fit
  - *information-driven* coordination vs. *action-driven* coordination fits better
  - but we might as well use the old terms, while we understand their limitations



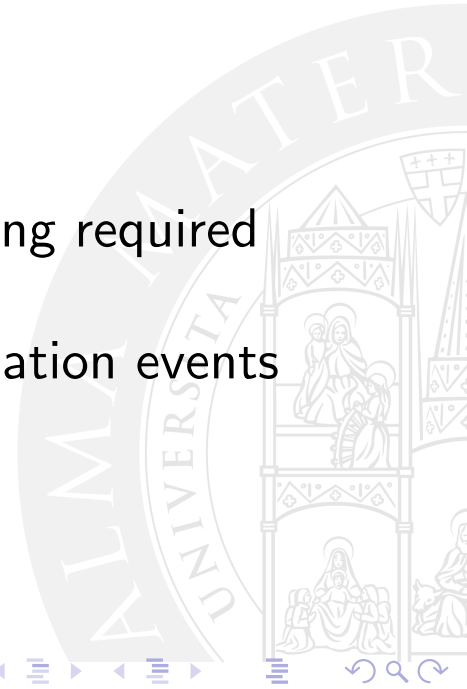
Hybrid Coordination Models

- Generally speaking, control-driven coordination does not fit so well information-driven contexts, like Web-based ones, for instance
  - control-driven models like Reo [Arbab, 2004] need to be adapted to contexts like agent-based ones, mainly to deal with the issue of autonomy in distributed systems [Dastani et al., 2005]
  - control should not pass through the component boundaries in order to avoid coupling in distributed systems
- We need features of both approaches to coordination
  - *hybrid* coordination models
  - adding for instance a control-driven layer to a Linda-based one
- What should be added to a tuple-based model to make it hybrid, and how?



Towards Tuple Centres

- What should be left unchanged?
  - no new primitives
  - basic Linda primitives are preserved, both syntax and semantics
  - matching mechanism preserved, still depending on the communication language of choice
  - multiple tuple spaces, flat name space
- New features?
  - ability to define new coordinative behaviours embodying required coordination policies
  - ability to associate coordinative behaviours to coordination events

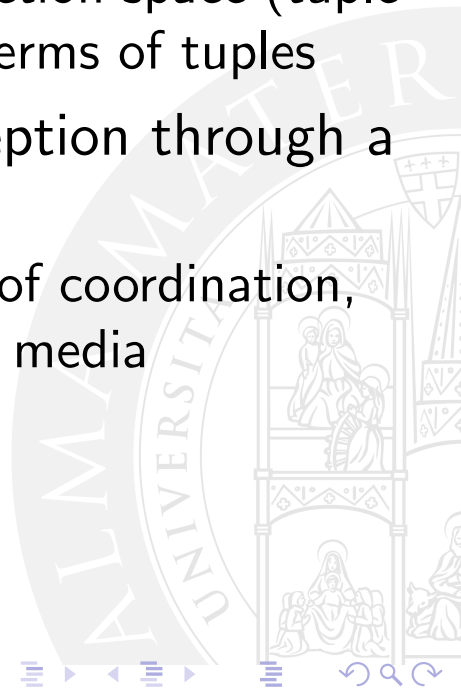


Outline

Outline

Ideas from the Dining Philosophers I

1. Keeping information representation and perception separated
   - in the tuple space
   - this would enable process interaction protocols to be organised around the desired / required process perception of the interaction space (tuple space), independently of its *actual* representation in terms of tuples
2. Properly relating information representation and perception through a suitably defined tuple-space behaviour
   - so, processes could get rid of the unnecessary burden of coordination, by embedding coordination laws into the coordination media



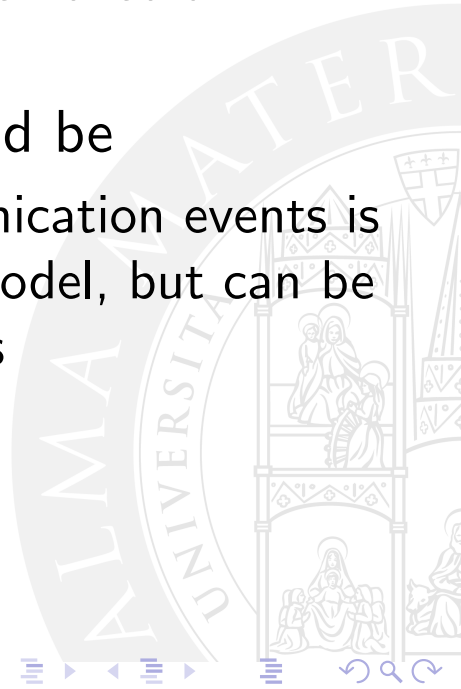
Ideas from the Dining Philosophers II

In the Dining Philosophers example...

- ...this would amount to representing each chopstick as a single `chop(`i`)` tuple in the tuple space, while enabling philosophers to perceive chopsticks as pairs (tuples `chops(`i`,`j`)`), so that philosophers could acquire / release two chopsticks by means of a single tuple space operation `in(chops(`i`,`j`))` / `out(chops(`i`,`j`))`.
- How could we do that, in the example, and in general?

A Possible Solution I

- A twofold solution
  1. maintaining the standard tuple space interface
  2. making it possible to enrich the behaviour of a tuple space in terms of the state transitions performed in response to the occurrence of standard communication events
- So, in principle, the new tuple-based abstraction should be
  - a tuple space whose behaviour in response to communication events is no longer fixed once and for all by the coordination model, but can be defined according to the required coordination policies



A Possible Solution II

Consequences

- Since it has exactly the same interface, a tuple centre is perceived by processes as a standard tuple space
- However, since its behaviour can be specified so as to encapsulate the coordination rules governing process interaction, a tuple centre may behave in a completely different way with respect to a tuple space

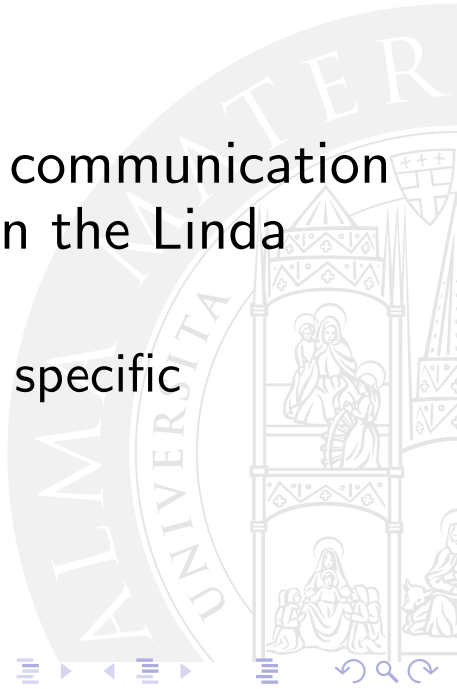
Tuple Centres

Definition

- A tuple centre is a tuple space enhanced with a *behaviour specification*, defining the behaviour of a tuple centre in response to interaction events [Omicini and Denti, 2001]
- The *behaviour specification* of tuple centre
  - is expressed in terms of a *reaction specification language*, and
  - associates any tuple-centre event to a (possibly empty) set of computational activities, which are called *reactions*
- More precisely, a reaction specification language
  - enables the definitions of computational activities within a tuple centre, called reactions, and
  - makes it possible to associate reactions to the events that occur in a tuple centre

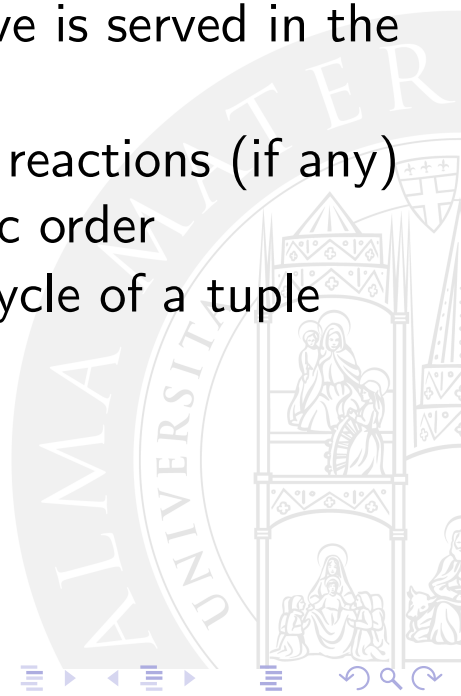
Reactions

- Each reaction can in principle
  - access and modify the current tuple centre state—like adding or removing tuples)
  - access the information related to the triggering event—such as the performing process, the primitive invoked, the tuple involved, etc.)—which is made completely observable
  - invoke link primitives upon other tuple centres
- As a result, the semantics of the standard tuple space communication primitives is no longer constrained to be as simple as in the Linda model—i.e., adding, reading, and removing tuples
  - instead, it can be made as complex as required by the specific application needs



Reaction Execution I

- The main cycle of a tuple centre works as follows
  - when a primitive invocation reaches a tuple centre, all the corresponding reactions (if any) are triggered, and then executed in a non-deterministic order
  - once all the reactions have been executed, the primitive is served in the same way as in standard Linda
  - upon completion of the invocation, the corresponding reactions (if any) are triggered, and then executed in a non-deterministic order
  - once all the reactions have been executed, the main cycle of a tuple centre may go on possibly serving another invocation



Reaction Execution II

- As a result, tuple centres exhibit a couple of fundamental features
  - since an empty behaviour specification brings no triggered reactions independently of the invocation, the behaviour of a tuple centre defaults to a tuple space when no behaviour specification is given
  - from the process's viewpoint, the result of the invocation of a tuple centre primitive is the sum of the effects of the primitive itself and of all the reactions it triggers, perceived altogether as a single-step transition of the tuple centre state

Tuple Centre's State vs. Process's Perception

- Reactions are executed in such a way that the observable behaviour of a tuple centre in response to a communication event is still perceived by processes as a single-step transition of the tuple-centre state
  - as in the case of tuple spaces
  - so tuple centres are perceived as tuple spaces by processes
- Unlike a standard tuple space, whose state transitions are constrained to adding, reading or deleting one single tuple, the perceived transition of a tuple centre state can be made as complex as needed
  - this makes it possible to decouple the process's view of the tuple centre (perceived as a standard tuple space) from the actual state of a tuple centre, and to relate them so as to embed the coordination laws governing the distributed system

Tuple Centres & Hybrid Coordination

- Tuple centres promote a form of hybrid coordination
  - aimed at preserving the advantages of data-driven models
  - while addressing their limitations in terms of control capabilities
- On the one hand, a tuple centre is basically an information-driven coordination medium, which is perceived as such by processes
- On the other hand, a tuple centre also features some capabilities which are typical of action-driven models, like
  - the full observability of events
  - the ability to selectively react to events
  - the ability to implement coordination rules by manipulating the interaction space

Outline

Dining Philosophers in ReSpecT

- The spaghetti bowl, or, more easily, the table where the bowl and the chopstick are, and the philosophers are seated, are represented by tuple centre `table`
- Chopsticks are represented as tuples `chop(`i`)`, that represents the left chopstick for the $i-th$ philosopher
  - philosopher i needs chopsticks i (left) and $(i+1) mod N$ (right)
- A philosopher tries to eat by getting his chopstick pair from the tuple centre by means of a `in(chops(`i`,`i`+1 mod N)` invocation
- A philosopher starts to think by releasing his own chopstick pair to the tuple centre by means of a `out(chops(`i`,`i`+1 mod N)` invocation

Dining Philosophers in ReSpecT: Philosopher Protocol

```
philosopher(I,J) :-
    think,                          % thinking
    table ? in(chops(I,J)),         % waiting to eat
    eat,                            % eating
    table ? out(chops(I,J)),        % waiting to think
!,  philosopher(I,J).
```

Dining Philosophers in ReSpecT: Philosopher Protocol

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Results

Dining Philosophers in ReSpecT: Philosopher Protocol

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```

Results

+ fairness, no deadlock

Dining Philosophers in ReSpecT: Philosopher Protocol

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```

Results

+ fairness, no deadlock
+ trivial philosopher's interaction protocol

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Results

- \+ fairness, no deadlock
- \+ trivial philosopher's interaction protocol
- ? shared resources handled properly?

Dining Philosophers in ReSpecT: Philosopher Protocol

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    eat,                            % eating
    table ? out(chops(I,J)),        % waiting to think
!,  philosopher(I,J).
```

Results

- \+ fairness, no deadlock
- \+ trivial philosopher's interaction protocol
- ? shared resources handled properly?
- ? starvation still possible?

Dining Philosophers in ReSpecT: `table` Behaviour Specification

Dining Philosophers in ReSpecT: `table` Behaviour Specification

```
reaction( out(chops(C1,C2)), (operation, completion), (      % (1)
    in(chops(C1,C2)), out(chop(C1)), out(chop(C2)) )).
```

Dining Philosophers in ReSpecT: `table` Behaviour Specification

```
reaction( out(chops(C1,C2)), (operation, completion), (      % (1)
    in(chops(C1,C2)), out(chop(C1)), out(chop(C2)) )).
reaction( in(chops(C1,C2)), (operation, invocation), (       % (2)
    out(required(C1,C2)) )).
```

Dining Philosophers in ReSpecT: `table` Behaviour Specification

```
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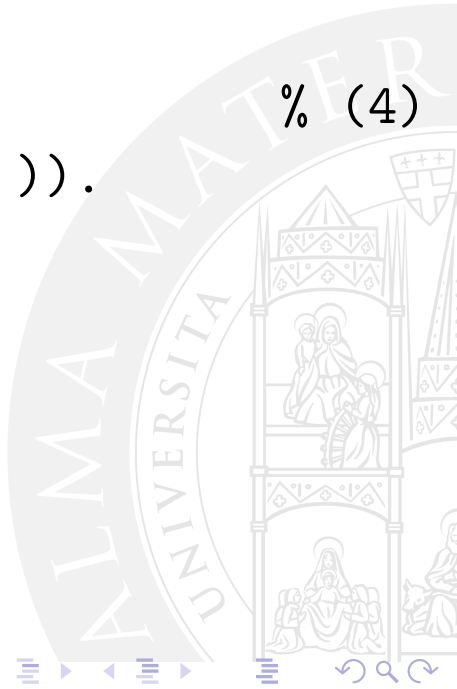
    in(chops(C1,C2)), out(chop(C1)), out(chop(C2)) )).
reaction( in(chops(C1,C2)), (operation, invocation), (       % (2)
    out(required(C1,C2)) )).
reaction( in(chops(C1,C2)), (operation, completion), (       % (3)
    in(required(C1,C2)) )).
```

Dining Philosophers in ReSpecT: `table` Behaviour Specification

```
reaction( out(chops(C1,C2)), (operation, completion), (      % (1)
    in(chops(C1,C2)), out(chop(C1)), out(chop(C2)) )).
reaction( in(chops(C1,C2)), (operation, invocation), (       % (2)
    out(required(C1,C2)) )).
reaction( in(chops(C1,C2)), (operation, completion), (       % (3)
    in(required(C1,C2)) )).
reaction( out(required(C1,C2)), internal, (                  % (4)
    in(chop(C1)), in(chop(C2)),  out(chops(C1,C2)) )).
```



Dining Philosophers in ReSpecT: `table` Behaviour Specification

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reaction( out(chops(C1,C2)), (operation, completion), (      % (1)
    in(chops(C1,C2)), out(chop(C1)), out(chop(C2)) )).
reaction( in(chops(C1,C2)), (operation, invocation), (       % (2)
    out(required(C1,C2)) )).
reaction( in(chops(C1,C2)), (operation, completion), (       % (3)
    in(required(C1,C2)) )).
reaction( out(required(C1,C2)), internal, (                  % (4)
    in(chop(C1)), in(chop(C2)),  out(chops(C1,C2)) )).
reaction( out(chop(C)), internal, (                          % (5)
    rd(required(C,C2)), in(chop(C)), in(chop(C2)),
    out(chops(C,C2)) )).
reaction( out(chop(C)), internal, (                          % (5')
    rd(required(C1,C)), in(chop(C1)), in(chop(C)),
    out(chops(C1,C)) )).
```

Dining Philosophers in ReSpecT: Results

Results

protocol	no deadlock
protocol	fairness
protocol	trivial philosopher's interaction protocol
tuple centre	shared resources handled properly
-	starvation still possible

Distributed Dining Philosophers

Dining Philosophers in a distributed setting

- N philosophers are distributed along the network
  - each philosopher is assigned a seat, represented by the tuple centre `seat(i,j)`
  - `seat(i,j)` denotes that the associated philosopher needs chopstick pair chops(i,j) so as to eat
- each chopstick `i` is represented as a tuple `chop(i)` in the `table` tuple centre
- each philosopher expresses his intention to eat / think by emitting a tuple `wanna_eat` / `wanna_think` in his `seat(i,j)` tuple centre
  - everything else is handled automatically in ReSpecT, embedded in the tuple centre behaviour
- *N* individual tuple centres (`seat(i,j)`) + 1 social tuple centre (`table`) connected in a star network

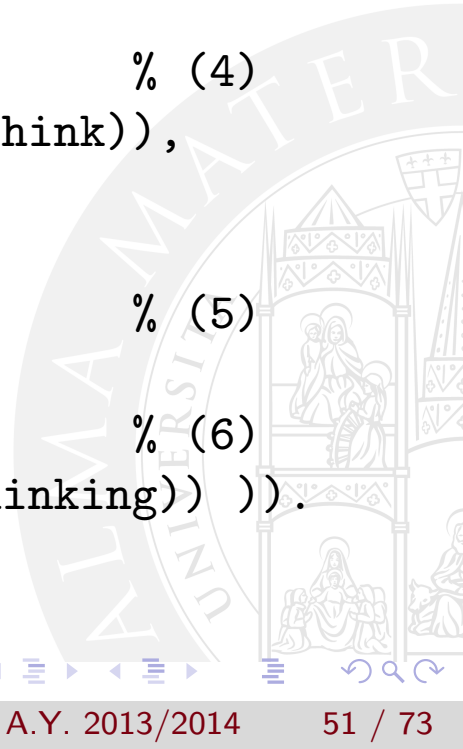
Distributed Dining Philosophers: Individual Interaction

Philosopher–seat interaction (*use*)

- four states, represented by tuple `philosopher(_)`
  - `thinking`, `waiting_to_eat`, `eating`, `waiting_to_think`
- determined by
  - the `out(wanna_eat)` / `out(wanna_think)` invocations, expressing the philosopher's intentions
  - the interaction with the `table` tuple centre, expressing the availability of `chop` resources
- tuple `chops(i,j)` only occurs in tuple centre `seat(i,j)` in the `philosopher(eating)` state
- state transitions only occur when they are safe
  - from `waiting_to_think` to `thinking` only when chopsticks are safely back on the `table`
  - from `waiting_to_eat` to `eating` only when chopsticks are actually at the `seat`

ReSpecT code for seat(*i*, *j*) tuple centres

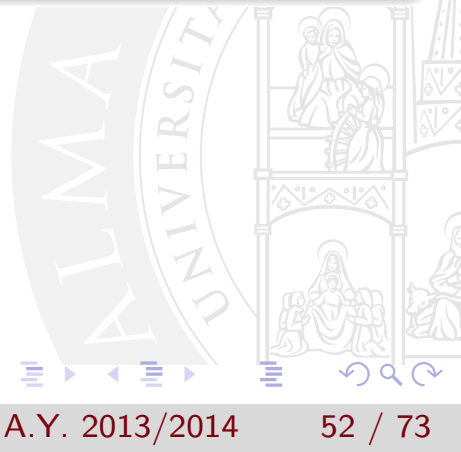
```
reaction( out(wanna_eat), (operation, invocation), (          % (1)
    in(philosopher(thinking)), out(philosopher(waiting_to_eat)),
    current_target(seat(C1,C2)), table@node ? in(chops(C1,C2)) )).
reaction( out(wanna_eat), (operation, completion),            % (2)
    in(wanna_eat)).
reaction( in(chops(C1,C2)), (link_out, completion), (         % (3)
    in(philosopher(waiting_to_eat)), out(philosopher(eating)),
    out(chops(C1,C2)) )).
reaction( out(wanna_think), (operation, invocation), (        % (4)
    in(philosopher(eating)), out(philosopher(waiting_to_think)),
    current_target(seat(C1,C2)), in(chops(C1,C2)),
    table@node ? out(chops(C1,C2)) )).
reaction( out(wanna_think), (operation, completion),          % (5)
    in(wanna_think) ).
reaction( out(chops(C1,C2)), (link_out, completion), (        % (6)
    in(philosopher(waiting_to_think)), out(philosopher(thinking)) )).
```



Distributed Dining Philosophers: Social Interaction

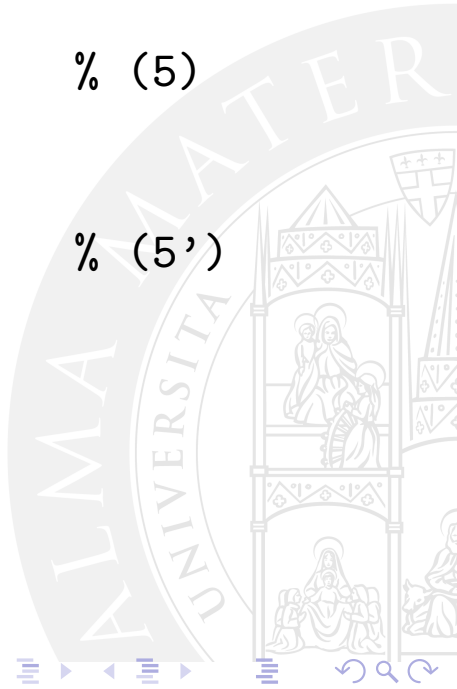
Seat–table interaction (*link*)

- tuple centre `seat(i,j)` requires / returns tuple `chops(i,j)` from / to `table` tuple centre
- tuple centre `table` transforms tuple `chops(i,j)` into a tuple pair `chop(i)`, `chop(j)` whenever required, and back `chop(i)`, `chop(j)` into `chops(i,j)` whenever required and possible



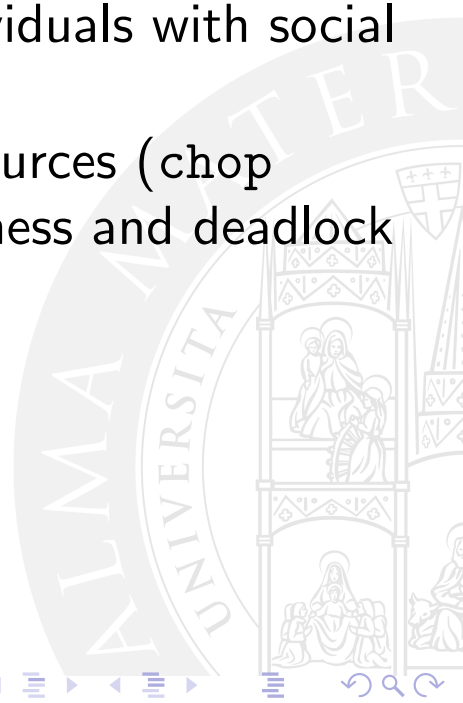
ReSpecT code for table tuple centre

```
reaction( out(chops(C1,C2)), (link_in, completion), (          % (1)
    in(chops(C1,C2)), out(chop(C1)), out(chop(C2)) )).
reaction( in(chops(C1,C2)), (link_in, invocation), (           % (2)
    out(required(C1,C2)) )).
reaction( in(chops(C1,C2)), (link_in, completion), (           % (3)
    in(required(C1,C2)) )).
reaction( out(required(C1,C2)), internal, (                    % (4)
    in(chop(C1)), in(chop(C2)), out(chops(C1,C2)) )).
reaction( out(chop(C)), internal, (                            % (5)
    rd(required(C,C2)), in(chop(C)), in(chop(C2)),
    out(chops(C,C2)) )).
reaction( out(chop(C)), internal, (                            % (5')
    rd(required(C1,C)), in(chop(C1)), in(chop(C)),
    out(chops(C1,C)) )).
```



Distributed Dining Philosophers: Features I

- Full separation of concerns
  - philosophers just express their intentions, in terms of simple tuples
  - individual tuple centre (`seat(i,j)` tuple centres) handle individual behaviours and state, and mediate interaction of individuals with social tuple centre (`table` tuple centre)
  - the social tuple centre (`table`) deals with shared resources (`chop` tuples) and ensures global system properties, like fairness and deadlock avoidance



Distributed Dining Philosophers: Features II

- At any time, one could look at the coordination media, and find exactly the consistent representation of the current distributed state
  - properly distributed, suitably encapsulated
    - the state of shared resources is in the shared distributed abstraction, the state of single processes is into individual local abstractions
  - accessible, represented in a declarative way
    - the state of individual philosophers is exposed through accessible media as far as the portion representing their social interaction is concerned

Outline

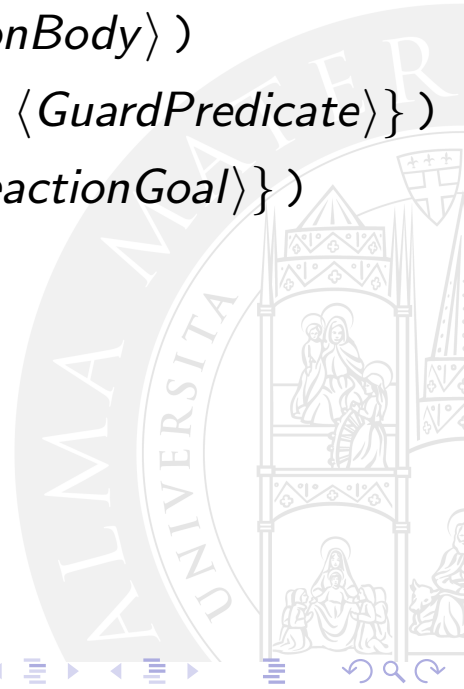
ReSpecT Basic Syntax for Reactions

Logic Tuples

- ReSpecT tuple centres adopt logic tuples for both ordinary tuples and specification tuples
- ordinary tuples are simple first-order logic (FOL) facts, written with a Prolog syntax
  - while ordinary logic tuples are typically ground facts, there is nothing to constrain them to be such
- specification tuples are logic tuples of the form `reaction(`E`,`G`,`R`)`
  - if event Ev occurs in the tuple centre,
  - which matches event descriptor E such that $\theta = mgu(E,Ev)$, and
  - guard G is true,
  - then reaction $R\theta$ to Ev is triggered for execution in the tuple centre

ReSpecT Syntax: Structure

$$
\begin{array}{rcl}
\langle \mathit{Specification} \rangle & ::= & \{ \langle \mathit{SpecificationTuple} \rangle \ . \} \\
\langle \mathit{SpecificationTuple} \rangle & ::= & \texttt{reaction(} \langle \mathit{Event} \rangle \texttt{ ,} [\langle \mathit{Guard} \rangle \texttt{ ,}] \langle \mathit{ReactionBody} \rangle \texttt{)} \\
\langle \mathit{Guard} \rangle & ::= & \langle \mathit{GuardPredicate} \rangle \mid \texttt{(} \langle \mathit{GuardPredicate} \rangle \{ \texttt{ ,} \langle \mathit{GuardPredicate} \rangle \} \texttt{)} \\
\langle \mathit{ReactionBody} \rangle & ::= & \langle \mathit{ReactionGoal} \rangle \mid \texttt{(} \langle \mathit{ReactionGoal} \rangle \{ \texttt{ ,} \langle \mathit{ReactionGoal} \rangle \} \texttt{)}
\end{array}
$$



ReSpecT Behaviour Specification

- a behaviour specification $\langle Specification \rangle$ is a logic theory of FOL tuples `reaction/3`
- a specification tuple contains an event descriptor $\langle Event \rangle$, a guard $\langle Guard \rangle$ (optional), and a sequence $\langle ReactionBody \rangle$ of $\langle ReactionGoal \rangle$s
  - a `reaction/2` specification tuple implicitly defines an empty guard

ReSpecT Event Descriptor

$$\langle Event \rangle \quad ::= \quad \langle Predicate \rangle \, (\, \langle Tuple \rangle \,) \mid \ldots$$

- the simplest event descriptor $\langle Event \rangle$ is the invocation of a primitive $\langle Predicate \rangle \, (\, \langle Tuple \rangle \,)$
- an event descriptor $\langle Event \rangle$ is used to match with with *admissible events*

ReSpecT Admissible (Tuple Centre) Event

$$
\begin{array}{rcl}
\langle \mathit{TCEvent} \rangle & ::= & \langle \mathit{OpEvent} \rangle \mid \ldots \\
\langle \mathit{OpEvent} \rangle & ::= & \langle \mathit{OpStartCause} \rangle \, , \langle \mathit{OpEventCause} \rangle \, , \langle \mathit{OpResult} \rangle \\
\langle \mathit{OpStartCause} \rangle & ::= & \langle \mathit{CoordOp} \rangle \, , \langle \mathit{AgentId} \rangle \, , \langle \mathit{TCId} \rangle \\
\langle \mathit{OpEventCause} \rangle & ::= & \langle \mathit{OpStartCause} \rangle \mid \langle \mathit{LinkOp} \rangle \, , \langle \mathit{TCId} \rangle \, , \langle \mathit{TCId} \rangle \\
\langle \mathit{OpResult} \rangle & ::= & \langle \mathit{Tuple} \rangle \, , \ldots
\end{array}
$$

- a ReSpecT admissible event includes its *prime cause* $\langle \mathit{StartCause} \rangle$, its *direct cause* $\langle \mathit{EventCause} \rangle$, and the $\langle \mathit{Result} \rangle$ of the tuple centre activity
  - prime and direct cause may coincide—such as when a process invocation reaches its target tuple centre
  - or, they might be different—such as when a link primitive is invoked by a tuple centre reacting to a process' primitive invocation upon another tuple centre
  - the result is undefined in the invocation stage: it is defined in the completion stage
- a reaction specification tuple `reaction(`E`,`G`,`R`)` and an admissible event ϵ match if E unifies with the $\langle \mathit{CoordOp} \rangle \mid \langle \mathit{LinkOp} \rangle$ part of $\epsilon.\langle \mathit{OpEventCause} \rangle$

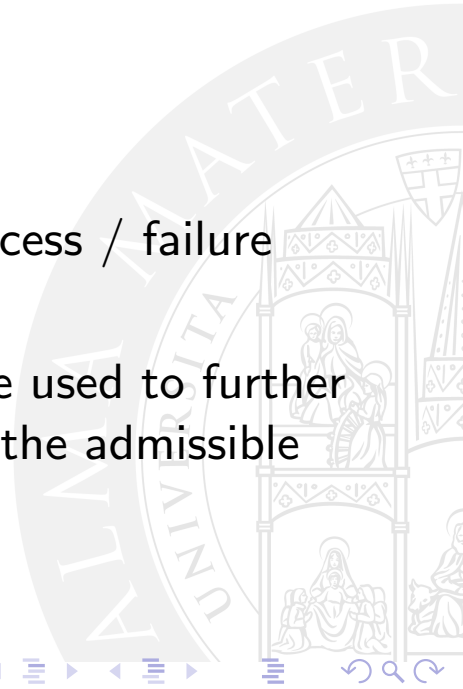
Event Model vs. Event Representation

- Understanding the difference between ReSpecT admissible events $\langle TCEvent \rangle$ and event descriptors $\langle Event \rangle$ is essential not to understand ReSpecT – who cares, after all – but first of all to understand the main issues of pervasive systems
- Admissible events is how we capture and model all the relevant events: essentially, our *ontology for events*
- Event descriptors is how we write events in our language – here, ReSpecT –: essentially, our *language for events*
- The ReSpecT VM is where the two things clash, and is exactly based on that: it's how we capture and observe events, and how we react to them properly
- This is an essential point in *any* technology dealing with situated computations

ReSpecT Guards

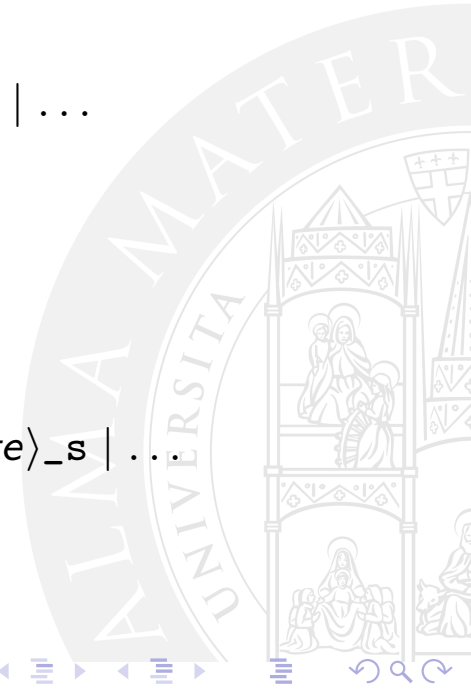
$$
\begin{array}{rcl}
\langle \mathit{Guard} \rangle & ::= & \langle \mathit{GuardPredicate} \rangle \mid \\
 & & (\langle \mathit{GuardPredicate} \rangle \{ , \langle \mathit{GuardPredicate} \rangle \}) \\
\langle \mathit{GuardPredicate} \rangle & ::= & \texttt{request} \mid \texttt{response} \mid \texttt{success} \mid \texttt{failure} \\
 & & \texttt{endo} \mid \texttt{exo} \mid \texttt{intra} \mid \texttt{inter} \\
 & & \texttt{from\_agent} \mid \texttt{to\_agent} \mid \texttt{from\_tc} \mid \texttt{to\_tc} \mid \ldots
\end{array}
$$

- A triggered reaction is actually executed only if its guard is true
- All guard predicates are ground ones, so their have always a success / failure semantics
- Guard predicates concern properties of the event, so they can be used to further select some classes of events after the initial matching between the admissible event and the event descriptor



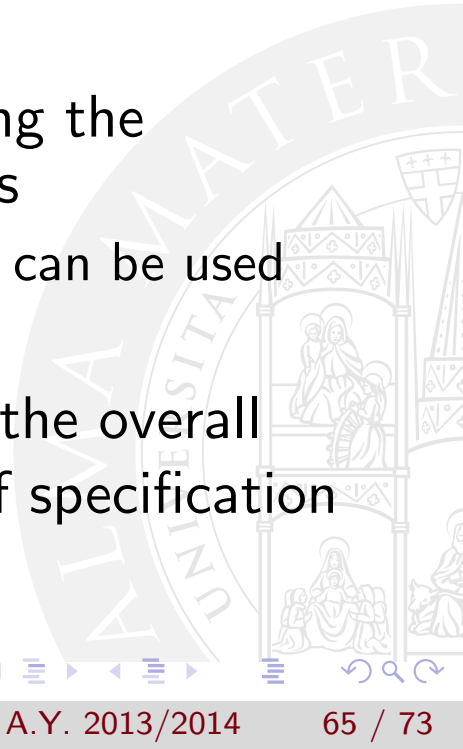
ReSpecT Reactions I

$$
\begin{array}{rcl}
\langle \textit{ReactionGoal} \rangle & ::= & \langle \textit{Predicate} \rangle \texttt{(} \langle \textit{Tuple} \rangle \texttt{)} \mid \\
& & \langle \textit{TupleCentre} \rangle \texttt{?} \langle \textit{Predicate} \rangle \texttt{(} \langle \textit{Tuple} \rangle \texttt{)} \mid \\
& & \langle \textit{ObservationPredicate} \rangle \texttt{(} \langle \textit{Tuple} \rangle \texttt{)} \mid \\
& & \langle \textit{ComputationGoal} \rangle \mid \texttt{(} \langle \textit{ReactionGoal} \rangle \texttt{;} \langle \textit{ReactionGoal} \rangle \texttt{)} \mid \\
& & \ldots \\
\langle \textit{Predicate} \rangle & ::= & \langle \textit{StatePredicate} \rangle \mid \langle \textit{ForgePredicate} \rangle \\
\langle \textit{StatePredicate} \rangle & ::= & \langle \textit{BasicPredicate} \rangle \mid \langle \textit{PredicativePredicate} \rangle \mid \ldots \\
\langle \textit{BasicPredicate} \rangle & ::= & \langle \textit{GetterPredicate} \rangle \mid \langle \textit{SetterPredicate} \rangle \\
\langle \textit{GetterPredicate} \rangle & ::= & \texttt{in} \mid \texttt{rd} \mid \texttt{no} \\
\langle \textit{SetterPredicate} \rangle & ::= & \texttt{out} \\
\langle \textit{PredicativePredicate} \rangle & ::= & \langle \textit{GetterPredicate} \rangle \texttt{p} \\
\langle \textit{ForgePredicate} \rangle & ::= & \langle \textit{BasicPredicate} \rangle \texttt{\_s} \mid \langle \textit{PredicativePredicate} \rangle \texttt{\_s} \mid \ldots
\end{array}
$$



ReSpecT Reactions II

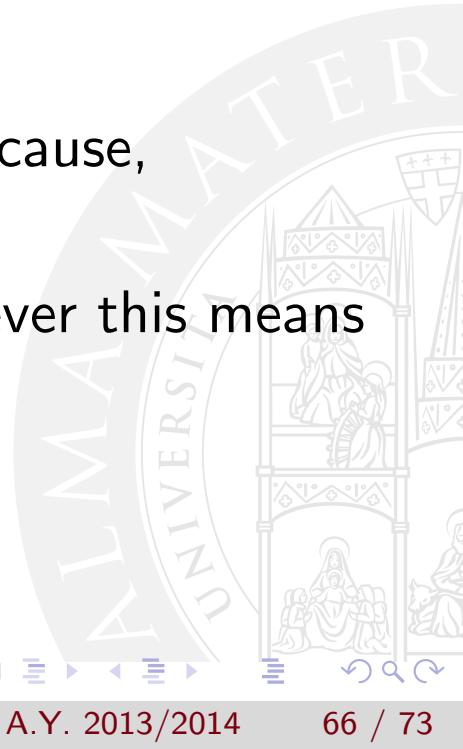
- A reaction goal is either a primitive invocation (possibly, a link), a predicate recovering properties of the event, or some logic-based computation
- Sequences of reaction goals are executed transactionally with an overall success / failure semantics
- Tuple centre predicates are uniformly used for agent invocations, internal operations, and link invocations
- The same predicates are substantially used for changing the specification state, with essentially the same semantics
  - *pred*_s invocations affect the specification state, and can be used within reactions, also as links
- `no` works as a test for absence, `get` and `set` work on the overall theory (either the one of ordinary tuples, or the one of specification tuples)



ReSpecT Observation Predicates

$$\begin{aligned} \langle \textit{ObservationPredicate} \rangle &::= \langle \textit{EventView} \rangle \_ \langle \textit{EventInformation} \rangle \\ \langle \textit{EventView} \rangle &::= \texttt{current} \mid \texttt{event} \mid \texttt{start} \\ \langle \textit{EventInformation} \rangle &::= \texttt{predicate} \mid \texttt{tuple} \mid \texttt{source} \mid \texttt{target} \mid \ldots \end{aligned}$$

- `event` & `start` clearly refer to immediate and prime cause, respectively
- `current` refers to what is currently happening, whenever this means something useful—typically, to the result

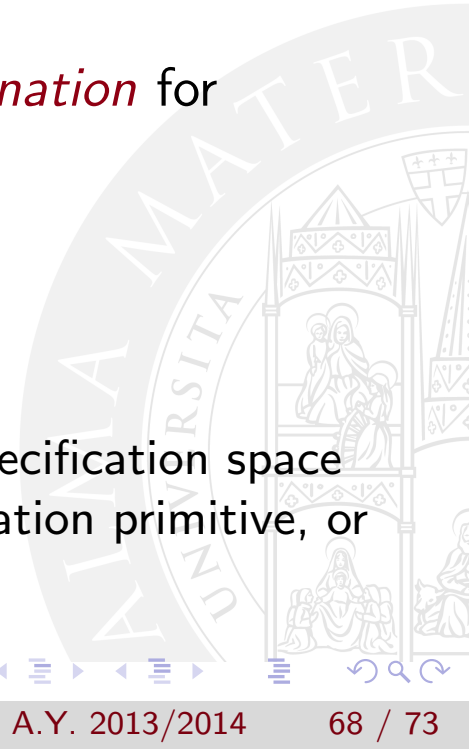


Properties of ReSpecT Tuple Centres

- ReSpecT tuple centres
  - encapsulate knowledge in terms of logic tuples
  - encapsulates behaviour in terms of ReSpecT specifications
- ReSpecT tuple centres are
  - inspectable
  - malleable
  - linkable

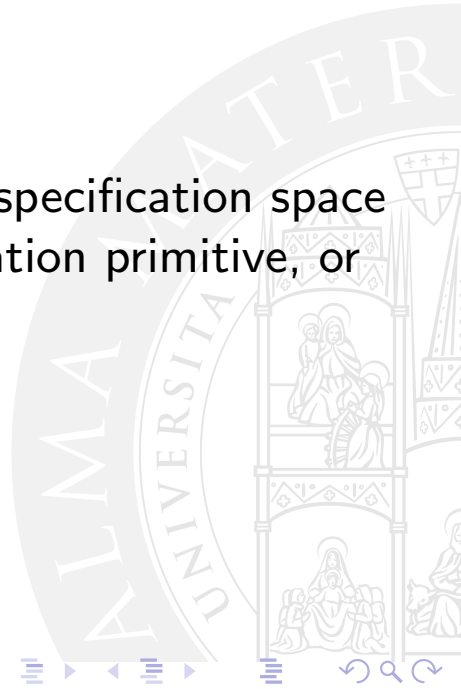
Inspectability of ReSpecT Tuple Centres

- ReSpecT tuple centres: twofold space for tuples
  - tuple space: ordinary (logic) tuples
    - for knowledge, information, messages, communication
    - working as the (logic) *theory of communication* for distributed systems
  - specification space: specification (logic, ReSpecT) tuples
    - for behaviour, function, coordination
    - working as the (logic) *theory of coordination* for distributed systems
- Both spaces are inspectable
  - by engineers, via ReSpecT inspectors
  - by processes, via `rd` & `no` primitives
    - `rd` & `no` for the tuple space; `rd_s` & `no_s` for the specification space
    - either directly or indirectly, through either a coordination primitive, or another tuple centre



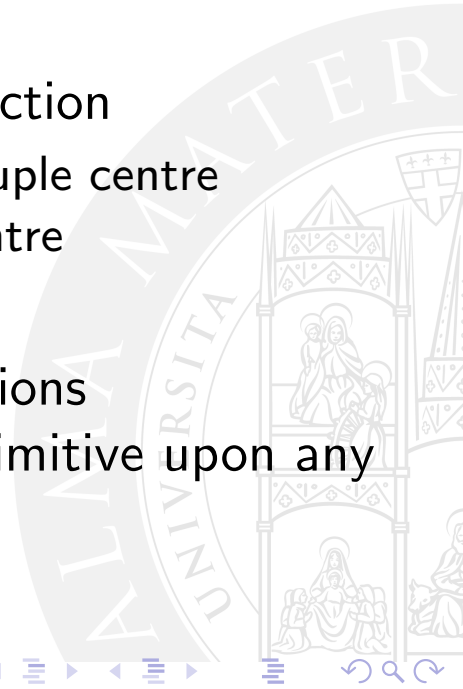
Malleability of ReSpecT Tuple Centres

- The behaviour of a ReSpecT tuple centre is defined by the ReSpecT tuples in the specification space
  - it can be adapted / changed by changing its ReSpecT specification
- ReSpecT tuple centres are malleable
  - by engineers, via ReSpecT tools
  - by processes, via `in` & `out` primitives
    - `in` & `out` for the tuple space; `in_s` & `out_s` for the specification space
    - either directly or indirectly, through either a coordination primitive, or another tuple centre



Linkability of ReSpecT Tuple Centres

- Every tuple centre coordination primitive is also an ReSpecT primitive for reaction goals, and a primitive for linking, too
  - all primitives are asynchronous
    - so they do not affect the transactional semantics of reactions
  - all primitives have a request / response semantics
    - including `out` / `out_s`
    - so reactions can be defined to handle both primitive invocations & completions
  - all primitives could be executed within a ReSpecT reaction
    - as either a reaction goal executed within the same tuple centre
    - or as a link primitive invoked upon another tuple centre
- ReSpecT tuple centres are linkable
  - by using tuple centre identifiers within ReSpecT reactions
  - any ReSpecT reaction can invoke any coordination primitive upon any tuple centre in the network



Summing Up

Tuple-based models

- Governing distributed systems: from data-oriented to hybrid coordination models
- From LINDA tuple spaces to ReSpecT tuple centres
- ReSpecT: a language for Turing-equivalent coordination policies
  - an event-driven language
  - event modelling vs. event representation

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Tuple-based Coordination of Distributed Systems

Distributed Systems

Sistemi Distribuiti

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