# Tuple-based Coordination

## Distributed Systems L-A

Sistemi Distribuiti L-A

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# Outline

1. Introduction to Tuple-based Coordination
   - Tuple-based Coordination & Linda
   - Hybrid Coordination Models

2. ReSpecT: Programming Tuple Spaces
   - Tuple Centres
   - Dining Philosophers with ReSpecT
   - ReSpecT: Language & Semantics

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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

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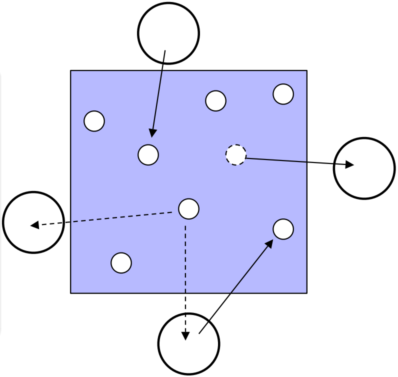

# Tuple-based / Space-based Coordination Systems

## 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 that matches 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('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

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# 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
  - 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
- Many other bulk primitives have been proposed and implemented to address particular classes of problems

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# 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`

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## 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

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**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

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  - easy aggregation of knowledge
  - semantic interpretation: a tuple contains all information concerning an given item
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# Features of Linda: Generative Communication

## Communication orthogonality

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

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# 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
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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
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# Dining Philosophers in Linda: A Simple Philosopher Protocol

## Philosopher using ins and outs

```
philosopher(I,J) :-
    think,                            % thinking
    in(chop(I)), in(chop(J)),         % waiting to eat
    eat,                              % eating
    out(chop(I)), out(chop(J)),       % waiting to think
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## Issues

+ shared resources handled correctly
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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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# Dining Philosophers in Tuple-based Models: Solution?

- The behaviour of the coordination medium should be *adjustable* according to the coordination problem
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# 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
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# 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 agent-based contexts, mainly to deal with the issue of autonomy in distributed systems [Dastani et al., 2005]
  - no coordination medium could say "do this, do that" to a coordinated entity, when a coordinable is an autonomous agent
- We need features of both approaches to coordination
  - *hybrid* coordination models
  - adding for instance a control-driven layer to a Linda-based one
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# 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
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# Ideas from the Dining Philosophers

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

**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(`$i$`,`$j$`))`.
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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 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

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  - 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 processes as a standard tuple space
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# A Possible Solution

- A twofold solution
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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*
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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 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
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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
  - 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

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# 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
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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 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
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# 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
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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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## Results

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

# Dining Philosophers in ReSpecT: Philosopher Protocol

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# 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)) )).
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   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( out(chops(C1,C2)), (operation, completion), (      % (1)
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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
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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 process (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
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# Timed Dining Philosophers: table ReSpecT Code

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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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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 ReSpecT Code

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reaction( out(chops(C1,C2)), (operation, completion), (     % (1)
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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)), out(chops(C,C2)) )).
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reaction( out(chops(C1,C2)), (operation, completion), (     % (1)
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    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')
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    out(used(C1,C2,T)),
    out_s(time(T1),(in(used(C1,C2,T)), out(chop(C1)), out(chop(C2)))) )).
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# Timed Dining Philosophers: table ReSpecT Code

```
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(required(C1,C2)) )).
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    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)) )).
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    rd(required(C1,C)), in(chop(C1)), in(chop(C)), out(chops(C1,C)) )).
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    out(used(C1,C2,T)),
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    out(used(C1,C2,T)),
    out_s(time(T1),(in(used(C1,C2,T)), out(chop(C1)), out(chop(C2)))) )).
```

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

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```
reaction( out(chops(C1,C2)), (operation, completion), (     % (1)
    in(chops(C1,C2)) )).
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    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 in 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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## 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
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## Philosopher–seat interaction (*use*)

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# 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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# ReSpecT code for table tuple centre

```
reaction( out(chops(C1,C2)), (link_in, completion), (         %
    in(chops(C1,C2)), out(chop(C1)), out(chop(C2)) )).
reaction( in(chops(C1,C2)), (link_in, invocation), (          %
    out(required(C1,C2)) )).
reaction( in(chops(C1,C2)), (link_in, completion), (          %
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reaction( out(required(C1,C2)), internal, (                   %
    in(chop(C1)), in(chop(C2)), out(chops(C1,C2)) )).
reaction( out(chop(C)), internal, (                           %
    rd(required(C,C2)), in(chop(C)), in(chop(C2)),
    out(chops(C,C2)) )).
reaction( out(chop(C)), internal, (                           %
    rd(required(C1,C)), in(chop(C1)), in(chop(C)),
    out(chops(C1,C)) )).
```

# Distributed Dining Philosophers: Features

- 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
- 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

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# Outline

1. Introduction to Tuple-based Coordination
   - Tuple-based Coordination & Linda
   - Hybrid Coordination Models

2. ReSpecT: Programming Tuple Spaces
   - Tuple Centres
   - Dining Philosophers with ReSpecT
   - ReSpecT: Language & Semantics

# 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,
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# 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
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# 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*⟩ `)` \|<br>⟨*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` \|<br>`intra` \| `inter` \| `from_agent` \| `to_agent` \| `from_tc` \| `to_tc` \|<br>`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 |

# ReSpecT Behaviour Specification

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

- 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

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

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 & & \quad \langle \mathit{SimpleTCEvent} \rangle \; , \\
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- a behaviour specification $\langle \mathit{TCSpecification} \rangle$ is a logic theory of FOL tuples `reaction/3`
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  - a `reaction/2` specification tuple implicitly defines an empty guard

# ReSpecT Event Descriptor

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

- an event descriptor $\langle \mathit{SimpleTCEvent} \rangle$ is either the invocation of a primitive $\langle \mathit{SimpleTCPredicate} \rangle$ `(` $\langle \mathit{Tuple} \rangle$ `)` or a time event `time(` $\langle \mathit{Time} \rangle$ `)`
  - more generally, a time event could become the descriptor of an environment-related event
- an event descriptor $\langle \mathit{SimpleTCEvent} \rangle$ is used to match with with *admissible events*

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

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

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- an event descriptor $\langle \mathit{SimpleTCEvent} \rangle$ is used to match with with *admissible events*

# ReSpecT Admissible Event

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

- an admissible 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 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
- a reaction specification tuple `reaction(E,G,R)` and an admissible event $\epsilon$ 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

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$$
\begin{array}{rcl}
\langle GeneralTCEvent \rangle & ::= & \langle StartCause \rangle \ \texttt{,} \ \langle Cause \rangle \ \texttt{,} \ \langle TCCycleResult \rangle \\
\langle StartCause \rangle \, , \langle Cause \rangle & ::= & \langle SimpleTCEvent \rangle \ \texttt{,} \ \langle Source \rangle \ \texttt{,} \ \langle Target \rangle \ \texttt{,} \ \langle Time \rangle \\
\langle Source \rangle \, , \langle Target \rangle & ::= & \langle ProcessIdentifier \rangle \mid \langle TCIdentifier \rangle \\
\langle ProcessIdentifier \rangle & ::= & \langle ProcessName \rangle \, \texttt{@} \, \langle NetworkLocation \rangle \\
\langle ProcessName \rangle & \text{is} & \text{a Prolog ground term} \\
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\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{ProcessIdentifier} \rangle \mid \langle \mathit{TCIdentifier} \rangle \\
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\langle \mathit{TCCycleResult} \rangle & ::= & \perp \mid \{\langle \mathit{Tuple} \rangle\}
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# ReSpecT Guards

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

- 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 Guards

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

$$\langle \mathit{GuardPredicate} \rangle ::= \texttt{request} \mid \texttt{response} \mid \texttt{success} \mid \texttt{failure} \mid \texttt{endo} \mid \texttt{exo} \mid \texttt{intra} \mid \texttt{inter} \mid \texttt{from\_agent} \mid \texttt{to\_agent} \mid \texttt{from\_tc} \mid \texttt{to\_tc} \mid \texttt{before(} \langle \mathit{Time} \rangle \texttt{)} \mid \texttt{after(} \langle \mathit{Time} \rangle \texttt{)}$$

$$\langle \mathit{Time} \rangle \text{ is a non-negative integer}$$

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\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 \\
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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 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`

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

`from_agent,to_tc` `operation`

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# ⟨*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

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# ⟨*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

`from_tc,to_tc,endo,inter` link_out

`from_tc,to_tc,exo,intra` link_in

`from_tc,to_tc,endo,intra` internal

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| 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

from_tc,to_tc,endo,inter link_out

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# ReSpecT Reactions

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

- 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

# 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 \\
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# ReSpecT Tuple Centre Predicates

$\langle SimpleTCPredicate \rangle$ ::= $\langle TCStatePredicate \rangle$ | $\langle TCForgePredicate \rangle$
$\langle TCStatePredicate \rangle$ ::= `in` | `inp` | `rd` | `rdp` | `out` | `no` | `get` | `set`
$\langle TCForgePredicate \rangle$ ::= $\langle TCStatePredicate \rangle$`_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
- `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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# 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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# 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) | $\theta = mgu(nc, \texttt{Obs})$ |

# 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
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# 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
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- 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
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# 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
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  - all primitives have a request / response semantics
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1. Introduction to Tuple-based Coordination
   - Tuple-based Coordination & Linda
   - Hybrid Coordination Models

2. ReSpecT: Programming Tuple Spaces
   - Tuple Centres
   - Dining Philosophers with ReSpecT
   - ReSpecT: Language & Semantics

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# Tuple-based Coordination

## Distributed Systems L-A

Sistemi Distribuiti L-A

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