Tuple-based Coordination

Distributed Systems L-A

Sistemi Distribuiti L-A

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Ingegneria Due

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Outline

1. Introduction to Tuple-based Coordination
2. ReSpecT: Programming Tuple Spaces

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   - 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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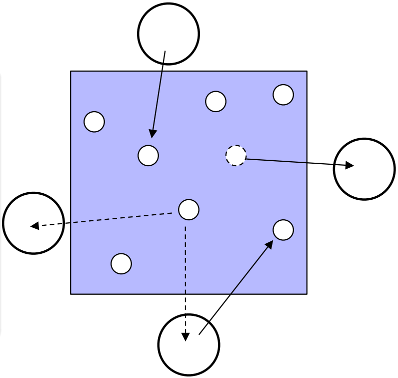

Tuple-based / Space-based Coordination Systems

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

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- 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

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

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

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

Main Features of Tuple-based Coordination

Main features of the Linda model

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Features of Linda: Tuples

- A tuple is an ordered collection of knowledge chunks, possibly heterogeneous in sort
  - a record-like structure
  - with no need of field names
  - easy aggregation of knowledge
  - semantic interpretation: a tuple contains all information concerning an given item
- Tuple structure based on
  - arity
  - type
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  - information content
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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
  - space uncoupling (also called distributed naming): no need to coexist in space for two processes to interact
  - time uncoupling : no need for simultaneity for two processes 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
  - based on tuple templates & matching mechanism
- *Information-driven coordination*
  - patterns of coordination based on data / information availability
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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
- Each philosopher needs a pair of chopsticks to eat—and can access the two chopsticks on his left and on his right
- Each chopstick is shared by two adjacent philosophers
- When a philosopher needs to think, he gets rid of chopsticks

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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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Dining Philosophers in Linda: A Simple Philosopher Protocol

Philosopher using ins and outs

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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
– starvation, deadlock and unfairness still possible

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- Coordination is limited to writing, reading, consuming, suspending on one tuple at a time
  - the behaviour of the coordination medium is fixed once and for all
  - coordination problems that fits it are solved satisfactorily, those that do not fit are not
- Bulk primitives are not a general-purpose solution
  - adding ad hoc primitives does not solve the problem in general
  - and does not fit open scenarios—where instead a limited number of well-known primitives are the perfect solution
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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
  - the behaviour of the coordination medium should *not* be fixed once and for all
  - all coordination problems should fits some admissible behaviour of the coordination medium
  - with no need to either add new *ad hoc* primitives, or change the semantics of the old ones
- In this way, coordination media could *encapsulate* solutions to coordination problems
  - represented in terms of coordination policies
  - enacted in terms of coordinative behaviour of the coordination media
- What is needed is a way to *define the behaviour* of a coordination medium according to the specific coordination issues
  - a general *computational model for coordination media*
  - along with a suitably expressive *programming language* to define the behaviour of coordination media

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  - all coordination problems should fits some admissible behaviour of the coordination medium
  - with no need to either add new *ad hoc* primitives, or change the semantics of the old ones
- In this way, coordination media could *encapsulate* solutions to coordination problems
  - represented in terms of coordination policies
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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
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  - *information-driven* coordination vs. *action-driven* coordination fits better
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- 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
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  - adding for instance a control-driven layer to a Linda-based one
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- 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?
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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 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
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- 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

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

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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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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
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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
  - this makes it possible to decouple the process's view of the tuple centre (perceived as a standard tuple space) from the actual state of a tuple centre, and to relate them so as to embed the coordination laws governing the distributed system

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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
  - the ability to implement coordination rules by manipulating the interaction space

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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

Dining Philosophers in ReSpecT

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

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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).
```

Results

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

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    eat,                            % eating
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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

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

Dining Philosophers in ReSpecT: 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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    in(chop(C1)), in(chop(C2)),  out(chops(C1,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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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
    - late releases (by processes 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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    table ? in(chops(I,J)),         % waiting to eat
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With respect to Dining Philosopher's protocol. . .

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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)) )).
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 ReSpecT Code

```
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    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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```
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    out(used(C1,C2,T)),
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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)), out(chops(C,C2)) )).
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```
reaction( out(chops(C1,C2)), (operation, completion), (       % (1)
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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 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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Distributed Dining Philosophers

Dining Philosophers in a distributed setting

- N philosophers are distributed along the network
  - each philosopher is assigned a seat, represented by the tuple centre `seat(i,j)`
  - `seat(i,j)` denotes that the associated philosopher needs chopstick pair chops(i,j) so as to eat
- each chopstick `i` is represented as a tuple `chop(i)` in the `table` tuple centre
- each philosopher expresses his intention to eat / think by emitting a tuple `wanna_eat` / `wanna_think` in his `seat(i,j)` tuple centre
  - everything else is handled automatically in ReSpecT, embedded in the tuple centre behaviour
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- 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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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), (           %
    in(required(C1,C2)) )).
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 tuple 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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  - which matches event descriptor E such that $\theta = mgu(E,Ev)$, and
  - guard G is true,
  - then reaction $R\theta$ to *Ev* is triggered for execution in the tuple centre

ReSpecT 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⟩ ) |
                             ⟨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
```

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

ReSpecT Behaviour Specification

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

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

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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 ⟨*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 events*

ReSpecT Event Descriptor

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

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

ReSpecT Admissible Event

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

- 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 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

ReSpecT Admissible Event

$$\langle \textit{GeneralTCEvent} \rangle ::= \langle \textit{StartCause} \rangle \,\texttt{,}\, \langle \textit{Cause} \rangle \,\texttt{,}\, \langle \textit{TCCycleResult} \rangle$$
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$$\langle \textit{Source} \rangle \,,\, \langle \textit{Target} \rangle ::= \langle \textit{ProcessIdentifier} \rangle \mid \langle \textit{TCIdentifier} \rangle$$
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\end{array}
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ReSpecT Guards

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

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

$\langle \mathit{Time} \rangle$ 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

ReSpecT Guards

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

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

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ReSpecT Guards

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

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

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

- A triggered reaction is actually executed only if its guard is true
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- 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`

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request invocation, inv, req, pre

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ReSpecT Reactions

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

- 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

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

- 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

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`

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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
  - working as the (logic) *theory of coordination* for distributed systems

- Both spaces are inspectable
  - by engineers, via ReSpecT inspectors
  - by processes, via `rd` & `no` primitives
    - `rd` & `no` for the tuple space; `rd_s` & `no_s` for the specification space
    - either directly or indirectly, through either a coordination primitive, or another tuple centre

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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
    - so they do not affect the transactional semantics of reactions
  - all primitives have a request / response semantics
    - including out / out_s
    - so reactions can be defined to handle both primitive invocations & completions
  - all primitives could be executed within a ReSpecT reaction
    - as either a reaction goal executed within the same tuple centre
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- ReSpecT tuple centres are linkable
  - by using tuple centre identifiers within ReSpecT reactions

    $$< \mathit{TCIdentifier} > @ < \mathit{NetworkLocation} > ? < \mathit{SimpleTCPredicate} >$$

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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
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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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Distributed Systems L-A
Sistemi Distribuiti L-A

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