

Nature-inspired Coordination for Complex Multi-Agent Systems

Andrea Omicini
andrea.omicini@unibo.it

Dipartimento di Informatica – Scienza e Ingegneria (DISI)
ALMA MATER STUDIORUM—Università di Bologna

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1 Why?

2 Examples

- Early
- Modern
- Issues

3 Tuples

4 Trends



Disclaimer

Talking about Multi-Agent Systems (MAS)

- For many, MAS is about “Agents”
- For many others, it is more about “Multi” (-Agents)
- Today, we focus mostly on the “Systems” part



Outline

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Why Nature-inspired Models?

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

Why Multi-Agent Systems?

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

Why 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]



Why 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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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]

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



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

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, 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, 2013]
- 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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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



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



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 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



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
- e.g., [González Pérez et al., 2013]



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



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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.



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.



Bibliography II



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.



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).



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 III



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.



González Pérez, P. P., Omicini, A., and Sbaraglia, M. (2013).
A biochemically-inspired coordination-based model for simulating intracellular signalling pathways.
Journal of Simulation.
Special Issue on 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 IV



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



Mamei, M. and Zambonelli, F. (2004).
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. (2006).
Field-Based Coordination for Pervasive Multiagent Systems. Models, Technologies, and Applications.
Springer Series in Agent Technology. Springer.



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 V



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.



Nardini, E., Omicini, A., and Viroli, M. (2013).

Semantic tuple centres.

Science of Computer Programming.

Special Issue on Self-Organizing Coordination. To appear.



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.



Omicini, A. (2013).

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.



Bibliography VI



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.



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 VII



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.



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 VIII



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.



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.



Bibliography IX



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.



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.



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 X



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.



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.



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.



Bibliography XI



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.



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.



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Nature-inspired Coordination for Complex Multi-Agent Systems

Andrea Omicini
andrea.omicini@unibo.it

Dipartimento di Informatica – Scienza e Ingegneria (DISI)
ALMA MATER STUDIORUM—Università di Bologna

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