Tuple-based Coordination: From Linda to A&A ReSpecT

Multiagent Systems LS
Sistemi Multiagente LS

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Outline

Coordination: Sketching a Meta-model

The *medium of coordination*

- "fills" the interaction space
- enables / promotes / governs the admissible / desirable / required interactions among the interacting entities
- according to some *coordination laws*
  - enacted by the behaviour of the medium
  - defining the semantics of coordination

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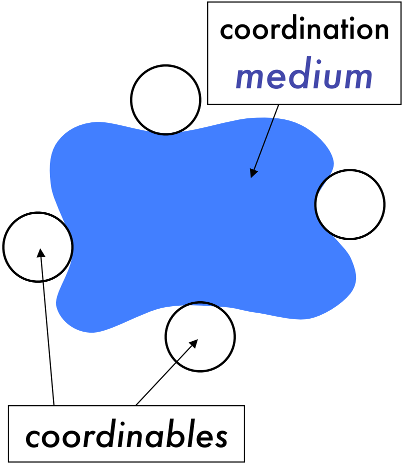

Coordination in Distributed Programming

Coordination model as a glue

A coordination model is the glue that binds separate activities into an ensemble [Gelernter and Carriero, 1992]

Coordination model as an agent interaction framework

A coordination model provides a framework in which the interaction of active and independent entities called agents can be expressed [Ciancarini, 1996]

Issues for a coordination model

A coordination model should cover the issues of creation and destruction of agents, communication among agents, and spatial distribution of agents, as well as synchronization and distribution of their actions over time [Ciancarini, 1996]

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A constructive approach

Which are the components of a coordination system?

Coordination entities Entities whose mutual interaction is ruled by the model, also called the *coordinables*

Coordination media Abstractions enabling and ruling agent interactions

Coordination laws Rules defining the behaviour of the coordination media in response to interaction

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Coordinables

Original definition [Ciancarini, 1996]

These are the entity types that are coordinated. These could be Unix-like processes, threads, concurrent objects and the like, and even users.

examples Processes, threads, objects, human users, agents, ...

focus Observable behaviour of the coordinables

question Are we anyhow concernd here with the internal machinery / functioning of the coordinable, in principle?

→ This issue will be clear when comparing Linda & TuCSoN agents

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- examples: Semaphors, monitors, channels, tuple spaces, blackboards, pipes, ...
- focus: The core around which the components of the system are organised
- question: Which are the possible computational models for coordination media?
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Original definition [Ciancarini, 1996]

A coordination model should dictate a number of laws to describe how agents coordinate themselves through the given coordination media and using a number of coordination primitives. Examples are laws that enact either synchronous or asynchronous behaviors or exploit explicit or implicit naming schemes for coordination entities.

- Coordination laws define the behaviour of the coordination media in response to interaction
  - a notion of (admissible interaction) event is required to define a model
- Coordination laws are expressed in terms of
  - the *communication language*, as the syntax used to express and exchange data structures

  examples: tuples, XML elements, FOL terms, (Java) objects, ...
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The basics

- *Coordinables* synchronise, cooperate, compete
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  - by *associatively* accessing, consuming and producing tuples

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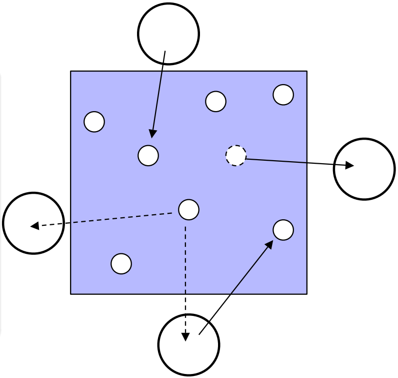

Tuple-based / Space-based Coordination Systems

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

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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 matching tuples and templates

- examples: pattern matching, unification, ...

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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('Denti Enrico','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('Denti Enrico',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

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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), rp(TT)
: (non-)destructive reading, non-determinism, and syntax structure is maintained

≠in(TT), rp(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

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≠`in(TT)`, `rp(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

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

- Linda primitives (including predicative ones) deal with a 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
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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 agents
  - 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`

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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
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- *Communication orthogonality*: both senders and the receivers can interact even without having prior knowledge about each others
  - space uncoupling (also called distributed naming): no need to coexist in space for two agents to interact
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- *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
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- *Information-driven coordination*
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  - 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

- `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

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Our Running Example: The Dining Philosophers Problem

Dining Philosophers [Dijkstra, 2002]

- In the classical Dining Philosopher problem, N philosopher agents 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
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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

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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)
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        out(chop(I)), out(chop(J)), % waiting to think
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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
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  - coordination problems that fits it are solved satisfactorily, those that do not fit are not
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  - and does not fit open scenarios—where instead a limited number of well-known primitives are the perfect solution
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- The behaviour of the coordination medium should be *adjustable* according to the coordination problem
  - the behaviour of the coordination medium should *not* be fixed once and for all
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  - 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
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Outline

Data- vs. Control-driven Coordination

- What if we need to start an activity after, say, at least N agents 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
- Of course, this does not fit our agent / A&A framework, where (passage of) control is blacklisted
  - *information-driven* coordination vs. *action-driven* coordination clearly fits better
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  - 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 from the coordination side
    - ability to define new coordinative behaviours embodying required coordination policies
    - ability to associate coordinative behaviours to coordination events
- New features from the artifact side?
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Outline

Feature List: From A&A to Tuple-based Coordination

- Coordinable are agents
  - tuple-space coordination primitives are (communication / pragmatical) actions
- Coordination abstractions are artifacts
  - tuple spaces as specialised artifacts for agent coordination
- Some relevant features of (coordination) artifacts

inspectability & controllability observing / controlling tuple space structure, state & behaviour
- for monitoring / debugging purposes

malleability / forgeability adapting / changing tuple space function / state & behaviour
- for incremental development, but also for run-time adaptation & change

linkability & distribution composing distributed tuple spaces
- for separation of concerns, encapsulation & scalability

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Ideas from the Dining Philosophers

1. Keeping information representation and perception separated
   - in the tuple space
   - this would enable agent interaction protocols to be organised around the desired / required agent 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, agents could get rid of the unnecessary burden of coordination, by embedding coordination laws into the coordination media

In the Dining Philosophers example. . .

- . . . this would amount to representing each chopstick as a single `chop(`i`)` tuple in the tuple space, while enabling philosopher agents to perceive chopsticks as pairs (tuples `chops(`i`,`j`)`), so that agent 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?

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A Possible Solution

- 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
- This is the motivation behind the very notion of *tuple centre*
  - 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

Consequences

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

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Tuple Centres

Definition [Omicini and Denti, 2001]

- A tuple centre is a tuple space enhanced with a *behaviour specification*, defining the behaviour of a tuple centre in response to interaction events
- 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
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  - 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*
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Tuple Centres

Definition [Omicini and Denti, 2001]

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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 agent, the primitive invoked, the tuple involved, etc.)—which is made completely observable
  - invoke link primitives upon other tuple centres
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Reaction Execution

- 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
- 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
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Tuple Centre's State vs. Agent'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 agents 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 agents
- 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 agent'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 multiagent system

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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 agents
- 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
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Outline

1. Introduction to (Tuple-based) Coordination
   - Coordination: A Meta-model
   - Tuple-based Coordination & Linda
2. ReSpecT: Programming Tuple Spaces
   - Hybrid Coordination Models
   - Tuple Centres
   - Dining Philosophers with A&A ReSpecT
   - A&A ReSpecT: Language & Semantics

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)
- An agent 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

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Dining Philosophers in ReSpecT: Philosopher Protocol

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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).
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Results

- \+ fairness, no deadlock
- \+ trivial philosopher's interaction protocol
- ? shared resources handled properly?
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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)) )).
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)),
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reaction( in(chops(C1,C2)), (operation, completion), (       % (3)
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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)),
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    rd(required(C1,C)), in(chop(C1)), in(chop(C)),
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```

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)) )).
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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: `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)) )).
reaction( out(chop(C)), internal, (                          % (5)
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    out(chops(C1,C)) )).
```

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)) )).
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    out(required(C1,C2)) )).
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    in(chop(C1)), in(chop(C2)),  out(chops(C1,C2)) )).
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    rd(required(C,C2)), in(chop(C)), in(chop(C2)),
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```

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

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Distributed Dining Philosophers

Dining Philosophers in a distributed setting

- N philosopher agents 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 A&A ReSpecT, embedded in the tuple centre / artifact behaviour
- N individual artifacts (`seat(i,j)`) + 1 social artifact (`table`) connected in a star network

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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
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A&A 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

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A&A 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)) )).
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Distributed Dining Philosophers: Features

- Full separation of concerns
  - philosopher agents just express their intentions, in terms of simple tuples
  - individual artifacts (`seat(i,j)` tuple centres) handle individual behaviours and state, and mediate interaction of individuals with social artifacts (`table` tuple centre)
  - the social artifact (`table` tuple centre) deals with shared resources (`chop` tuples) and ensures global system properties, like fairness and deadlock avoidance
- At any time, one could look at the coordination artifacts, 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 agents is into individual local abstractions
  - accessible, represented in a declarative way
    - the state of individual philosophers is exposed through accessible artifacts as far as the portion representing their social interaction is concerned

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  - individual artifacts (`seat(i,j)` tuple centres) handle individual behaviours and state, and mediate interaction of individuals with social artifacts (`table` tuple centre)
  - the social artifact (`table` tuple centre) deals with shared resources (`chop` tuples) and ensures global system properties, like fairness and deadlock avoidance
- At any time, one could look at the coordination artifacts, 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 agents is into individual local abstractions
  - accessible, represented in a declarative way
    - the state of individual philosophers is exposed through accessible artifacts as far as the portion representing their social interaction is concerned

Distributed Dining Philosophers: Features

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Timed Dining Philosophers

- An example for situatedness in the spatio-temporal fabric
- `table` tuple centre stores the maximum amount of time for any agent (philosopher) to use the resource (to eat using chops)
  - in terms of a tuple `max_eating_time(@Time)`
  - if this time expires the locks are automatically released—chopsticks are re-inserted by the table tuple centre
  - late releases (by agents through seat tuple centres) are to be ignored—linkability used to make seat tuple centres consistent
- With a very simple extension using timed reactions, Distributed Timed Dining Philosophers are done
  - see [Omicini et al., 2005]

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Timed Dining Philosophers: Philosopher

```
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).
```

With respect to Dining Philosopher's protocol. . .

. . . this is left unchanged

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```

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Timed Dining Philosophers: table A&A ReSpecT Code

```
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)) )).
reaction( in(chops(C1,C2)), (operation, completion), (       % (6)
    current_time(T), rd(max eating time(Max)), T1 is T + Max,
    out(used(C1,C2,T)),
    out_s(time(T1),(in(used(C1,C2,T)), out(chop(C1)), out(chop(C2)))) )).
```

Timed Dining Philosophers: table A&A ReSpecT Code

```
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)) )).
reaction( in(chops(C1,C2)), (operation, completion), (       % (6)
    current_time(T), rd(max eating time(Max)), T1 is T + Max,
    out(used(C1,C2,T)),
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```

Timed Dining Philosophers: table A&A ReSpecT Code

```
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)) )).
reaction( in(chops(C1,C2)), (operation, completion), (       % (6)
    current_time(T), rd(max eating time(Max)), T1 is T + Max,
    out(used(C1,C2,T)),
    out_s(time(T1),(in(used(C1,C2,T)), out(chop(C1)), out(chop(C2)))) )).
```

Timed Dining Philosophers: table A&A ReSpecT Code

```
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)) )).
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    current_time(T), rd(max eating time(Max)), T1 is T + Max,
    out(used(C1,C2,T)),
    out_s(time(T1),(in(used(C1,C2,T)), out(chop(C1)), out(chop(C2)))) )).
```

Timed Dining Philosophers: `table` A&A ReSpecT Code

```
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)) )).
reaction( in(chops(C1,C2)), (operation, completion), (       % (6)
    current_time(T), rd(max eating time(Max)), T1 is T + Max,
    out(used(C1,C2,T)),
    out_s(time(T1),(in(used(C1,C2,T)), out(chop(C1)), out(chop(C2)))) )).
```

Timed Dining Philosophers: table A&A ReSpecT Code

```
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)) )).
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reaction( in(chops(C1,C2)), (operation, completion), (      % (6)
    current_time(T), rd(max eating time(Max)), T1 is T + Max,
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```
reaction( out(chops(C1,C2)), (operation, completion), (      % (1)
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```
reaction( out(chops(C1,C2)), (operation, completion), (     % (1)
    in(chops(C1,C2)) )).
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    in(used(C1,C2,_)), out(chop(C1)), out(chop(C2)) )).
reaction( in(chops(C1,C2)), (operation, invocation), (      % (2)
    out(required(C1,C2)) )).
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```
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Timed Dining Philosophers in A&A ReSpecT: Results

Results

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

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Outline

A&A ReSpecT Basic Syntax for Reactions

Logic Tuples

- A&A 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
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  - then reaction $R\theta$ to *Ev* is triggered for execution in the tuple centre

A&A ReSpecT Core Syntax

⟨*TCSpecification*⟩	::=	{⟨*SpecificationTuple*⟩ .}
⟨*SpecificationTuple*⟩	::=	`reaction(` ⟨*SimpleTCEvent*⟩ `,` [⟨*Guard*⟩ `,`] ⟨*Reaction*⟩ `)`
⟨*SimpleTCEvent*⟩	::=	⟨*SimpleTCPredicate*⟩ `(` ⟨*Tuple*⟩ `)` | `time(` ⟨*Time*⟩ `)`
⟨*Guard*⟩	::=	⟨*GuardPredicate*⟩ | `(` ⟨*GuardPredicate*⟩ {`,` ⟨*GuardPredicate*⟩} `)`
⟨*Reaction*⟩	::=	⟨*ReactionGoal*⟩ | `(` ⟨*ReactionGoal*⟩ {`,` ⟨*ReactionGoal*⟩} `)`
⟨*ReactionGoal*⟩	::=	⟨*TCPredicate*⟩ `(` ⟨*Tuple*⟩ `)` | ⟨*ObservationPredicate*⟩ `(` ⟨*Tuple*⟩ `)` | ⟨*Computation*⟩ | `(` ⟨*ReactionGoal*⟩ `;` ⟨*ReactionGoal*⟩ `)`
⟨*TCPredicate*⟩	::=	⟨*SimpleTCPredicate*⟩ | ⟨*TCLinkPredicate*⟩
⟨*TCLinkPredicate*⟩	::=	⟨*TCIdentifier*⟩ `?` ⟨*SimpleTCPredicate*⟩
⟨*SimpleTCPredicate*⟩	::=	⟨*TCStatePredicate*⟩ | ⟨*TCForgePredicate*⟩
⟨*TCStatePredicate*⟩	::=	`in` | `inp` | `rd` | `rdp` | `out` | `no` | `get` | `set`
⟨*TCForgePredicate*⟩	::=	⟨*TCStatePredicate*⟩`_s`
⟨*ObservationPredicate*⟩	::=	⟨*EventView*⟩`_`⟨*EventInformation*⟩
⟨*EventView*⟩	::=	`current` | `event` | `start`
⟨*EventInformation*⟩	::=	`predicate` | `tuple` | `source` | `target` | `time`
⟨*GuardPredicate*⟩	::=	`request` | `response` | `success` | `failure` | `endo` | `exo` | `intra` | `inter` | `from_agent` | `to_agent` | `from_tc` | `to_tc` | `before(` ⟨*Time*⟩ `)` | `after(` ⟨*Time*⟩ `)`
⟨*Time*⟩	is	a non-negative integer
⟨*Tuple*⟩	is	Prolog term
⟨*Computation*⟩	is	a Prolog-like goal performing arithmetic / logic computations
⟨*TCIdentifier*⟩	::=	⟨*TCName*⟩ `@` ⟨*NetworkLocation*⟩
⟨*TCName*⟩	is	a Prolog ground term
⟨*NetworkLocation*⟩	is	a Prolog string representing either an IP name or a DNS entry

A&A ReSpecT Behaviour Specification

$$
\begin{array}{rcl}
\langle \textit{TCSpecification} \rangle & ::= & \{ \langle \textit{SpecificationTuple} \rangle \;.\} \\
\langle \textit{SpecificationTuple} \rangle & ::= & \texttt{reaction(} \\
 & & \quad \langle \textit{SimpleTCEvent} \rangle \;, \\
 & & \quad [\langle \textit{Guard} \rangle \;,] \\
 & & \quad \langle \textit{Reaction} \rangle \\
 & & \texttt{)}
\end{array}
$$

- a behaviour specification ⟨*TCSpecification*⟩ is a logic theory of FOL tuples `reaction/3`
- a specification tuple contains an event descriptor ⟨*SimpleTCEvent*⟩, a guard ⟨*Guard*⟩ (optional), and a sequence ⟨*Reaction*⟩ of reaction goals
  - a `reaction/2` specification tuple implicitly defines an empty guard

A&A ReSpecT Behaviour Specification

$$\langle \mathit{TCSpecification} \rangle ::= \{\langle \mathit{SpecificationTuple} \rangle \;.\}$$

$$\langle \mathit{SpecificationTuple} \rangle ::= \texttt{reaction(} \; \langle \mathit{SimpleTCEvent} \rangle \;, \; [\langle \mathit{Guard} \rangle \;,] \; \langle \mathit{Reaction} \rangle \; \texttt{)}$$

- a behaviour specification ⟨*TCSpecification*⟩ is a logic theory of FOL tuples `reaction/3`
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\langle \mathit{TCSpecification} \rangle & ::= & \{ \langle \mathit{SpecificationTuple} \rangle \ . \} \\
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& & \quad \langle \mathit{SimpleTCEvent} \rangle \ , \\
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& & \quad \langle \mathit{Reaction} \rangle \\
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  - a `reaction/2` specification tuple implicitly defines an empty guard

A&A ReSpecT Event Descriptor

$$\langle \mathit{SimpleTCEvent} \rangle \ ::= \ \langle \mathit{SimpleTCPredicate} \rangle \, \texttt{(} \, \langle \mathit{Tuple} \rangle \, \texttt{)} \ | \ \texttt{time(} \, \langle \mathit{Time} \rangle \, \texttt{)}$$

- an event descriptor ⟨*SimpleTCEvent*⟩ is either the invocation of a primitive ⟨*SimpleTCPredicate*⟩ `(` ⟨*Tuple*⟩ `)` or a time event `time(` ⟨*Time*⟩ `)`
  - more generally, a time event could become the descriptor of an environment-related event
- an event descriptor ⟨*SimpleTCEvent*⟩ is used to match with with *admissible A&A events*

A&A ReSpecT Event Descriptor

$$\langle \mathit{SimpleTCEvent} \rangle \quad ::= \quad \langle \mathit{SimpleTCPredicate} \rangle \; \texttt{(} \; \langle \mathit{Tuple} \rangle \; \texttt{)} \; | \; \texttt{time(} \; \langle \mathit{Time} \rangle \; \texttt{)}$$

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A&A ReSpecT Event Descriptor

$$\langle \mathit{SimpleTCEvent} \rangle ::= \langle \mathit{SimpleTCPredicate} \rangle \, \texttt{(} \, \langle \mathit{Tuple} \rangle \, \texttt{)} \mid \texttt{time(} \, \langle \mathit{Time} \rangle \, \texttt{)}$$

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- an event descriptor ⟨*SimpleTCEvent*⟩ is used to match with with *admissible A&A events*

A&A ReSpecT Admissible Event

$$
\begin{array}{rcl}
\langle \mathit{GeneralTCEvent} \rangle & ::= & \langle \mathit{StartCause} \rangle \, , \langle \mathit{Cause} \rangle \, , \langle \mathit{TCCycleResult} \rangle \\
\langle \mathit{StartCause} \rangle \, , \langle \mathit{Cause} \rangle & ::= & \langle \mathit{SimpleTCEvent} \rangle \, , \langle \mathit{Source} \rangle \, , \langle \mathit{Target} \rangle \, , \langle \mathit{Time} \rangle \\
\langle \mathit{Source} \rangle \, , \langle \mathit{Target} \rangle & ::= & \langle \mathit{AgentIdentifier} \rangle \mid \langle \mathit{TCIdentifier} \rangle \\
\langle \mathit{AgentIdentifier} \rangle & ::= & \langle \mathit{AgentName} \rangle \, \texttt{@} \, \langle \mathit{NetworkLocation} \rangle \\
\langle \mathit{AgentName} \rangle & \text{is} & \text{a Prolog ground term} \\
\langle \mathit{TCCycleResult} \rangle & ::= & \bot \mid \{ \langle \mathit{Tuple} \rangle \}
\end{array}
$$

- an admissible A&A event descriptor includes its prime cause, its immediate cause, and the result of the tuple centre response
  - prime cause and immediate cause may coincide—such as when an agent 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 an agent primitive invocation upon another tuple centre
- a reaction specification tuple $\texttt{reaction}(E,G,R)$ and an admissible A&A event ϵ match if E unifies with $\epsilon.\langle \mathit{Cause} \rangle . \langle \mathit{SimpleTCEvent} \rangle$
- the result is undefined in the invocation stage, whereas it is defined in the completion stage

A&A ReSpecT Admissible Event

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\begin{array}{rcl}
\langle \mathit{GeneralTCEvent} \rangle & ::= & \langle \mathit{StartCause} \rangle \texttt{,} \langle \mathit{Cause} \rangle \texttt{,} \langle \mathit{TCCycleResult} \rangle \\
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\langle \mathit{Source} \rangle \texttt{,} \langle \mathit{Target} \rangle & ::= & \langle \mathit{AgentIdentifier} \rangle \mid \langle \mathit{TCIdentifier} \rangle \\
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- a reaction specification tuple `reaction(`E`,`G`,`R`)` and an admissible A&A event ϵ match if E unifies with $\epsilon.\langle \mathit{Cause} \rangle.\langle \mathit{SimpleTCEvent} \rangle$
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\langle \textit{Source} \rangle \texttt{,} \langle \textit{Target} \rangle & ::= & \langle \textit{AgentIdentifier} \rangle \mid \langle \textit{TCIdentifier} \rangle \\
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\langle \mathit{AgentName} \rangle &\ \text{is}\ \ \text{a Prolog ground term} \\
\langle \mathit{TCCycleResult} \rangle &::= \bot \mid \{\langle \mathit{Tuple} \rangle\}
\end{aligned}
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A&A ReSpecT Guards

$\langle Guard \rangle$ ::= $\langle GuardPredicate \rangle$ |
($\langle GuardPredicate \rangle$ { , $\langle GuardPredicate \rangle$ })

$\langle GuardPredicate \rangle$ ::= `request` | `response` | `success` | `failure` |
`endo` | `exo` | `intra` | `inter` |
`from_agent` | `to_agent` | `from_tc` | `to_tc` |
`before(` $\langle Time \rangle$ `)` | `after(` $\langle Time \rangle$ `)`

$\langle Time \rangle$ is a non-negative integer

- 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

A&A ReSpecT Guards

$\langle \mathit{Guard} \rangle$ ::= $\langle \mathit{GuardPredicate} \rangle$ |
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`endo` | `exo` | `intra` | `inter` |
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A&A ReSpecT Guards

$$
\begin{array}{rcl}
\langle \mathit{Guard} \rangle & ::= & \langle \mathit{GuardPredicate} \rangle \mid \\
 & & (\,\langle \mathit{GuardPredicate} \rangle \,\{\, ,\, \langle \mathit{GuardPredicate} \rangle \}\,) \\
\langle \mathit{GuardPredicate} \rangle & ::= & \texttt{request} \mid \texttt{response} \mid \texttt{success} \mid \texttt{failure} \mid \\
 & & \texttt{endo} \mid \texttt{exo} \mid \texttt{intra} \mid \texttt{inter} \mid \\
 & & \texttt{from\_agent} \mid \texttt{to\_agent} \mid \texttt{from\_tc} \mid \texttt{to\_tc} \mid \\
 & & \texttt{before(}\,\langle \mathit{Time} \rangle\,\texttt{)} \mid \texttt{after(}\,\langle \mathit{Time} \rangle\,\texttt{)} \\
\langle \mathit{Time} \rangle & \text{is} & \text{a non-negative integer}
\end{array}
$$

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- 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

Semantics of Guard Predicates in A&A ReSpecT

Guard atom	True if
$Guard(\epsilon, (g, G))$	$Guard(\epsilon, g) \wedge Guard(\epsilon, G)$
$Guard(\epsilon, \texttt{endo})$	$\epsilon.Cause.Source = c$
$Guard(\epsilon, \texttt{exo})$	$\epsilon.Cause.Source \neq c$
$Guard(\epsilon, \texttt{intra})$	$\epsilon.Cause.Target = c$
$Guard(\epsilon, \texttt{inter})$	$\epsilon.Cause.Target \neq c$
$Guard(\epsilon, \texttt{from\_agent})$	$\epsilon.Cause.Source$ *is an agent*
$Guard(\epsilon, \texttt{to\_agent})$	$\epsilon.Cause.Target$ *is an agent*
$Guard(\epsilon, \texttt{from\_tc})$	$\epsilon.Cause.Source$ *is a tuple centre*
$Guard(\epsilon, \texttt{to\_tc})$	$\epsilon.Cause.Target$ *is a tuple centre*
$Guard(\epsilon, \texttt{before}(t))$	$\epsilon.Cause.Time < t$
$Guard(\epsilon, \texttt{after}(t))$	$\epsilon.Cause.Time > t$
$Guard(\epsilon, \texttt{request})$	$\epsilon.TCCycleResult$ *is undefined*
$Guard(\epsilon, \texttt{response})$	$\epsilon.TCCycleResult$ *is defined*
$Guard(\epsilon, \texttt{success})$	$\epsilon.TCCycleResult \neq \bot$
$Guard(\epsilon, \texttt{failure})$	$\epsilon.TCCycleResult = \bot$

⟨*GuardPredicate*⟩ aliases

`request` `invocation`, `inv`, `req`, `pre`

`response` `completion`, `compl`, `resp`, `post`

`before(`*Time*`),after(`*Time'*`)` `between(`*Time*`,`*Time'*`)`

`from_agent,to_tc` `operation`

`from_tc,to_tc,endo,inter` `link_out`

`from_tc,to_tc,exo,intra` `link_in`

`from_tc,to_tc,endo,intra` `internal`

⟨*GuardPredicate*⟩ aliases

`request`	`invocation`, `inv`, `req`, `pre`
`response`	`completion`, `compl`, `resp`, `post`
`before(`*Time*`)`,`after(`*Time'*`)`	`between(`*Time*`,`*Time'*`)`
`from_agent`,`to_tc`	`operation`
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`request` `invocation`, `inv`, `req`, `pre`

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`from_tc,to_tc,endo,intra` `internal`

⟨*GuardPredicate*⟩ aliases

`request` invocation, inv, req, pre

`response` completion, compl, resp, post

`before(Time),after(Time')` between(Time,Time')

`from_agent,to_tc` operation

`from_tc,to_tc,endo,inter` link_out

`from_tc,to_tc,exo,intra` link_in

`from_tc,to_tc,endo,intra` internal

A&A ReSpecT Reactions

$$
\begin{aligned}
\langle \mathit{Reaction} \rangle &::= \langle \mathit{ReactionGoal} \rangle \mid \\
&\quad (\langle \mathit{ReactionGoal} \rangle \{ , \langle \mathit{ReactionGoal} \rangle \}) \\
\langle \mathit{ReactionGoal} \rangle &::= \langle \mathit{TCPredicate} \rangle (\langle \mathit{Tuple} \rangle) \mid \\
&\quad \langle \mathit{ObservationPredicate} \rangle (\langle \mathit{Tuple} \rangle) \mid \\
&\quad \langle \mathit{Computation} \rangle \mid \\
&\quad (\langle \mathit{ReactionGoal} \rangle ; \langle \mathit{ReactionGoal} \rangle) \\
\langle \mathit{TCPredicate} \rangle &::= \langle \mathit{SimpleTCPredicate} \rangle \mid \langle \mathit{TCLinkPredicate} \rangle \\
\langle \mathit{TCLinkPredicate} \rangle &::= \langle \mathit{TCIdentifier} \rangle \; ? \; \langle \mathit{SimpleTCPredicate} \rangle
\end{aligned}
$$

- 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

A&A ReSpecT Reactions

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\langle \mathit{Reaction} \rangle & ::= & \langle \mathit{ReactionGoal} \rangle \mid \\
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A&A ReSpecT Tuple Centre Predicates

$$\langle SimpleTCPredicate \rangle ::= \langle TCStatePredicate \rangle \mid \langle TCForgePredicate \rangle$$

$$\langle TCStatePredicate \rangle ::= \texttt{in} \mid \texttt{inp} \mid \texttt{rd} \mid \texttt{rdp} \mid \texttt{out} \mid \texttt{no} \mid \texttt{get} \mid \texttt{set}$$

$$\langle TCForgePredicate \rangle ::= \langle TCStatePredicate \rangle \texttt{\_s}$$

- 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)

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A&A ReSpecT Tuple Centre Predicates

$\langle \mathit{SimpleTCPredicate} \rangle$ ::= $\langle \mathit{TCStatePredicate} \rangle$ | $\langle \mathit{TCForgePredicate} \rangle$

$\langle \mathit{TCStatePredicate} \rangle$ ::= `in` | `inp` | `rd` | `rdp` | `out` | `no` | `get` | `set`

$\langle \mathit{TCForgePredicate} \rangle$ ::= $\langle \mathit{TCStatePredicate} \rangle$`_s`

- 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
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A&A ReSpecT Observation Predicates

⟨*ObservationPredicate*⟩	::=	⟨*EventView*⟩_⟨*EventInformation*⟩
⟨*EventView*⟩	::=	`current` | `event` | `start`
⟨*EventInformation*⟩	::=	`predicate` | `tuple` |
		`source` | `target` | `time`

- `event` & `start` clearly refer to immediate and prime cause, respectively—`current` refers to what is currently happening, whenever this means something useful
- ⟨*EventInformation*⟩ aliases

  `predicate` `pred`, `call`; *deprecated*: `operation`, `op`

  `tuple` `arg`

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$$\langle ObservationPredicate \rangle ::= \langle EventView \rangle\_\langle EventInformation \rangle$$
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Semantics of Observation Predicates

$$\langle (r, R), Tu, \Sigma, Re, Out \rangle_{\epsilon} \longrightarrow_{e} \langle R\theta, Tu, \Sigma, Re, Out \rangle_{\epsilon}$$

r	where
event_predicate(Obs)	$\theta = mgu(\epsilon.Cause.SimpleTCEvent.SimpleTCPredicate, \texttt{Obs})$
event_tuple(Obs)	$\theta = mgu(\epsilon.Cause.SimpleTCEvent.Tuple, \texttt{Obs})$
event_source(Obs)	$\theta = mgu(\epsilon.Cause.Source, \texttt{Obs})$
event_target(Obs)	$\theta = mgu(\epsilon.Cause.Target, \texttt{Obs})$
event_time(Obs)	$\theta = mgu(\epsilon.Cause.Time, \texttt{Obs})$
start_predicate(Obs)	$\theta = mgu(\epsilon.StartCause.SimpleTCEvent.SimpleTCPredicate, \texttt{Obs})$
start_tuple(Obs)	$\theta = mgu(\epsilon.StartCause.SimpleTCEvent.Tuple, \texttt{Obs})$
start_source(Obs)	$\theta = mgu(\epsilon.StartCause.Source, \texttt{Obs})$
start_target(Obs)	$\theta = mgu(\epsilon.StartCause.Target, \texttt{Obs})$
start_time(Obs)	$\theta = mgu(\epsilon.StartCause.Time, \texttt{Obs})$
current_predicate(Obs)	$\theta = mgu(\texttt{current\_predicate}, \texttt{Obs})$
current_tuple(Obs)	$\theta = mgu(\texttt{Obs}, \texttt{Obs}) = \{\}$
current_source(Obs)	$\theta = mgu(c, \texttt{Obs})$
current_target(Obs)	$\theta = mgu(c, \texttt{Obs})$
current_time(Obs)	$\theta = mgu(nc, \texttt{Obs})$

Re-interpreting ReSpecT

- ReSpecT tuple centres as coordination artifacts
    - tuple centres as social artifacts
    - tuple centres as individual artifacts?
    - tuple centres as environment artifacts?
- ReSpecT tuple centres
    - encapsulate knowledge in terms of logic tuples
    - encapsulates behaviour in terms of ReSpecT specifications
- A&A ReSpecT tuple centres are
    - inspectable
        - not controllable
    - malleable
    - (linkable)
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Inspectability of A&A ReSpecT Tuple Centres

- A&A 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 MAS

  specification space specification (logic, ReSpecT) tuples
  - for behaviour, function, coordination
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- Both spaces are inspectable
  - by MAS engineers, via ReSpecT inspectors
  - by agents, 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 artifact / tuple centre

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Malleability of A&A 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
- A&A ReSpecT tuple centres are malleable
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Linkability of A&A ReSpecT Tuple Centres

- Every tuple centre coordination primitive is also an A&A 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 A&A ReSpecT reaction
    - as either a reaction goal executed within the same tuple centre
    - or as a link primitive invoked upon another tuple centre
- A&A ReSpecT tuple centres are linkable
  - by using tuple centre identifiers within ReSpecT reactions

    $< TCIdentifier > @ < NetworkLocation > ? < SimpleTCPredicate >$
  - any A&A ReSpecT reaction can invoke any coordination primitive upon any tuple centre in the network

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1. Introduction to (Tuple-based) Coordination
   - Coordination: A Meta-model
   - Tuple-based Coordination & Linda

2. ReSpecT: Programming Tuple Spaces
   - Hybrid Coordination Models
   - Tuple Centres
   - Dining Philosophers with A&A ReSpecT
   - A&A ReSpecT: Language & Semantics

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Tuple-based Coordination: From Linda to A&A ReSpecT

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