A Self-Organising Solution to the Collective Sort Problem in Distributed Tuple Spaces

Mirko Viroli Matteo Casadei Luca Gardelli

Alma Mater Studiorum – Università di Bologna
{mirko.viroli,m.casadei,luca.gardelli}@unibo.it

ACM SAC 2007
Track on Coordination Models and Languages
Seul - Korea
March 12, 2007

What is Coordination?

Settings

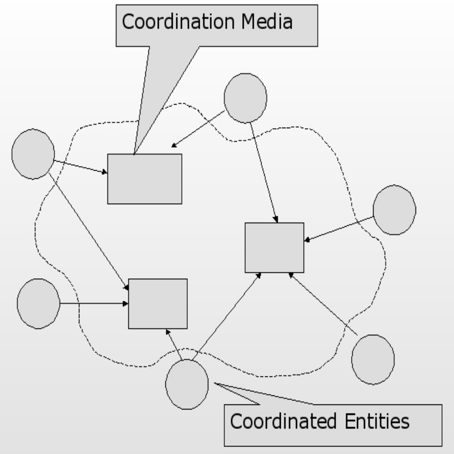
- A distributed or concurrent system
- Composed of different entities: agents, processes, components
- Coordination is government of their interactions!

Example models and technologies

- Channels: as in REO model
- Spaces: as in LINDA and all its derivations
  - TuCSoN, LIME, TSPACES, TOTA, KLAIM, ...

Even direct communication is a particular case ...

A General Meta-Model



Architecture

- Many coordinated entities
- The coordination space hosting *coordination media*
- Coordinated enties interacting with media through primitives

Complex systems, Self-Organization, Emergent Behaviours

Complex systems

- Systems whose dynamics is hardly predictable
- Small changes in initial conditions may lead to completely different behaviours
- They are hard to design: behaviour really emerges without a priori intention

Self-organization as source of complexity

- Designed to adapt to unpredictable changes of the surrounding conditions
- Organization emerges at the global level as a result of local interaction of entities
- A naturally inspired metaphor indeed!

Self-Organization and Coordination

A Reference Scenario

- Should design a coordination space
- Agents require services related to mutual awareness and retrieval of resources
- The system should adapt to dynamism in topology and handle unpredictable agent behaviour and movements

Related Works

- TOTA: co-fields for awareness
- SWARMLINDA: dynamic movement of tuples in the network
- Many other examples related to stigmergy

The TOTA Solution

TOTA Architecture

- One tuple space in each node of the dynamic network
- Tuples are:
  - put in the local space by agents
  - TOTA spread them in the neighborhood
  - a distributed data structure resembling a *field* is created
  - agents perceive tuples and behave accordingly

Local/global

- Interactions are all local, movements are local
- Yet, a global behaviour emerges, in the stigmergy style!

Some patterns

Inspired by nature

- Diffusion: some data chunk locally stored, automatically spread around
- Aggregation: homogeneous data chunks in the same place are collected
- Evaporation: data chunks keep fading until completely vanishing
- Collective Sorting: data chunks are moved according to similarity properties

Problem

Definition

Inspired by brood and larvae sorting by ants

- Take a distributed flat set of tuple spaces $(S_1, \ldots, S_n)$
- Each holding tuples of different kinds $(K_1, \ldots, K_n)$
- Design a self-organizing solution where:
  - Locally: a tuple can be moved from one space to the other according to local criteria
  - Globally: tuples with same kind are collected in a single space, tuples with different kind are collected in different spaces

Why is this interesting?

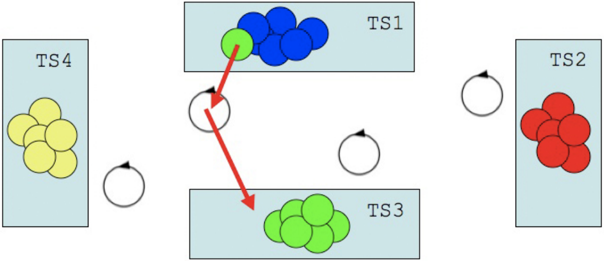
Where is Emergence and Adaptiveness?

- The space where a given kind aggregates is uncertain (bifurcation effect)
- Full sorting should be reached independently of initial conditions and ongoing perturbations

Usefulness for Coordination

- If tuples represent information, after a while agents know where to retrieve them
- Supporting tuple space optimization and load balancing
- E.g. having similar tuples in the same place eases consistency checking

An Architecture for the Solution



Elements

- One manager agent for each space S (or possibly more)
- It has the burden of moving tuples away from S, at a certain rate
- Decisions taken by relying on a pointwise primitive (*rd*)
- Avoiding global counting operations
- The whole sorting service transparent to user agents

Uniform read

Movement criterion

- How an agent may decide to move a tuple T away from a space S?
- The agent should recognise that the kind of T is aggregating more elsewhere..
- We need a new pointwise primitive supporting this reasoning

Uniform read primtive

- $urd(K_1, \ldots, K_n)$
- Reads one tuple belonging to any kind K_i, probabilistically!
- The more tuples of kind K_i occur in the space, the more likely one such tuple is read
- This primitive could be implemented e.g. in ReSpecT

The manager agent agenda

Step-by-step behaviour

Consider an agent managing space S, and executing this agenda with a fixed rate r:

- it draws a tuple kind K of interest, randomly
- it draws a candidate destination tuple space D, randomly
- it performs a *urd* on S, obtaining a tuple of kind K_S
- it performs a *urd* on D, obtaining a tuple of kind K_D
- it $K = K_D \neq K_S$ it moves a tuple of kind K from S to D

Intuition

If $K = K_D \neq K_S$ holds, it is likely that D aggegates K more than what S is doing

A Design Methodology

How we proceed now?

We have an intuition of the strategy, how to design a correct solution?

- Express the design as a formal language
- Execute stochastic simulations, evaluate the results
- If not satisfied, tune the design and proceed again

A pillar work in this direction

- D.Gillespie, "Exact Stochastic Simulation of Coupled Chemical Reacions", 1977
- It shows that complex chemical processes (large, discrete systems), can be described by a stochastic approach, rather than by standard differential equations

Stochastic modelling

Start from a stochastic model of a system...

It is basically a transition system $\langle S, A, \rightarrow \rangle$, where:

- S is the set of states of the system of interest
- A is the set of actions (labels for system evolution)
- $\rightarrow \subseteq S \times A \times \mathbb{R} \times S$ is the transition relation
- (write $s \xrightarrow{a:r} s'$ for $\langle s, a, r, s' \rangle \in \rightarrow$)

$s \xrightarrow{a:r} s'$ means the system may move from s to s' by action a occurring with rate r (average Δt is $1/r$)

Stochastic simulation

General schema

- Start from an initial state
- Choose a new state and a time increase probabilistically
- Proceed and keep track of the evolution history (e.g. to draw a chart)

A simulation step is as follows

- Let $a_1 : r_1, \ldots a_n : r_n$ be the actions(rates) available in current state
- Draw two random numers in $[0, 1]$, say τ_1 and τ_2
- Use τ_1 to select an $a_i : r_i$ (probability is $r_i / \sum r_j$)
- Use τ_2 to identify the time increase: $\Delta t = -ln(1/\tau_2) / \sum r_j$

A MAUDE library

What is MAUDE

- It is basically a meta-language for transition systems
- Based on term-rewriting logic
- Can express custom syntax, and rules of transition/rewriting

A library for stochastic simulations

- The user expresses the transition system $\langle S, A, \rightarrow \rangle$
- The library implements the simulation engine and yields a simulation trace
- The resulting output file is used to chart results

With respect to other simulation frameworks like SPiM and Repast, MAUDE is a general-purpose tool.

A simple example, Sodium-chloride reaction 1/2

Maude code

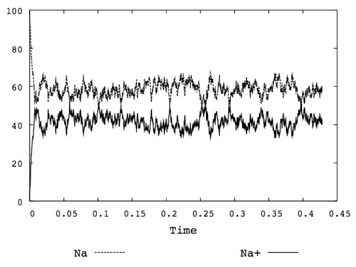
```
op <_,_,_,_> : Nat Nat Nat Nat -> State .
ops ionization deionization : -> Action .
vars Na Na+ Cl Cl- : Nat .

eq  < Na,Na+,Cl,Cl- > ==>  =
   ( ionization   # (float(Na * Cl) * 1.0)}
                       ->  [< p Na,s Na+,p Cl,s Cl- >]  );
   ( deionization # (float(Na+ * Cl-) * 2.0)}
                       ->  [< s Na,p Na+,s Cl,p Cl- >]  ) .
```

A simple example, Sodium-chloride reaction 2/2

Trace

```
<
   [300 : < 100,0,100,0 > @ 0.0],
   [299 : < 99,1,99,1 > @ 5.2282294378567067e-5],
   [298 : < 98,2,98,2 > @ 6.9551290710937174e-5],
   [297 : < 97,3,97,3 > @ 8.5491215950091466e-5],
   ...
   [7 : < 61,39,61,39 > @ 3.9845251139158447e-2],
   [6 : < 60,40,60,40 > @ 3.9980318990300842e-2],
   [5 : < 59,41,59,41 > @ 4.029131950475788e-2],
   [4 : < 58,42,58,42 > @ 4.0294167525983679e-2],
   [3 : < 57,43,57,43 > @ 4.0424914101137542e-2],
   [2 : < 58,42,58,42 > @ 4.0506028901053114e-2],
   [1 : < 59,41,59,41 > @ 4.0661029058233995e-2],
   [0 : < 60,40,60,40 > @ 4.0695684943167353e-2]
>
```

Chart



Modelling Collective Sort in MAUDE

An initial configuration

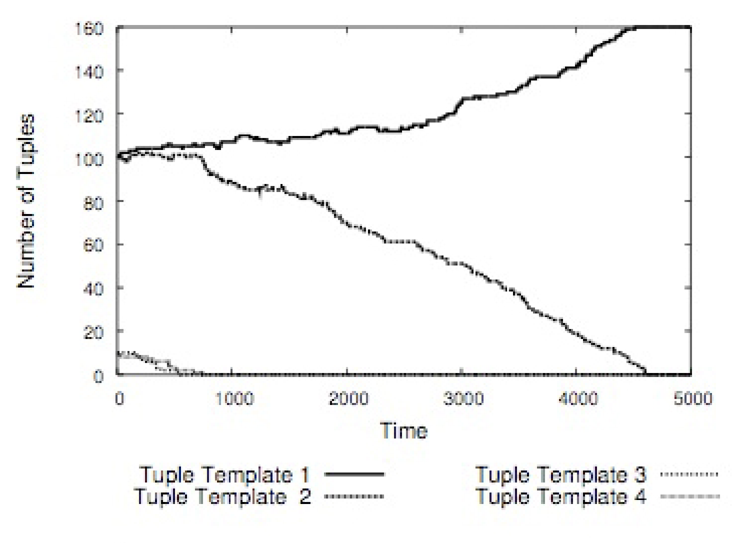
```
< 0 @ (a[100])|(b[100])|(c[10])|(d[10]) > |
< 1 @ (a[0])  |(b[100])|(c[10])|(d[10]) > |
< 2 @ (a[10]) |(b[50]) |(c[50])|(d[10]) > |
< 3 @ (a[50]) |(b[10]) |(c[10])|(d[50]) >
```

Semantic Rules

- Basically, one for each step of the agent agenda
- The first one creates a new agent (state) at rate *r*
- The other rules evolve this state as decisions are taken
- The latter possibly changes the configuration of tuples

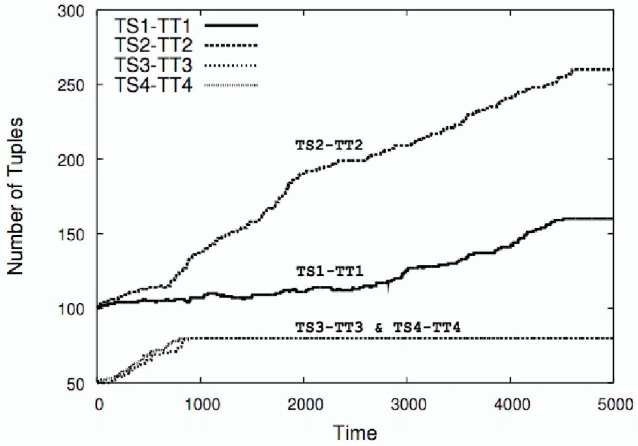
Results 1/3

Behaviour in tuple space S_0



Results 2/3

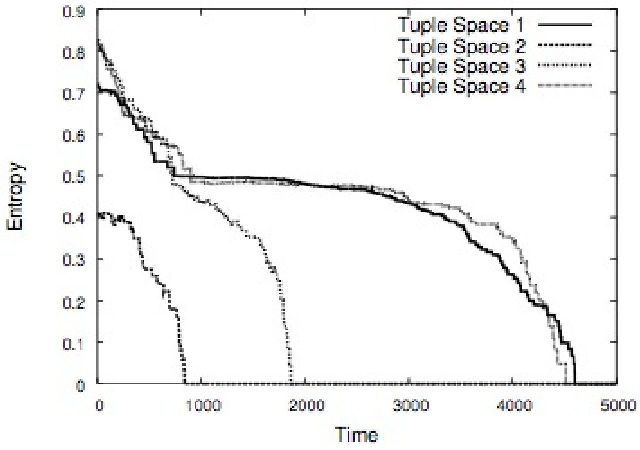
Winning tuple in each tuple space



Results 3/3

Entropy in each tuple space

Computed as: $\sum -c_K * ln\, c_K$ (c_K is the concentration of K)



What about convergence?

Local minima for entropy exist!

An example:

```
< 0 @ (a[20]) |(b[0])   |(c[0]) |(d[0]) > |
< 1 @ (a[140])|(b[0])   |(c[0]) |(d[0]) > |
< 2 @ (a[0])  |(b[260])|(c[0]) |(d[0]) > |
< 3 @ (a[0])  |(b[0])   |(c[80])|(d[80]) >
```

- The concentration of tuple `a` in 0 and 1 is 100% (full aggregation)
- Tuples `c` and `d` are never moved away!

This general situation is quite frequent when using complex systems as optimization tools

The vacuum tuple solution

The problem

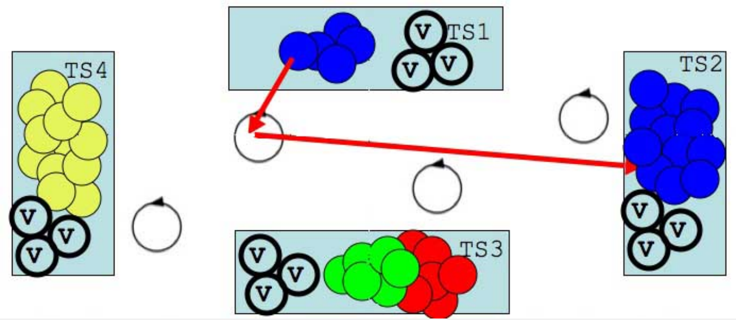
- Some tuple spaces might be simply empty (how *urd* works?)
- Not only the relative concentration but also absolute value should be considered
- We need a form of *simulated annealing*!

A solution

- Each tuple space has also a (fixed) number of vacuum tuples
- If the destination tuple is vacuum, then move the source tuple there!!

Vacuum architecture

A picture



A new agenda

Step-by-step behaviour

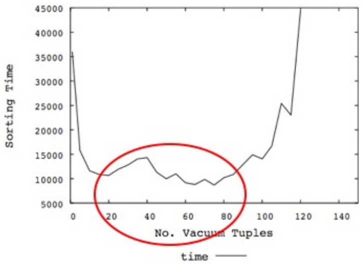
Consider an agent managing space S, and executing this agenda with a fixed rate r:

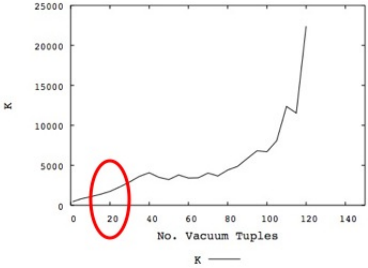
- it draws a tuple kind K of interest, randomly
- it draws a candidate destination tuple space D, randomly
- it performs a *urd* on S, obtaining a tuple of kind K_S
- it performs a *urd* on D, obtaining a tuple of kind K_D
- if $K = K_D \neq K_S$ it moves a tuple of kind K from S to D
- if $K \neq K_S$ and $K_D = \mathrm{v}$ it moves a tuple of kind K from S to D

Intuition

If $K_D = \mathrm{v}$ the destination has some emptyness, and hence we move the tuple

New simulations





K = Number of moved tuples

- Good overall *performance* is achieved when vacuum concentration is **20%** of the final number of tuples
- How can this be designed in advance?
- We need an adaptive mechanism for vacuum!

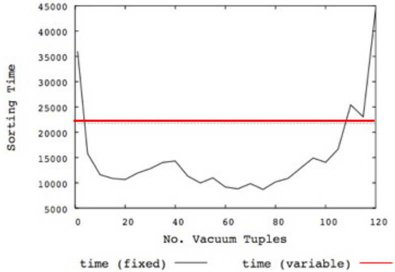
Agent for adaptive vacuum

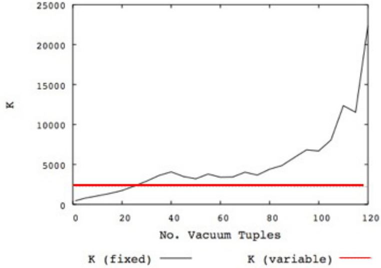
Step-by-step behaviour

Consider an agent managing space S, and executing this agenda with a fixed rate r:

- it draws a tuple kind K of interest, randomly
- it draws a candidate destination tuple space D, randomly
- it performs a *urd* on S, obtaining a tuple of kind K_S
- it performs a *urd* on D, obtaining a tuple of kind K_D
- if $K = K_D \neq K_S$ it moves a tuple of kind K from S to D
- if $K \neq K_S$ and $K_D = \mathtt{v}$ it moves a tuple of kind K from S to D
- if $K = K_D \neq K_S$ it drops one vacuum tuple from S
- if $K = K_D = K_S$ it adds one vacuum tuple to S

New simulations





K = Number of moved tuples

- The obtained performance is sufficiently far from the *bad* zone
- No significant performance impact on instances that normally converge

Conclusions

Experience

- Coordination and Self-Organization
- Provide design-support to adaptive behaviour

Future Work

Putting our simulation framework to test in other contexts

- Cellular automata
- Chemical/Biological modelling
- Towards new computation paradigms