Nature-Inspired Coordination & Self-Organisation

Autonomous Systems

Sistemi Autonomi

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Outline

Nature-inspired Models for SOS

Complex natural systems

- such as physical, chemical, biochemical, biological, social systems
- natural system exhibit *features*
  - such as distribution, opennes, situation, fault tolerance, robustness, adaptiveness, ...
- which we would like to understand, capture, then bring to *computational* systems

Nature-Inspired Computing (NIC)

- For instance, NIC [Liu and Tsui, 2006] summarises decades of research activities, putting emphasis on
  - autonomy of components
  - self-organisation of systems

Multi-Agent Systems for SOS

MAS as complex systems [Omicini and Zambonelli, 2004]

- Agents as sources of complexity
  - **Autonomy** Unpredictable behaviour
  - **Sociality** Non-compositional behaviours
  - **Situatedness** Unpredictable interaction with the environment
- Multi-Agent Systems (MAS) as sources of complexity
  - Multiplicity of interacting components
  - Global vs. local structure and behaviour—macro vs. micro level

MAS for complex systems [Zambonelli and Omicini, 2004]

MAS as tools for

- Modelling complex systems
- Engineering complex system

Interaction & Coordination?

Interaction

- most of the complexity of complex computational systems – MAS included – comes from interaction [Omicini et al., 2006]
- along with an essential part of their expressive power [Wegner, 1997]

Coordination

- since coordination is essentially the science of managing the space of interaction [Wegner, 1997]
- coordination models and languages [Ciancarini, 1996] provide abstractions and technologies for the engineering of complex computational systems [Ciancarini et al., 2000]

Nature-inspired Coordination for MAS

Coordination issues in natural systems

- coordination issues did not first emerge in computational systems
- [Grassé, 1959] noted that in termite societies *"The coordination of tasks and the regulation of constructions are not directly dependent from the workers, but from constructions themselves."*

Coordination as the key issue

- many well-known examples of natural systems – and, more generally, of complex systems – seemingly rely on simple yet powerful coordination mechanisms for their key features—such as self-organisation
- it makes sense to focus on nature-inspired coordination models as the core of complex nature-inspired MAS

Outline

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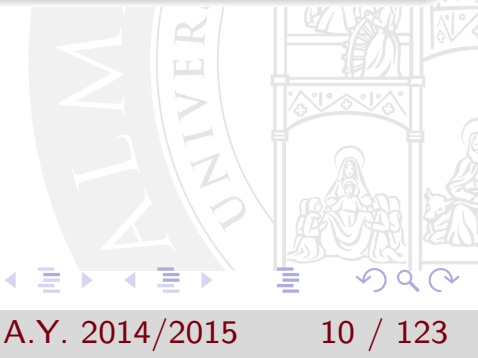
Stigmergy I

Stigmergy in insect societies

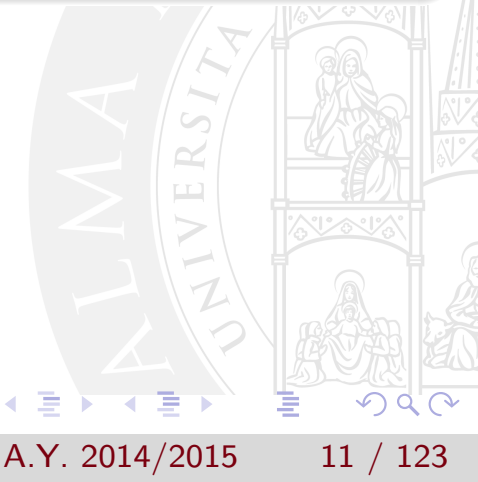
- nature-inspired models of coordination are grounded in studies on the behaviour of social insects, like ants or termites
- [Grassé, 1959] introduced the notion of stigmergy as the fundamental coordination mechanism in termite societies
- in ant colonies, pheromones act as environment markers for specific social activities, and drive both the *individual* and the *social* behaviour of ants



Stigmergy II

Stigmergy in computational systems

- nowadays, stigmergy generally refers to a set of nature-inspired coordination mechanisms mediated by the *environment*
- *digital pheromones* [Parunak et al., 2002] and other *signs* made and sensed in a shared environment [Parunak, 2006] can be exploited for the engineering of adaptive and self-organising MAS



Chemical Coordination

Chemical reactions as (natural) coordination laws

- inspiration comes from the idea that complex physical phenomena are driven by the (relatively) simple chemical reactions
- coordinating the behaviours of a huge amount of agents, as well as the global system evolution

Chemical reactions as (computational) coordination laws

- Gamma [Banâtre and Le Métayer, 1990] is a *chemistry-inspired coordination* model—as for the CHAM (chemical abstract machine) model [Berry, 1992]
- coordination in Gamma is conceived as the evolution of a space governed by chemical-like rules, globally working as a rewriting system [Banâtre et al., 2001]

Outline

Field-based Coordination

Computational fields as coordination laws

- field-based coordination models like Co-fields [Mamei and Zambonelli, 2006] are inspired by the way masses and particles move and self-organise according to gravitational/electromagnetic fields
- there, computational force fields – generated either by the mobile agents or by the pervasive coordination infrastructure – propagate across the environment, and drive the actions and motion of the agent themselves

(Bio)chemical Coordination

Chemical reactions as coordination laws

- chemical tuple spaces [Viroli et al., 2010] exploit the chemical metaphor at its full extent—beyond Gamma
- data, devices, and software agents are represented in terms of chemical reactants, and system behaviour is expressed by means of chemical-like laws
- which are actually time-dependent and stochastic
- embedded within the coordination medium
- biochemical tuple spaces [Viroli and Casadei, 2009] add *compartments*, *diffusion*, and *stochastic behaviour* of coordination primitives

Outline

Basic Issues of Nature-inspired Coordination I

Environment

- environment is essential in nature-inspired coordination
  - it works as a mediator for agent interaction — through which agents can communicate and coordinate indirectly
  - it is active — featuring autonomous dynamics, and affecting agent coordination
  - it has a structure — requiring a notion of *locality*, and allowing agents of any sort to *move* through a topology

! nowadays, everybody knows about the essential role of *environment* in a MAS [Weyns et al., 2007]

? *do we also know how to design and engineer MAS environment?*

Basic Issues of Nature-inspired Coordination II

Stochastic behaviour

- complex systems typically require probabilistic models
  - *don't know* / *don't care* non-deterministic mechanisms are not expressive enough to capture all the properties of complex systems such as biochemical and social systems
  - probabilistic mechanisms are required to fully capture the dynamics of coordination in nature-inspired systems
  - coordination models should feature (possibly simple yet) expressive mechanisms to provide coordinated systems with stochastic behaviours

? *do we know how to embed stochastic behaviours in a MAS?*

Outline

The Ancestor

LINDA [Gelernter, 1985]

- LINDA is the ancestor of all tuple-based coordination models [Rossi et al., 2001]
- in LINDA, agents synchronise, cooperate, compete
  - based on tuples
  - available in the tuple spaces, working as the coordination media
  - by *associatively* accessing, consuming and producing tuples
- the same holds for any tuple-based coordination model

LINDA is *not* a Nature-inspired Model

Warning

LINDA is *not* a Nature-inspired Model

So, *why* LINDA?

Why tuple-based models?

Why Tuple-based Models? I

Expressiveness

- LINDA is sort of a *core* coordination model
- making it easy to face and solve many typical problems of complex distributed systems
- *complex* coordination problems are solved with *few, simple* primitives
- whatever the model used to measure expressiveness of coordination, tuple-based languages are highly-expressive [Busi et al., 1998]

Why Tuple-based Models? II

Environment-based coordination

- generative communication [Gelernter, 1985] requires *permanent* coordination abstractions
- so, the *coordination infrastructure* provides agents with tuple spaces as coordination services
  - *coordination as a service* (CaaS) [Viroli and Omicini, 2006]
- they can be interpreted as coordination artefacts shaping computational *environment* [Omicini et al., 2004]
  - and used with different levels of awareness by both intelligent and "stupid" agents [Omicini, 2013a]
- as such, they can be exploited to support environment-based coordination [Ricci et al., 2005]

Why Tuple-based Models? III

Extensibility

- whatever its expressiveness, LINDA was conceived as a coordination model for closed, parallel systems
- so, in fact, some relevant problems of today open, concurrent systems cannot be easily solved with LINDA either in practice or in theory
- as a result, tuple-based models have been extended with new simple yet powerful mechanisms
- generating a plethora of tuple-based coordination models [Rossi et al., 2001]

Why Tuple-based Models? IV

Nature-inspired extensions

- LINDA may *not* be nature-inspired, but many of its extensions *are*
- many of the coordination models depicted before
  - stigmergy [Parunak, 2006]
  - field-based [Mamei and Zambonelli, 2004a]
  - chemical [Viroli et al., 2010] and biochemical [Viroli and Casadei, 2009]
- along with many others, such as
  - cognitive stigmergy [Ricci et al., 2007]
  - pervasive ecosystems [Viroli et al., 2012]
- are actually nature-inspired tuple-based coordination models

Toward Self-organising Coordination I

Just *some* is not enough

- capturing just *some* of the principles and mechanisms of natural systems does not ensure to capture their *essence*
- for instance, chemical coordination models such as Gamma and CHAM exploit the raw schema of computation as chemical reaction, but are *not* expressive enough to fully reproduce any non-trivial chemical system
- in fact, *e.g.*, even the simplest model for real chemical reactions requires a notion of *reaction rate*
- neither Gamma nor CHAM provide for such a notion, they are not expressive enough to fully match the behaviour of real chemical systems

Toward Self-organising Coordination II

Self-organising coordination [Viroli et al., 2009]

- most of the traditional coordination models feature abstractions enacting coordination laws that are typically *reactive*, (mostly) *deterministic*, and *global* as well
- in complex systems featuring self-* properties, instead, coordination patterns typically appear at the global level by emergence, from *probabilistic*, *time-dependent* coordination laws based on *local* criteria
- in particular, many coordination models either implicitly or explicitly recognise that full expressiveness requires addressing the issues of time dependency and stochasticity

Examples I

StoKlaim

- StoKlaim [De Nicola et al., 2006] – a *stochastic* extension of the Linda-derived Klaim model for mobile coordination [De Nicola et al., 1998] – adds distribution rates to coordination primitives—thus making it possible the modelling of non-deterministic real-life phenomena such as failure rates and inter-arrival times

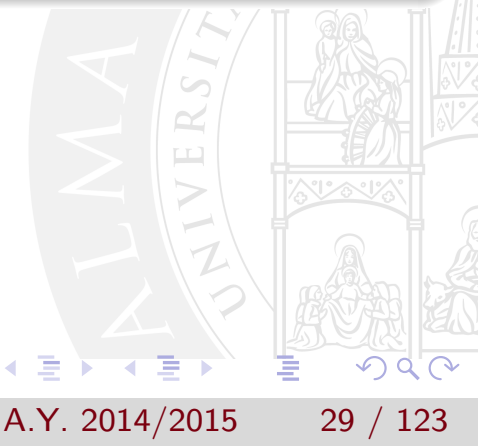
SwarmLinda

- SwarmLinda [Tolksdorf and Menezes, 2004] enhances Linda implementation with swarm intelligence to achieve features such as scalability, adaptiveness, and fault-tolerance—by modelling tuple templates as ants, featuring probabilistic behaviour when looking for matching tuples in a distributed setting

Examples II

Time-aware ReSpecT

- ReSpecT [Omicini and Denti, 2001] generally addresses *time dependency* by capturing time events and supporting the definition and enforcement of *timed coordination policies* [Omicini et al., 2005]—so, ReSpecT-programmed tuple centres can work as time-dependent abstractions for MAS coordination [Omicini et al., 2007]



Enough?

No.

- in the overall, the above-mentioned models *fail* to capture all the *essential features* of nature-inspired coordination
- this is why many novel research lines stretch existing tuple-based models to achieve the expressive power required to model and build MAS with a complexity comparable to natural systems [Omicini and Viroli, 2011]

Outline

Outline

Complexity as a Multi-disciplinary Notion

Complex systems everywhere

- The notion of *complexity* is definitely a *multi-disciplinary* one, ranging from physics to biology, from economics to sociology and organisation sciences
- Systems that are said *complex* are both natural and artificial ones

Natural vs. artificial complex systems

- We *observe* and *model* complex physical systems
- We *design* and *build* complex computational systems

Question

- Which features do *all* complex systems share independently of their nature?

Complexity & Interaction

. . . by a complex system I mean one made up of a large number of parts that interact in a non simple way [Simon, 1962]

Laws of complexity

- Some "laws of complexity" exists that characterise any complex system, *independently* of its specific nature [Kauffman, 2003]
- The precise source of what all complex systems share is still unknown in essence

Interaction

- We argue that interaction – its *nature*, *structure*, *dynamics* – is the key to understand some fundamental properties of complex systems of any kind

Interaction in Statistical Mechanics I

Independence from interaction

- Some physical systems are described under the assumption of mutual independence among particles—that is, the behaviour of the particles is unaffected by their mutual interaction
  - e.g., ideal gas [Boltzmann, 1964]
- There, the probability distribution of the whole system is the product of those of each of its particles
- In computer science terms, the *properties of the system* can be compositionally derived by the *properties of the individual components* [Wegner, 1997]

→ Neither macroscopic sudden shift nor abrupt change for the system as a whole: technically, those systems have no phase transitions—of course, while the "independence from interaction" hypothesis holds

Interaction in Statistical Mechanics II

Interacting systems

- Introducing interaction among particles structurally *changes* the *macroscopic properties*, along with the *mathematical* ones
- Interacting systems are systems where particles *do not behave independently* of each other
- The probability distribution of an interacting system does not factorise anymore
- In computer science terms, an interacting system is *non-compositional* [Wegner, 1997]

Interaction in Statistical Mechanics III

Interacting vs. non-interacting systems

- Only interacting systems can describe real cases beyond the idealised ones
  - e.g., they can explain phase transitions – like liquid-gas transition – and much more, such as collective emerging effects
- While a system made of independent parts can be represented by isolated single nodes, an *interacting system* is better described by *nodes connected by lines* or higher-dimensional objects
- From the point of view of information and communication theories, an ideal non-interacting gas is a system of *non-communicating nodes*, whereas an interacting system is made of *nodes connected by channels*

Complexity in Statistical Mechanics I

The case of magnetic particles

- The simplest standard prototype of an interacting system is the one made of magnetic particles
- There, individual particles can behave according to a magnetic field which leaves their probabilistic independence undisturbed
- At the same time, two magnetic particles interact with each other, and the strength of their interaction is a crucial tuning parameter to observe a phase transition
  - If interaction is weak, the effect of a magnetic field is smooth on the system
  - Instead, if the interaction is strong – in particular, higher than a threshold – even a negligible magnetic field can cause a powerful *cooperative effect* on the system

Complexity in Statistical Mechanics II

Interaction is not enough

- Interaction is a necessary ingredient for complexity in statistical mechanics but definitely not a sufficient one
- Complexity arises when the possible equilibrium states of a system grow very quickly with the number of particles, regardless of the simplicity of the laws governing each particle and their mutual interaction
- Roughly speaking, complexity is much more related to size in number, rather than to complexity of the laws ruling interaction

$\rightarrow$ we do *not* need *complex interaction* to make interaction lead to complexity

From Statistical Mechanics to Social Systems I

Large numbers

- The key point in statistical mechanics is to relate the *macroscopic* observables quantities – like pressure, temperature, etc. – to suitable *averages* of *microscopic* observables—like particle speed, kinetic energy, etc.
- Based on the *laws of large numbers*, the method works for those systems made of a large number of particles / basic components

From Statistical Mechanics to Social Systems II

Beyond the boundaries

- *Methods for complex systems* from statistical mechanics have expanded from physics to fields as diverse as biology [Kauffman, 1993], economics [Bouchaud and Potters, 2003, Mantegna and Stanley, 1999], and computer science itself [Mézard and Montanari, 2009, Nishimori, 2001]
- Recently, they have been applied to *social sciences* as well: there is evidence that the complex behaviour of many observed socio-economic systems can be approached with the *quantitative tools* from statistical mechanics
  - e.g., *Econophysics* for crisis events [Stanley, 2008]

From Statistical Mechanics to Social Systems III

Social systems as statistical mechanical systems

- A group of isolated individuals neither knowing nor communicating with each other is the typical example of a *compositional* social system
- No sudden shifts are expected in this case at the collective level, unless it is caused by strong external exogenous causes
- To obtain a *collective behaviour* displaying *endogenous* phenomena, the individual *agents* should meaningfully *interact* with each other
- The foremost issue here is that the nature of the interaction determines the nature of the collective behaviour at the aggregate level
  - e.g., a simple *imitative* interaction is capable to cause strong polarisation effects even in presence of extremely small external inputs

Modelling vs. Engineering

Physical vs. computational systems

- Physical systems are to be observed, understood, and possibly *modelled*
  - → For physical systems, the laws of interaction, and their role for complexity, are to be *taken as given*, to be possibly formalised mathematically by physicists
- Computational systems are to be *designed* and built
  - → For computational systems, the laws of interaction have first to be *defined* through amenable abstractions and computational models by computer scientists, then exploited by computer engineers in order to build systems

Coordinated Systems as Interacting Systems I

Coordination media for ruling interaction

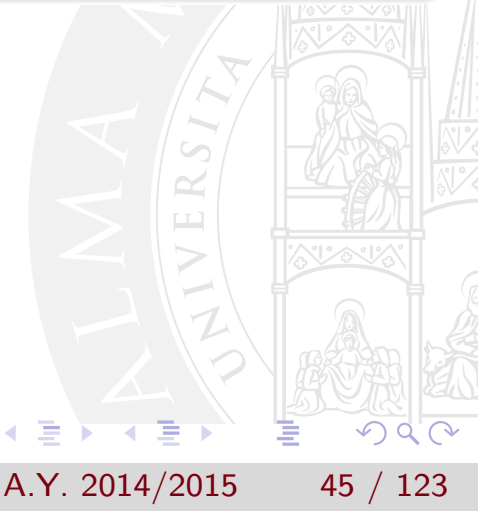
- Defining the abstractions for ruling the interaction space in computational systems basically means to define their *coordination model* [Gelernter and Carriero, 1992, Ciancarini, 1996, Ciancarini et al., 1999]
- *Global properties* of complex coordinated systems depending on interaction can be enforced through the *coordination model*, essentially based on its expressiveness [Zavattaro, 1998, Denti et al., 1998]
  - For instance, tuple-based coordination models have been shown to be expressive enough to support self-organising coordination patterns for nature-inspired distributed systems [Omicini, 2013b]

Coordinated Systems as Interacting Systems II

The role of coordination models

Coordination models could be exploited

- to *rule* the *interaction space*
- so as to *define* new sorts of *global*, macroscopic *properties* for *computational systems*, possibly inspired by physical ones



Coordinated Systems as Interacting Systems III

Research perspectives

One should understand

- how to relate methods from statistical mechanics with coordination models
- whether notions such as *phase*, *phase transition*, or any other macroscopic system property, could be transferred from statistical mechanics to computer science
- what such notions would imply for computational systems
- whether new, original notions could apply to computational systems
- which sort of coordination model could support such notions

Socio-Technical Systems

Humans vs. software

- Nowadays, a particularly-relevant class of *social systems* is represented by socio-technical systems
- In socio-technical systems
  - active components are mainly represented by *humans*
  - whereas interaction is almost-totally regulated by the *software infrastructure*
  - where *software agents* often play a key role
- This is the case, for instance, of *social platforms* like FaceBook [FaceBook, 2014] and LiquidFeedback [LiquidFeedback, 2014]

Physical & Computational Social Systems I

A twofold view of socio-technical systems

- The nature of socio-technical systems is twofold: they are both social systems and computational systems
  [Verhagen et al., 2013, Omicini, 2012]
- As *complex social systems*, their complex behaviour is in principle amenable of mathematical modelling and prediction through notions and tools from statistical mechanics
- As *complex computational systems*, they are designed and built around some (either implicit or explicit) notion of coordination, ruling the interaction within components of any sort—be them either software or human ones

Physical & Computational Social Systems II

Computational systems meet physical systems

- In socio-technical systems, macroscopic properties could be
  - described by exploiting the conceptual tools from physics
  - enforced by the coordination abstractions
- Socio-technical systems could exploit both
  - the notion of complexity by statistical mechanics, along with the mathematical tools for behaviour modelling and prediction, and
  - coordination models and languages to suitably shape the interaction space

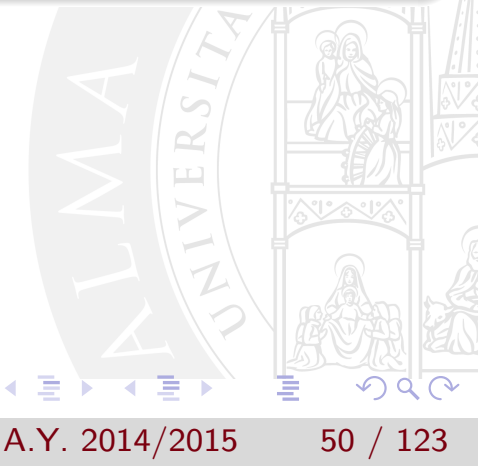
Physical & Computational Social Systems III

Vision

Complex socio-technical systems could be envisioned

- whose implementation is based on suitable coordination models
- whose macroscopic properties can be modelled and predicted by means of mathematical tools from statistical physics

thus reconciling the scientist and the engineer views over systems

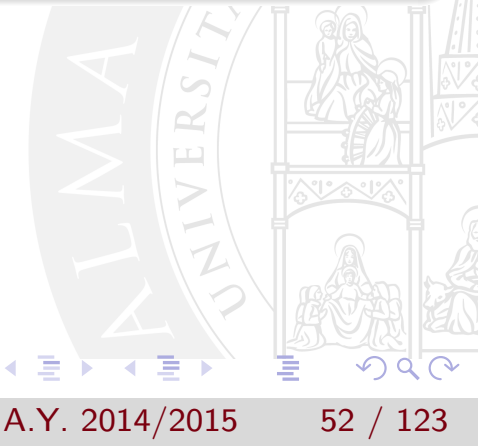


Outline

Coordination for Simulation I

Simulation of complex systems is a multidisciplinary issue

- . . . ranging from physics to biology, from economics to social sciences
- no complex system of any sort can be studied nowadays without the support of suitable simulation tools
- nowadays, experiments done *in silico* are at least as relevant as those *in vitro* and *in vivo*



Coordination for Simulation II

Interaction issues are prominent in complex systems

- coordination technologies potential core of agent-based simulation frameworks
- in particular, self-organising nature-inspired coordination models are well suited for the simulation of complex systems
- so, coordination middleware could play a central role in the development of rich agent-based simulation frameworks for complex systems

Case Study: Simulating Intracellular Signalling Pathways I

Intracellular signalling pathways

- Intracellular signalling involves several molecular processes along with a huge amount of signalling elements, including several kinds of proteins
- Signal transduction pathways activated by G-proteins interact with one another to form a complex network that regulates diverse cellular components and controls a wide range of cellular processes [Neves et al., 2002]
- The Ras-regulated signal transduction pathways are a classical example of this kind of network [Downward, 2003]

Case Study: Simulating Intracellular Signalling Pathways II

Interaction issues in intracellular signalling pathways

- To model intracellular signalling systems, complex interaction that governs their behaviour should be first of all considered and understood
- Though determining the kinetic equations of the biochemistry involved in vital functions is important, managing *interactions* for the cell to make the correct physiological decisions is even more so
- Simulation of intracellular signalling pathways could be framed as mostly a coordination issue
-

Case Study: Simulating Intracellular Signalling Pathways III

Biochemical coordination

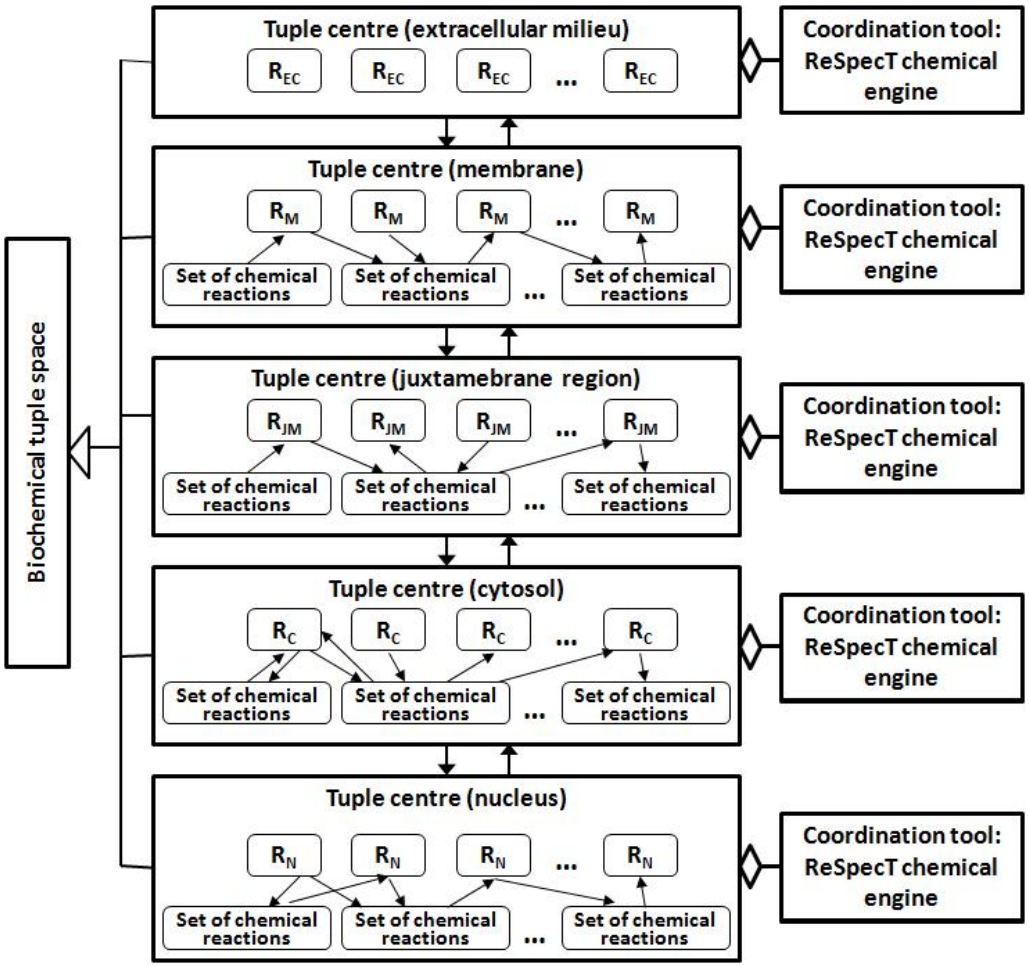
- *Biochemical tuple spaces* [Viroli and Casadei, 2009] are the core of a model for *self-organising coordination* (BTS-SOC)
- A biochemical tuple space is a tuple space working as a compartment where *biochemical reactions* take place
- Tuples in BTS-SOC are associated with an activity/pertinency value, resembling chemical *concentration*, and allowing chemical reactants to be represented as *tuples*
- Biochemical laws are represented as *coordination laws* by the coordination abstraction, evolving tuple concentration over time according to a rate in the same way as chemical substances into a solution
- Also, BTS-SOC laws allow for tuple *diffusion*, making it possible for products to cross compartment boundaries as a result of biochemical reactions

Case Study: Simulating Intracellular Signalling Pathways IV

Mapping cellular components and structures involved in intracellular signalling onto BTS-SOC abstractions [González Pérez et al., 2013]

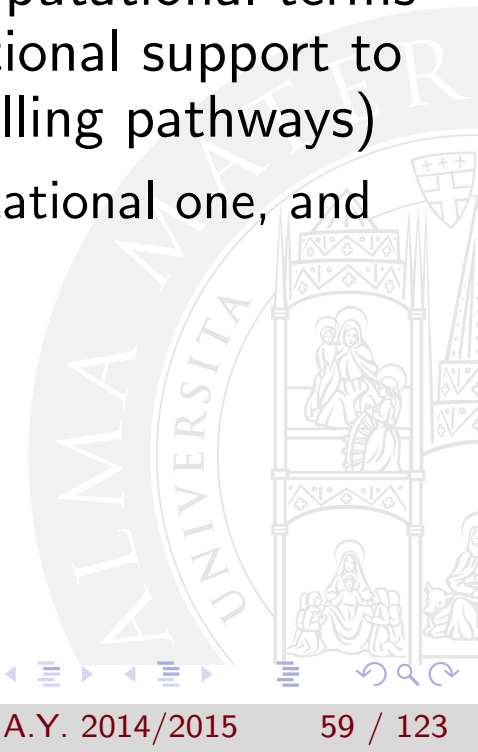
Cellular components and structures involved in intracellular signalling	**Computational abstractions of the BTS-SOC model**
Extracellular milieu and intracellular compartments *(i.e., membrane, juxtamembrane region, cytosol, nucleus)*	Tuple centres
Signalling components *(i.e., membrane receptors, proteins, enzymes and genes)*	Chemical reactions sets
Signalling molecules *(i.e., first and secondary messengers)*, activation and deactivation signals	Reactants and concentrations recorded as tuples in the tuple centre

Case Study: Simulating Intracellular Signalling Pathways V



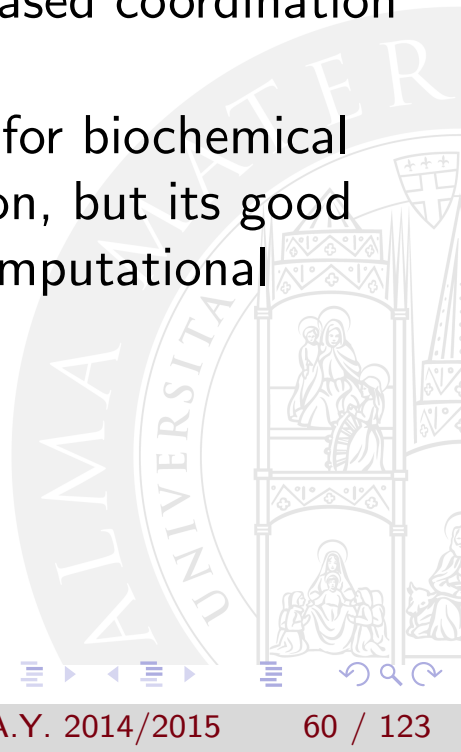
Some Final Remarks on Trans-disciplinary Research I

- The results of trans-disciplinary research efforts may appear quite obvious, once they are seen a posteriori
- Just above, a nature-inspired model developed in computational terms (biochemical tuple spaces) is exploited as a computational support to the simulation of a natural system (intracellular signalling pathways)
  - In other terms, from the natural world to the computational one, and back—and it works, as one might expect



Some Final Remarks on Trans-disciplinary Research II

- However, one should also understand that trans-disciplinary research succeeds when each translation of findings between the different fields involved actually enriches the associated concepts and techniques
  - Above, the BTS-SOC approach features the properties deriving from its biochemical inspiration along with those of tuple-based coordination for complex computation systems
  - When brought back to the 'natural domain' as a tool for biochemical simulation, BTS-SOC fits well for its natural inspiration, but its good performance in terms of expressive capabilities and computational efficiency *also* depends on its tuple-based structure



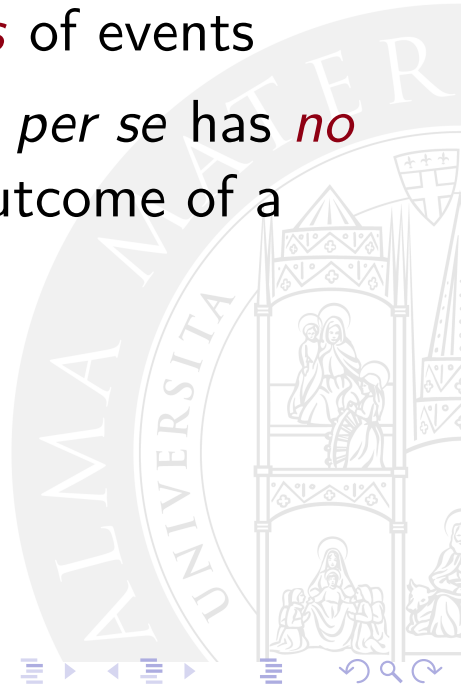
Some Final Remarks on Trans-disciplinary Research III

- So, while natural inspiration does not per se ensure the appropriateness of a computational approach to natural system simulation, it may in principle provide a sound grounding for the simulation of natural systems
  - Biochemical inspiration of the BTS-SOC model seems to couple well with the properties of tuple-based coordination
  - BTS-SOC turns out to be a suitable framework for the simulation of biochemical systems

Outline

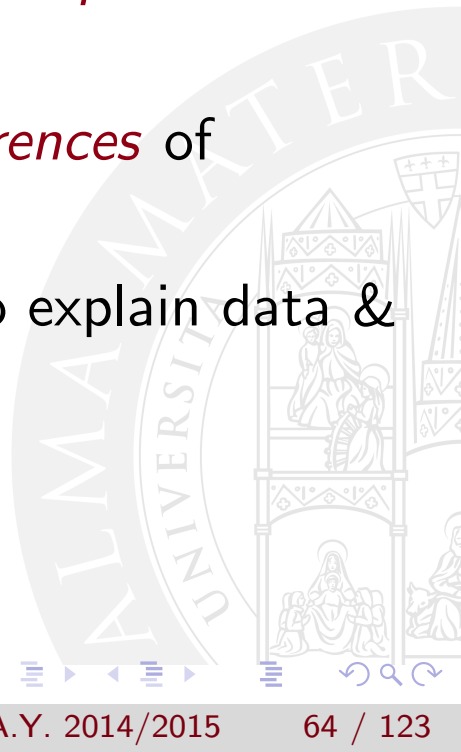
Probability

- *Probability* measures how likely some event will occur
- At its core, probability provides a mathematical framework to describe *casual* events
- . . . where casual essentially means non-deterministic
- By definition, probability deals with *single occurrences* of events
- From a scientific viewpoint, a probabilistic description *per se* has *no predictive value*: it cannot really predict the precise outcome of a phenomenon
- In any case, probability provides an *a priori* model for non-deterministic phenomena



Statistics & Probability

- *Statistics* describes / analyses / interprets phenomena starting from the data available about them
- Whenever a phenomenon has no *a priori* mathematical model (at least, not yet), statistics is concerned with getting one *a posteriori* from the available data
- Accordingly, statistics is concerned with *several occurrences* of (non-deterministic) events
- Probability typically provide the mathematical tools to explain data & build a model



Stochastic Systems

- *Stochastic systems* are non-deterministic systems
- A stochastic system is one whose states are determined probabilistically
- More generally, any phenomenon requiring probability for its description is (at least in part) stochastically by definition
- Roughly speaking, a probabilistic model for a stochastic system provides a *predictive framework* for a non-deterministic system

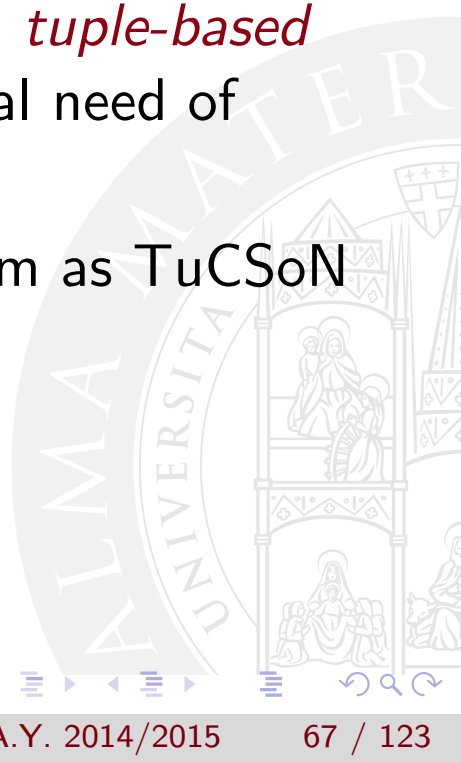
→ We cannot predict the single occurrence of a non-deterministic event, but we can predict the overall outcome of repeated occurrences of a non-deterministic event

Non-determinism, Coordination & Stochastic Behaviour

- Autonomous systems such as *adaptive* and *self-** ones are *stochastic systems* at their very heart
- Accordingly, a foremost feature of computational models for adaptive and self-* systems is *non-determinism*
- In order to obtain stochastic behaviours of computational systems, suitable mechanisms for non-determinism should be provided
- Since most of the complexity featured by adaptive and self-* systems depends on the interaction among components, coordination models should feature non-deterministic coordination mechanisms for stochastic behaviour

Issues

- Devising out some *basic mechanisms* for stochastic coordination
- Finding a *minimal* set of primitives for most (all) of the most relevant stochastic systems
- Showing how such mechanisms could be embedded as *tuple-based* co-ordination primitives, in order to address the general need of complex computational system engineering
- Defining their formal semantics and implementing them as TuCSoN primitives



Don't Care Non-determinism in Tuple-based Models

- LINDA features *don't know* non-determinism handled with a *don't care* approach:
  - **don't know** which tuple among the matching ones is retrieved by a getter operation (`in`, `rd`) can be neither specified nor predicted
  - **don't care** nonetheless, the coordinated system is designed so as to keep on working whichever is the matching tuple returned
- Instead, adaptive and self-organising systems require stochastic behaviours like *"most of the time do this"*, *"sometimes do that"*
- Possibly with some quantitative specification of *"most of the time"* and *"sometimes"*

→ As it is, non-determinism in tuple-based models does not fit the need of stochastic behaviour specification

LINDA "Local" Nature – In Time & Space

No context — In a single getter operation, only a *local*, point-wise property affects tuple retrieval: that is, the conformance of a tuple to the template, independently of the *spatial* context

- in fact, standard getter primitives return a matching tuple independently of the other tuples currently in the same space—so, they are *"context unaware"*

No history — Furthermore, in a sequence of getter operations, don't know non-determinism makes any prediction of the overall behaviour impossible. Again, then, only a point-wise property can be ensured even in *time*

- sequences of standard getter operations present no meaningful distribution over time

LINDA: How to Roll a Dice?

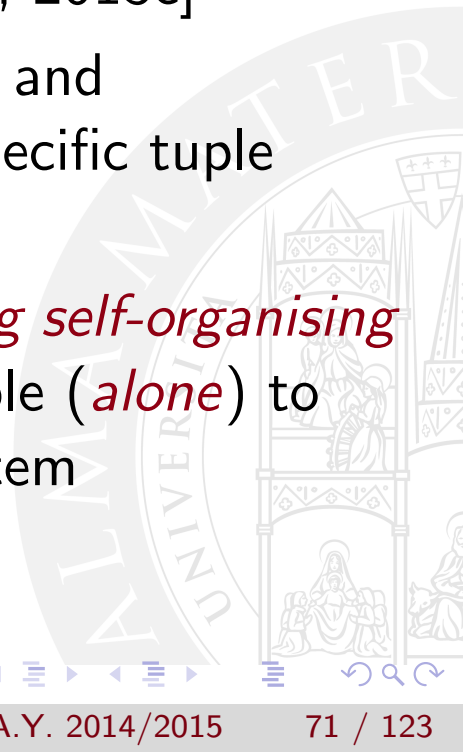
- We define tuple space `dice`
- We represent a six-face dice as a collection of six tuples: `face(1)`, `...`, `face(6)`
- We roll a dice by `rd`-ing a `face/1` tuple from `dice`:

```
dice ?  rd(face(X))
```

! We do *not* obtain the overall (stochastic) behaviour of a dice: for instance, it may reasonably happen that rolling the dice 10^9 times *always* results in `X / 1`—that is, we get "1" 10^9 times in a row.

uLinda: Probabilistic Non-determinism

- We define uniform coordination primitives (`uin`, `urd`) – first mentioned in [Gardelli et al., 2007] – as the *specialisation* of Linda getter primitives featuring probabilistic non-determinism instead of don't know non-determinism
- We call the new model uLinda [Mariani and Omicini, 2013c]
- Uniform primitives allow programmers to both specify and (statistically) predict the probability to retrieve one specific tuple among a bag of matching tuples
- Uniform primitives are the *"basic mechanisms enabling self-organising coordination"*—that is, a minimal set of constructs able (*alone*) to impact the observable properties of a coordinated system



uLinda: "Global" Nature

Situation & prediction

Uniform primitives replace don't know non-determinism with *probabilistic non-determinism* to

- situate a primitive invocation in space
  - uniform getter primitives return matching tuples based on the other tuples in the space—so, their behaviour is *context-aware*
- predict its behaviour in time
  - sequences of uniform getter operations tend to globally exhibit a *uniform distribution* over time

uLinda: How to Roll a Dice?

- Again, we define tuple space `dice`
- Again, we represent a six-face dice as a collection of six tuples: `face(1)`, ..., `face(6)`
- We roll a dice by `urd`-ing a `face/1` tuple from `dice`:

```
dice ? urd(face(X))
```

! Now, we *do* obtain the overall (stochastic) behaviour of a dice:

context — at every roll, the six faces of the dice `X / 1`, ..., `X / 6` have the same *probability* $P = 1/6$ to be selected

history — in the overall, repeating several times a roll, the six faces will tend to converge towards a uniform distribution

Informal Semantics

Operationally, uniform primitives behave as follows:

1. When executed, a uniform primitive takes a *snapshot* of the tuple space, "freezing" its state at a certain point in time—and space, being a single tuple space the target of basic LINDA primitives
2. The snapshot is then exploited to assign a probabilistic value $p_i \in [0, 1]$ to any tuple $t_{i \in \{1..n\}}$ in the space—where n is the total number of tuples in the space
3. There, non-matching tuples have value $p = 0$, matching tuples have value $p = 1/m$ (where $m \leq n$ is the number of matching tuples), and the overall sum of probability values is $\sum_{i=1..n} p_i = 1$
4. The choice of the matching tuple to be returned is then statistically based on the computed probabilistic values

Formal Semantics I

[!] In order to define the semantics of (getter) uniform primitives, we rely upon a simplified version of the process-algebraic framework in [Bravetti, 2008], in particular the $\uparrow$ operator, dropping multi-level priority probabilities.

uin semantics

$$[\textsc{Synch-C}]\quad \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \xrightarrow{T} \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \uparrow \{(t_1,v_1),..,(t_n,v_n)\}$$

$$[\textsc{Close-C}]\quad \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \uparrow \{(t_1,v_1),..,(t_n,v_n)\} \hookrightarrow \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \uparrow \{(t_1,p_1),..,(t_n,p_n)\}$$

$$[\textsc{Exec-C}]\quad \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \uparrow \{..,(t_j,p_j),..\} \xrightarrow{t_j}_{p_j} P[t_j/T] \mid \langle t_1,..,t_n\rangle \backslash t_j$$

Formal Semantics II

[!] As for standard LINDA getter primitives, the only difference between uniform reading (`urd`) and uniform consumption (`uin`) is the non-destructive semantics of the reading primitive—transition EXEC-R.

`urd` semantics

$$[\text{SYNCH-C}]\quad \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \xrightarrow{T} \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \uparrow \{(t_1,v_1),..,(t_n,v_n)\}$$

$$[\text{CLOSE-C}]\quad \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \uparrow \{(t_1,v_1),..,(t_n,v_n)\} \hookrightarrow \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \uparrow \{(t_1,p_1),..,(t_n,p_n)\}$$

$$[\text{EXEC-R}]\quad \mathtt{uin}_T.P \mid \langle t_1,..,t_n\rangle \uparrow \{..,(t_j,p_j),..\} \xrightarrow{t_j}_{p_j} P[t_j/T] \mid \langle t_1,..,t_n\rangle$$

Expressiveness: uLinda vs Linda

In [Bravetti et al., 2005], authors demonstrate that Linda-based languages *cannot* implement probabilistic models.

PME proof

The gain in expressiveness brought by uLinda is formally proven in [Mariani and Omicini, 2013a], where uniform primitives are shown to be strictly more expressive than standard Linda primitives according to probabilistic modular embedding (PME) [Mariani and Omicini, 2013b].

In particular

$$\text{uLinda} \succeq_p \text{Linda} \quad \wedge \quad \text{Linda} \not\succeq_p \text{uLinda} \implies \text{uLinda} \not\equiv_o \text{Linda}$$

where

- $\succeq_p$ stands for "probabilistically embeds"
- $\equiv_o$ means "(PME) observational equivalence"

Outline

Expressing Full Dynamics

Expressing the *full dynamics* of complex natural systems

- mostly, coordination models just capture *some* of the overall system dynamics
- which makes them basically *fail*
  - for instance, Gamma mimics chemical reactions, but does not capture essential issues in chemical processes such as reaction rates and concentration [Banâtre and Le Métayer, 1990, Banătre et al., 2001]
  - instead, *(bio)chemical tuple spaces* fully exploit the chemical metaphor by providing time-dependent and stochastic chemical laws [Viroli et al., 2010, Viroli and Casadei, 2009]
- more generally, the goal is to allow coordinated MAS to capture and express the full dynamics of complex natural systems

Outline

Core Mechanisms

Understanding the basic elements of expressiveness

- LINDA is a glaring example of a minimal set of coordination mechanisms providing a wide range of coordination behaviours
- the goal is understanding the minimal set of coordination primitives required to design complex stochastic behaviours
- for instance, *uniform coordination primitives* – that is, LINDA-like coordination primitives returning tuples matching a template with a uniform distribution [Gardelli et al., 2007] – seemingly capture the full-fledged dynamics of real chemical systems within the coordination abstractions

Outline

Blending Metaphors

Mixing abstractions & mechanisms from different conceptual sources

- most natural systems, when observed in their whole complexity, exhibit *layers* each one featuring its own metaphors and mechanisms
- correspondingly, many novel approaches to complex MAS coordination integrate diverse sources of inspiration, e.g.:
  - TOTA [Mamei and Zambonelli, 2004b] exploits mechanisms from both stigmergic and field-based coordination
  - the SAPERE coordination model for pervasive service ecosystems [Zambonelli et al., 2011, Viroli et al., 2012] integrates
    - the *chemical* metaphor for driving the evolution of coordination abstractions
    - *biochemical* abstractions for topology and diffusion
    - the notion of *ecosystem* in order to model the overall system structure and dynamics

Outline

Predicting Complex Behaviours

Engineering unpredictable systems around predictable abstractions

- coordination models are meant to harness the complexity of complex MAS [Ciancarini et al., 2000]
- coordination abstractions are often *at the core* of complex MAS
- while this does not make complex MAS generally predictable, it makes it possible in principle to make them *partially predictable*, based on the predictably of the core coordinative behaviour
- suitably-formalised coordination abstractions, along with a suitably-defined engineering methodology, could in principle ensure the predictability of given MAS properties within generally-unpredictable MAS

Outline

Knowledge-oriented Coordination I

Integrating nature-inspired with knowledge-oriented coordination

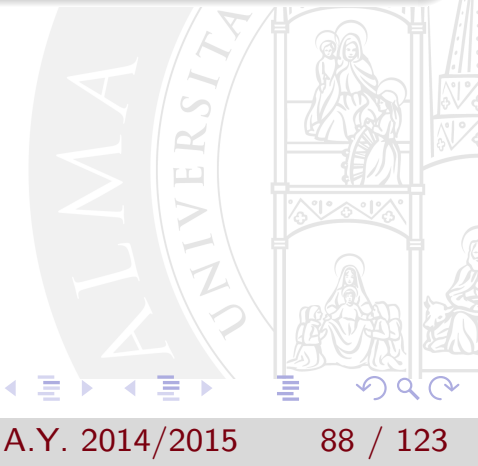
- intelligent MAS in knowledge intensive environments – as well as complex socio-technical systems, in general – require automatic understanding of data and information
- knowledge-oriented coordination exploits coordination abstractions enriched so as to allow for semantic interpretation by intelligent agents [Fensel, 2004, Nardini et al., 2013]
- for instance
  - chemical tuple spaces
  - SAPERE coordination abstractions and mechanisms
  - *semantic tuple centres* [Nardini et al., 2011]

  all relay on the semantic interpretation of coordination items

Knowledge-oriented Coordination II

Self-organisation of knowledge

- explicit search of information is going to become ineffective while the amount of available knowledge grows at incredible rates
- knowledge should autonomously organise and flow from producers to consumers
- knowledge self-organisation for knowledge-intensive MAS



Knowledge-oriented Coordination III

MoK (Molecules of Knowledge) [Mariani and Omicini, 2012a]

- Molecules of Knowledge is a a nature-inspired coordination model promoting knowledge self-organisation, where
  - sources of knowledge continuously produce and inject *atoms of knowledge* in biochemical compartments
  - knowledge atoms may then aggregate in *molecules* and diffuse
  - knowledge producers, managers and consumers are modelled as *catalysts*, whose workspaces are biochemical compartments, and their knowledge-oriented actions become enzymes influencing atoms aggregation and molecules diffusion
  - so as to make relevant knowledge spontaneously aggregate and autonomously move towards potentially interested knowledge workers
- the first application scenario for experimenting with MoK is *news management* [Mariani and Omicini, 2012b]

Conclusion I

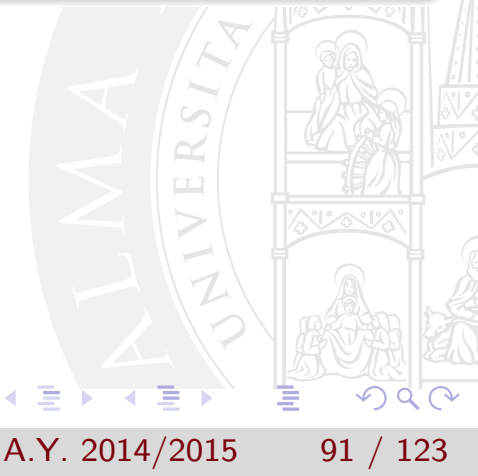
History and evolution

- starting from early chemical and stigmergic approaches, nature-inspired models of coordination evolved to become the potential *core* of *complex MAS*—such as pervasive, knowledge-intensive, and self-* MAS
- in this talk we shorty surveyed their history, devise their main issues, and point out the most promising trends
- focussing in particular on tuple-based coordination models, and adopted a *systemic view* over MAS

Conclusion II

In the overall...

- nature-inspired models of coordination already have a long history behind them
- and apparently a huge *potential* for development still to be explored
- to provide core abstractions and technologies for the engineering of complex MAS



Bibliography I


Banâtre, J.-P., Fradet, P., and Le Métayer, D. (2001).
Gamma and the chemical reaction model: Fifteen years after.
In Calude, C. S., Păun, G., Rozenberg, G., and Salomaa, A., editors, *Multiset Processing. Mathematical, Computer Science, and Molecular Computing Points of View*, volume 2235 of *LNCS*, pages 17–44. Springer.


Banâtre, J.-P. and Le Métayer, D. (1990).
The GAMMA model and its discipline of programming.
Science of Computer Programming, 15(1):55–77.


Berry, G. (1992).
The chemical abstract machine.
Theoretical Computer Science, 96(1):217–248.

Bibliography II


Boltzmann, L. (1964).
Lectures on Gas Theory.
University of California Press.


Bouchaud, J.-P. and Potters, M. (2003).
Theory of Financial Risk and Derivative Pricing: From Statistical Physics to Risk Management.
Cambridge University Press, Cambridge, UK, 2nd edition.


Bravetti, M. (2008).
Expressing priorities and external probabilities in process algebra via mixed open/closed systems.
Electronic Notes in Theoretical Computer Science, 194(2):31–57.

Bibliography III


Bravetti, M., Gorrieri, R., Lucchi, R., and Zavattaro, G. (2005).
Quantitative information in the tuple space coordination model.
Theoretical Computer Science, 346(1):28–57.


Busi, N., Gorrieri, R., and Zavattaro, G. (1998).
A process algebraic view of Linda coordination primitives.
Theoretical Computer Science, 192(2):167–199.


Ciancarini, P. (1996).
Coordination models and languages as software integrators.
ACM Computing Surveys, 28(2):300–302.


Ciancarini, P., Omicini, A., and Zambonelli, F. (1999).
Coordination technologies for Internet agents.
Nordic Journal of Computing, 6(3):215–240.

Bibliography IV


Ciancarini, P., Omicini, A., and Zambonelli, F. (2000).
Multiagent system engineering: The coordination viewpoint.
In Jennings, N. R. and Lespérance, Y., editors, *Intelligent Agents VI. Agent Theories, Architectures, and Languages*, volume 1757 of *LNAI*, pages 250–259. Springer.
6th International Workshop (ATAL'99), Orlando, FL, USA, 15–17 July 1999. Proceedings.


De Nicola, R., Ferrari, G., and Pugliese, R. (1998).
KLAIM: A kernel language for agent interaction and mobility.
IEEE Transaction on Software Engineering, 24(5):315–330.

Bibliography V


De Nicola, R., Latella, D., Katoen, J.-P., and Massink, M. (2006).
StoKlaim: A stochastic extension of Klaim.
Technical Report 2006-TR-01, Istituto di Scienza e Tecnologie dell'Informazione "Alessandro Faedo" (ISTI).


Denti, E., Natali, A., and Omicini, A. (1998).
On the expressive power of a language for programming coordination media.
In *1998 ACM Symposium on Applied Computing (SAC'98)*, pages 169–177, Atlanta, GA, USA. ACM.
Special Track on Coordination Models, Languages and Applications.


Downward, J. (2003).
Targeting RAS signalling pathways in cancer therapy.
Nature Reviews Cancer, 3(1):11–22.

Bibliography VI


FaceBook (2014).
Home page.
http://www.facebook.com.


Fensel, D. (2004).
Triple-space computing: Semantic web services based on persistent publication of information.
In Aagesen, F. A., Anutariya, C., and Wuwongse, V., editors, *Intelligence in Communication Systems*, volume 3283 of *LNCS*, pages 43–53.
IFIP International Conference (INTELLCOMM 2004), Bangkok, Thailand, 23–26 November 2004. Proceedings.

Bibliography VII


Gardelli, L., Viroli, M., Casadei, M., and Omicini, A. (2007).
Designing self-organising MAS environments: The collective sort case.
In Weyns, D., Parunak, H. V. D., and Michel, F., editors, *Environments for MultiAgent Systems III*, volume 4389 of *LNAI*, pages 254–271. Springer.
3rd International Workshop (E4MAS 2006), Hakodate, Japan, 8 May 2006. Selected Revised and Invited Papers.


Gelernter, D. (1985).
Generative communication in Linda.
ACM Transactions on Programming Languages and Systems, 7(1):80–112.

Bibliography VIII


Gelernter, D. and Carriero, N. (1992).
Coordination languages and their significance.
Communications of the ACM, 35(2):97–107.


González Pérez, P. P., Omicini, A., and Sbaraglia, M. (2013).
A biochemically-inspired coordination-based model for simulating intracellular signalling pathways.
Journal of Simulation, 7(3):216–226.
Special Issue: Agent-based Modeling and Simulation.


Grassé, P.-P. (1959).
La reconstruction du nid et les coordinations interindividuelles chez Bellicositermes natalensis et Cubitermes sp. la théorie de la stigmergie: Essai d'interprétation du comportement des termites constructeurs.
Insectes Sociaux, 6(1):41–80.

Bibliography IX


Kauffman, S. A. (1993).
The Origins of Order: Self-organization and Selection in Evolution.
Oxford University Press.


Kauffman, S. A. (2003).
Investigations.
Oxford University Press.


LiquidFeedback (2014).
Home page.
`http://liquidfeedback.org`.


Liu, J. and Tsui, K. C. (2006).
Toward nature-inspired computing.
Communications of the ACM, 49(10):59–64.

Bibliography X


Mamei, M. and Zambonelli, F. (2004a).
Programming pervasive and mobile computing applications with the TOTA middleware.
In *Pervasive Computing and Communications*, pages 263–273. 2nd IEEE Annual Conference (PerCom 2004), Orlando, FL, USA, 14–17 March 2004. Proceedings.


Mamei, M. and Zambonelli, F. (2004b).
Programming pervasive and mobile computing applications with the TOTA middleware.
In *Pervasive Computing and Communications*, pages 263–273. 2nd IEEE Annual Conference (PerCom 2004), Orlando, FL, USA, 14–17 March 2004. Proceedings.

Bibliography XI


Mamei, M. and Zambonelli, F. (2006).
Field-Based Coordination for Pervasive Multiagent Systems. Models, Technologies, and Applications.
Springer Series in Agent Technology. Springer.


Mantegna, R. N. and Stanley, H. E. (1999).
Introduction to Econophysics: Correlations and Complexity in Finance.

Cambridge University Press, Cambridge, UK.

Bibliography XII


Mariani, S. and Omicini, A. (2012a).
Molecules of Knowledge: Self-organisation in knowledge-intensive environments.
In Fortino, G., Bădică, C., Malgeri, M., and Unland, R., editors, *Intelligent Distributed Computing VI*, volume 446 of *Studies in Computational Intelligence*, pages 17–22. Springer.
6th International Symposium on Intelligent Distributed Computing (IDC 2012), Calabria, Italy, 24-26 September 2012. Proceedings.

Bibliography XIII


Mariani, S. and Omicini, A. (2012b).
Self-organising news management: The *Molecules of Knowledge* approach.
In Fernandez-Marquez, J. L., Montagna, S., Omicini, A., and Zambonelli, F., editors, *1st International Workshop on Adaptive Service Ecosystems: Natural and Socially Inspired Solutions (ASENSIS 2012)*, pages 11–16, SASO 2012, Lyon, France.
Pre-proceedings.


Mariani, S. and Omicini, A. (2013a).
Probabilistic embedding: Experiments with tuple-based probabilistic languages.
In *28th ACM Symposium on Applied Computing (SAC 2013)*, pages 1380–1382, Coimbra, Portugal.
Poster Paper.

Bibliography XIV


Mariani, S. and Omicini, A. (2013b).
Probabilistic modular embedding for stochastic coordinated systems.
In Julien, C. and De Nicola, R., editors, *Coordination Models and Languages*, volume 7890 of *LNCS*, pages 151–165. Springer.
15th International Conference (COORDINATION 2013), Florence, Italy, 3–6 June 2013. Proceedings.


Mariani, S. and Omicini, A. (2013c).
Tuple-based coordination of stochastic systems with uniform primitives.
In Baldoni, M., Baroglio, C., Bergenti, F., and Garro, A., editors, *From Objects to Agents*, volume 1099 of *CEUR Workshop Proceedings*, pages 8–15, Turin, Italy. Sun SITE Central Europe, RWTH Aachen University.
XIV Workshop (WOA 2013). Workshop Notes.

Bibliography XV


Mézard, M. and Montanari, A. (2009).
Information, Physics, and Computation.
Oxford University Press, Oxford, UK.


Nardini, E., Omicini, A., and Viroli, M. (2013).
Semantic tuple centres.
Science of Computer Programming, 78(5):569–582.
Special section: Self-Organizing Coordination.


Nardini, E., Omicini, A., Viroli, M., and Schumacher, M. I. (2011).
Coordinating e-health systems with TuCSoN semantic tuple centres.
Applied Computing Review, 11(2):43–52.


Neves, S. R., Ram, P. T., and Iyengar, R. (2002).
G protein pathways.
Science, 296(5573):1636–1639.

Bibliography XVI


Nishimori, H. (2001).
Statistical Physics of Spin Glasses and Information Processing: An Introduction, volume 111 of *International Series of Monographs on Physics*.
Clarendon Press, Oxford, UK.


Omicini, A. (2012).
Agents writing on walls: Cognitive stigmergy and beyond.
In Paglieri, F., Tummolini, L., Falcone, R., and Miceli, M., editors, *The Goals of Cognition. Essays in Honor of Cristiano Castelfranchi*, volume 20 of *Tributes*, chapter 29, pages 543–556. College Publications, London.

Bibliography XVII


Omicini, A. (2013a).
Agents writing on walls: Cognitive stigmergy and beyond.
In Paglieri, F., Tummolini, L., Falcone, R., and Miceli, M., editors, *The Goals of Cognition. Essays in Honor of Cristiano Castelfranchi*, chapter 29, pages 543–556. College Publications, London.


Omicini, A. (2013b).
Nature-inspired coordination for complex distributed systems.
In Fortino, G., Bădică, C., Malgeri, M., and Unland, R., editors, *Intelligent Distributed Computing VI*, volume 446 of *Studies in Computational Intelligence*, pages 1–6. Springer.
6th International Symposium on Intelligent Distributed Computing (IDC 2012), Calabria, Italy, 24-26 September 2012. Proceedings.
Invited paper.

Bibliography XVIII


Omicini, A. and Denti, E. (2001).
From tuple spaces to tuple centres.
Science of Computer Programming, 41(3):277–294.


Omicini, A., Ricci, A., and Viroli, M. (2005).
Time-aware coordination in ReSpecT.
In Jacquet, J.-M. and Picco, G. P., editors, *Coordination Models and Languages*, volume 3454 of *LNCS*, pages 268–282. Springer-Verlag. 7th International Conference (COORDINATION 2005), Namur, Belgium, 20–23 April 2005. Proceedings.

Bibliography XIX


Omicini, A., Ricci, A., and Viroli, M. (2006).
The multidisciplinary patterns of interaction from sciences to Computer Science.
In Goldin, D. Q., Smolka, S. A., and Wegner, P., editors, *Interactive Computation: The New Paradigm*, pages 395–414. Springer.


Omicini, A., Ricci, A., and Viroli, M. (2007).
Timed environment for Web agents.
Web Intelligence and Agent Systems, 5(2):161–175.

Bibliography XX


Omicini, A., Ricci, A., Viroli, M., Castelfranchi, C., and Tummolini, L. (2004).
Coordination artifacts: Environment-based coordination for intelligent agents.
In Jennings, N. R., Sierra, C., Sonenberg, L., and Tambe, M., editors, *3rd international Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2004)*, volume 1, pages 286–293, New York, USA. ACM.


Omicini, A. and Viroli, M. (2011).
Coordination models and languages: From parallel computing to self-organisation.
The Knowledge Engineering Review, 26(1):53–59.
Special Issue 01 (25th Anniversary Issue).

Bibliography XXI


Omicini, A. and Zambonelli, F. (2004).
MAS as complex systems: A view on the role of declarative approaches.
In Leite, J. A., Omicini, A., Sterling, L., and Torroni, P., editors, *Declarative Agent Languages and Technologies*, volume 2990 of *LNAI*, pages 1–17. Springer.
1st International Workshop (DALT 2003), Melbourne, Australia, 15 July 2003. Revised Selected and Invited Papers.


Parunak, H. V. D. (2006).
A survey of environments and mechanisms for human-human stigmergy.
In Weyns, D., Parunak, H. V. D., and Michel, F., editors, *Environments for Multi-Agent Systems II*, volume 3830 of *LNCS*, pages 163–186. Springer.

Bibliography XXII


Parunak, H. V. D., Brueckner, S., and Sauter, J. (2002).
Digital pheromone mechanisms for coordination of unmanned vehicles.

In Castelfranchi, C. and Johnson, W. L., editors, *1st International Joint Conference on Autonomous Agents and Multiagent systems*, volume 1, pages 449–450, New York, NY, USA. ACM.


Ricci, A., Omicini, A., Viroli, M., Gardelli, L., and Oliva, E. (2007).
Cognitive stigmergy: Towards a framework based on agents and artifacts.
In Weyns, D., Parunak, H. V. D., and Michel, F., editors, *Environments for MultiAgent Systems III*, volume 4389 of *LNCS*, pages 124–140. Springer.
3rd International Workshop (E4MAS 2006), Hakodate, Japan, 8 May 2006. Selected Revised and Invited Papers.

Bibliography XXIII


Ricci, A., Viroli, M., and Omicini, A. (2005).
Environment-based coordination through coordination artifacts.
In Weyns, D., Parunak, H. V. D., and Michel, F., editors, *Environments for Multi-Agent Systems*, volume 3374 of *LNAI*, pages 190–214. Springer.
1st International Workshop (E4MAS 2004), New York, NY, USA, 19 July 2004. Revised Selected Papers.


Rossi, D., Cabri, G., and Denti, E. (2001).
Tuple-based technologies for coordination.
In Omicini, A., Zambonelli, F., Klusch, M., and Tolksdorf, R., editors, *Coordination of Internet Agents: Models, Technologies, and Applications*, chapter 4, pages 83–109. Springer.

Bibliography XXIV

Simon, H. A. (1962).
The architecture of complexity.
Proceedings of the American Philosophical Society, 106(6):467–482.

Stanley, H. E. (2008).
Econophysics and the current economic turmoil.
American Physical Society News, 17(11):8.
The Back Page.

Tolksdorf, R. and Menezes, R. (2004).
Using Swarm Intelligence in Linda Systems.
In Omicini, A., Petta, P., and Pitt, J., editors, *Engineering Societies in the Agents World IV*, volume 3071 of *LNCS*, pages 49–65. Springer.
4th International Workshops (ESAW 2003), London, UK, 29-31 October 2003. Revised Selected and Invited Papers.

Bibliography XXV


Verhagen, H., Noriega, P., Balke, T., and de Vos, M., editors (2013). *Social Coordination: Principles, Artefacts and Theories (SOCIAL.PATH)*, AISB Convention 2013, University of Exeter, UK. The Society for the Study of Artificial Intelligence and the Simulation of Behaviour.


Viroli, M. and Casadei, M. (2009).
Biochemical tuple spaces for self-organising coordination.
In Field, J. and Vasconcelos, V. T., editors, *Coordination Languages and Models*, volume 5521 of *LNCS*, pages 143–162. Springer, Lisbon, Portugal.
11th International Conference (COORDINATION 2009), Lisbon, Portugal, June 2009. Proceedings.

Bibliography XXVI


Viroli, M., Casadei, M., Nardini, E., and Omicini, A. (2010).
Towards a chemical-inspired infrastructure for self-* pervasive applications.
In Weyns, D., Malek, S., de Lemos, R., and Andersson, J., editors, *Self-Organizing Architectures*, volume 6090 of *LNCS*, chapter 8, pages 152–176. Springer.
1st International Workshop on Self-Organizing Architectures (SOAR 2009), Cambridge, UK, 14-17 September 2009, Revised Selected and Invited Papers.

Bibliography XXVII


Viroli, M., Casadei, M., and Omicini, A. (2009).
A framework for modelling and implementing self-organising coordination.
In Shin, S. Y., Ossowski, S., Menezes, R., and Viroli, M., editors, *24th Annual ACM Symposium on Applied Computing (SAC 2009)*, volume III, pages 1353–1360, Honolulu, Hawai'i, USA. ACM.


Viroli, M. and Omicini, A. (2006).
Coordination as a service.
Fundamenta Informaticae, 73(4):507–534.
Special Issue: Best papers of FOCLASA 2002.

Bibliography XXVIII


Viroli, M., Pianini, D., Montagna, S., and Stevenson, G. (2012).
Pervasive ecosystems: a coordination model based on semantic chemistry.
In Ossowski, S., Lecca, P., Hung, C.-C., and Hong, J., editors, *27th Annual ACM Symposium on Applied Computing (SAC 2012)*, Riva del Garda, TN, Italy. ACM.


Wegner, P. (1997).
Why interaction is more powerful than algorithms.
Communications of the ACM, 40(5):80–91.


Weyns, D., Omicini, A., and Odell, J. J. (2007).
Environment as a first-class abstraction in multi-agent systems.
Autonomous Agents and Multi-Agent Systems, 14(1):5–30.
Special Issue on Environments for Multi-agent Systems.

Bibliography XXIX


Zambonelli, F., Castelli, G., Ferrari, L., Mamei, M., Rosi, A., Di Marzo, G., Risoldi, M., Tchao, A.-E., Dobson, S., Stevenson, G., Ye, Y., Nardini, E., Omicini, A., Montagna, S., Viroli, M., Ferscha, A., Maschek, S., and Wally, B. (2011).
Self-aware pervasive service ecosystems.
Procedia Computer Science, 7:197–199.
Proceedings of the 2nd European Future Technologies Conference and Exhibition 2011 (FET 11).


Zambonelli, F. and Omicini, A. (2004).
Challenges and research directions in agent-oriented software engineering.
Autonomous Agents and Multi-Agent Systems, 9(3):253–283.
Special Issue: Challenges for Agent-Based Computing.

Bibliography XXX


Zavattaro, G. (1998).
On the incomparability of Gamma and Linda.
Technical Report SEN-R9827, CWI, Amsterdam, The Netherlands.

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