

Nature-Inspired Coordination & Self-Organisation

Autonomous Systems
Sistemi Autonomi

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- 1 Nature-inspired Coordination
- 2 Examples
- 3 Tuples
- 4 Trends



Next in Line...

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Nature-inspired Models for SOS

Complex natural systems

- such as physical, chemical, biochemical, biological, social systems
- natural system exhibit *features*
 - such as distribution, openness, 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

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- 2 Examples**
- 3 Tuples
- 4 Trends



Focus on...

- 1 Nature-inspired Coordination
- 2 Examples
 - **Early**
 - Modern
 - Issues
- 3 Tuples
- 4 Trends
 - Coordination for Complex Systems
 - Coordination for Simulation
 - Coordination & Stochastic Systems
 - Full Dynamics
 - Core Mechanisms
 - Blending Metaphors
 - Predicting Complex Behaviours
 - Knowledge-oriented Coordination



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]

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- 2 Examples
 - Early
 - **Modern**
 - Issues
- 3 Tuples
- 4 Trends
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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

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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?*

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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, 2012]
- 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, 2004]
 - 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]



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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
- 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, 2013]

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 (STS)** [Whitworth, 2006]
- in STS
 - 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, 2017] and LiquidFeedback [LiquidFeedback, 2017]

Physical & Computational Social Systems I

A twofold view of socio-technical systems

- the nature of STS 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 STS, macroscopic properties could be
 - described by exploiting the conceptual tools from physics
 - enforced by the coordination abstractions
- STS 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



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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

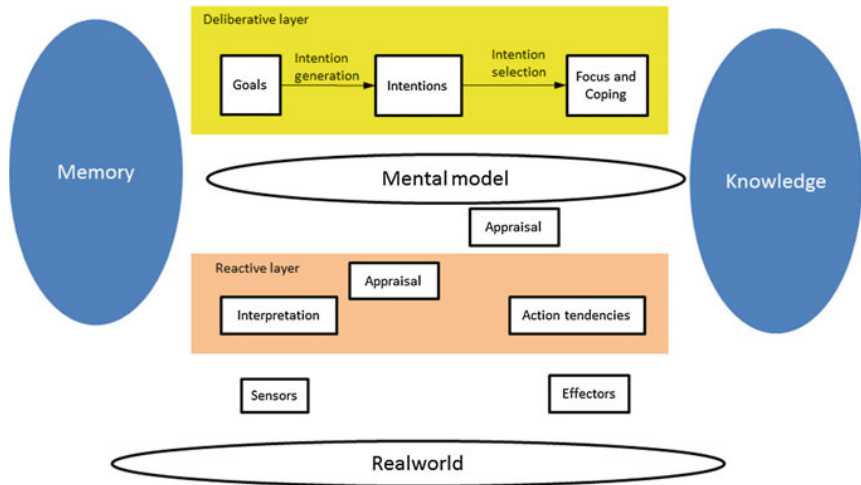
Case Study: Simulating Intracellular Signalling Pathways

IV

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

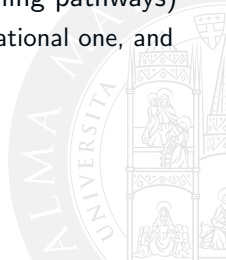
Cellular components and structures involved in intracellular signalling	Computational abstractions of the BTS-SOC model
Extracellular milieu and intracellular compartments (<i>i.e.</i> , <i>membrane</i> , <i>juxtamembrane region</i> , <i>cytosol</i> , <i>nucleus</i>)	Tuple centres
Signalling components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

Case Study: Simulating Intracellular Signalling Pathways V



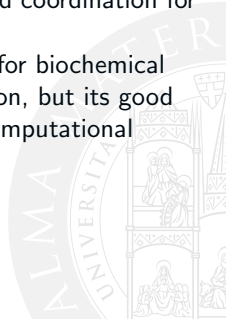
Some Final Remarks on Trans-disciplinary Research I

- 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



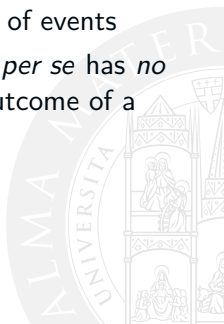
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 - Modern
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- 3 Tuples
- 4 Trends
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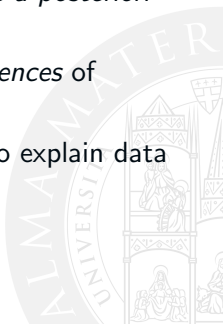
Probability

- **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



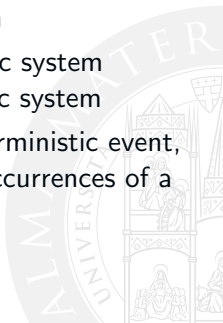
Statistics & Probability

- **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 provides the mathematical tools to explain data & build a model



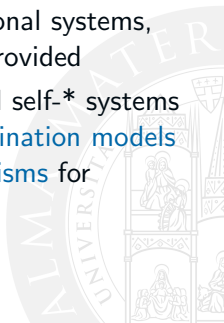
Stochastic Systems

- **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) stochastic 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



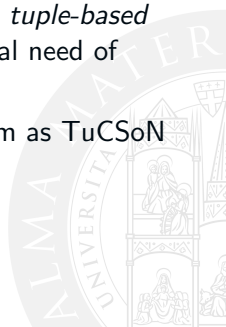
Non-determinism, Coordination & Stochastic Behaviour

- 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

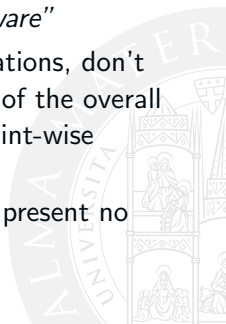


Don't Care Non-determinism in Tuple-based Models

- 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

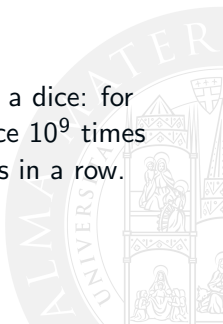


LINDA: How to Roll a Dice?

- 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 $X / 1, \dots, X / 6$ 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

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

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

$$\hookrightarrow$$

$$\text{uin}_T.P \mid \langle t_1, \dots, t_n \rangle \uparrow \{(t_1, p_1), \dots, (t_n, p_n)\}$$

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

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

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

$$[\text{CLOSE-C}] \text{ urd}_T.P \mid \langle t_1, \dots, t_n \rangle \uparrow \{(t_1, v_1), \dots, (t_n, v_n)\}$$

$$\quad \quad \quad \hookrightarrow$$

$$\text{ urd} \mid \langle t_1, \dots, t_n \rangle \uparrow \{(t_1, p_1), \dots, (t_n, p_n)\}$$

$$[\text{EXEC-R}] \text{ urd} \mid \langle t_1, \dots, t_n \rangle \uparrow \{\dots, (t_j, p_j), \dots\} \xrightarrow{t_j}_{p_j} P[t_j/T] \mid \langle t_1, \dots, t_n \rangle$$

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

$$\begin{aligned} \text{uLINDA} \succeq_p \text{LINDA} \quad \wedge \quad \text{LINDA} \not\preceq_p \text{uLINDA} \\ \implies \text{uLINDA} \not\equiv_o \text{LINDA} \end{aligned}$$

where

- \succeq_p stands for “probabilistically embeds”
- \equiv_o means “(PME) observational equivalence”

Focus on...

- 1 Nature-inspired Coordination
- 2 Examples
 - Early
 - Modern
 - Issues
- 3 Tuples
- 4 Trends
 - Coordination for Complex Systems
 - Coordination for Simulation
 - Coordination & Stochastic Systems
 - **Full Dynamics**
 - Core Mechanisms
 - Blending Metaphors
 - Predicting Complex Behaviours
 - Knowledge-oriented Coordination



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, Banâtre 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

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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

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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, 2004] 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

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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 predictability 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

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 - **Knowledge-oriented Coordination**



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 shortly 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



- 1 Nature-inspired Coordination
- 2 Examples
- 3 Tuples
- 4 Trends



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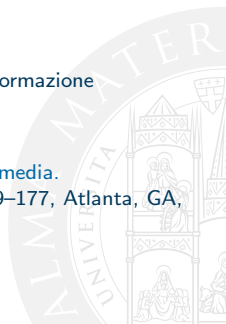
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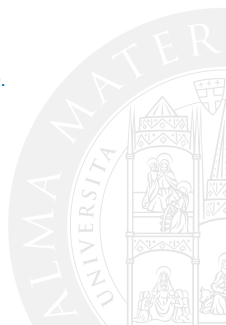
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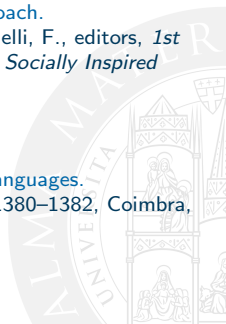


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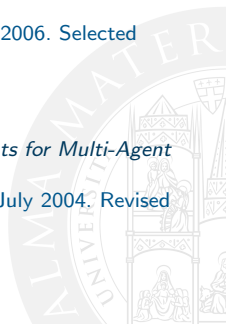
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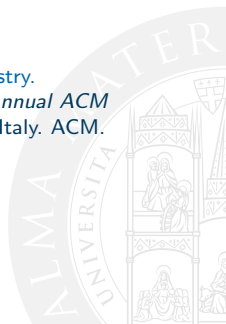
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