Nature-inspired Coordination for Complex Distributed Systems

Multiagent Systems LM

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Outline

Why Nature-inspired Models?

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, and on self-organisation of systems

Why Coordination Models?

Interaction

- most of the complexity of complex computational systems 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]

Why Nature-inspired Coordination?

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 computational systems

Outline

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 computational systems

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 components, 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 [Banătre et al., 2001]

Field-based Coordination

Computational fields as coordination laws

- field-based coordination models like TOTA [Mamei and Zambonelli, 2004] are inspired by the way masses and particles move and self-organise according to gravitational/electromagnetic fields [Mamei and Zambonelli, 2006]
- there, computational force fields, generated either by the active components or by the pervasive coordination infrastructure, propagate across the environment, and drive the actions and motion of the component 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

Basic Issues of Nature-inspired Coordination I

Environment

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

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

Outline

The Ancestor

LINDA [Gelernter, 1985]

- LINDA is the ancestor of all tuple-based coordination models [Rossi et al., 2001]
- in LINDA, coordinables 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

So, *why* LINDA?

Why tuple-based models???

Why Tuple-based Models? I

Expressiveness

- LINDA is a sort of *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, tuple spaces are provided as coordination services by the *coordination infrastructure* [Viroli and Omicini, 2006]
- they can be interpreted as coordination artefacts shaping computational *environment* [Omicini et al., 2004]
- 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 the coordination of distributed processes [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 distributed systems with a complexity comparable to natural systems [Omicini and Viroli, 2011]

Outline

Expressing Full Dynamics

Expressing the *full dynamics* of natural systems

- 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 systems to express the full dynamics of complex natural systems

Blending Patterns and Metaphors

Mixing abstractions & mechanisms from different conceptual sources

- for instance, the SAPERE coordination model for pervasive service ecosystems [Zambonelli et al., 2011, Viroli et al., 2012] exploits
  - 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
- this mostly resembles natural systems, when they are observed in their whole complexity, crossing their many layers

Semantic Coordination

Integrating nature-inspired with knowledge-oriented coordination

- intelligent distributed systems in knowledge intensive environments, as well as complex socio-technical systems, require automatic understanding of data and information
- knowledge-oriented coordination [Nardini et al., 2013] exploits coordination abstractions capable of semantic interpretation
- for instance
  - both chemical tuple spaces and SAPERE abstractions relay on the semantic interpretation of coordination items—in the same way as *semantic tuple centres* [Nardini et al., 2011]
  - MoK (Molecules of Knowledge) is a a nature-inspired coordination model focussing on knowledge management [Mariani and Omicini, 2012], exploiting the full power of the biochemical metaphor to achieve knowledge self-organisation within knowledge-intensive environments

Understanding 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

Predicting Complex Behaviours

Engineering unpredictable systems around predictable abstractions

- coordination models and technologies are typically in charge of harnessing the complexity of articulated computational systems [Ciancarini et al., 2000]
- coordination abstractions are often at the core of complex systems
- while this does not make complex system 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 system properties within generally-unpredictable coordinated systems—such as nature-inspired systems

Coordination for Simulation

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*

Interaction issues are prominent in complex systems

- coordination technologies potential core of 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 simulation frameworks for complex systems
- e.g., [González Pérez et al., 2013]

Conclusion I

History and evolution

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

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 computational systems

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