

# Coordination Models

*From Parallel Computing to Self-Organisation*

## *Multiagent Systems LM*

*Sistemi Multiagente LM*

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- 1 Motivations
- 2 Classical Coordination Models
  - Tuple-based Models for Complex Systems Coordination
- 3 Nature-inspired Coordination Models
- 4 Coordination in Self-organising Systems
- 5 Challenges
  - The SAPERE Project
  - Self-Organising Coordination in Knowledge-Intensive Environments



# Complexity & Coordination—Again

## Complex computational systems. . .

- . . . intelligent, knowledge-intensive, pervasive, self-organising systems
- could be seen as the dynamic ensemble of a large number of distributed components, heterogeneous in nature, structure and behaviour
- put together *somehow* so as to build up a coherent overall system behaviour

## What is “somehow”?

- This is the key issue in the research for abstractions, models, technologies and methodologies for the engineering of complex systems
- This is the issue of *coordination models and languages* [Papadopoulos and Arbab, 1998, Busi et al., 2001]

# Evolution of Coordination Models I

## Origins of coordination models and languages

- Coordination models originated in the context of closed and parallel systems
- E.g., generative communication [Gelernter, 1985] as a means to enable/promote parallel computations



# Evolution of Coordination Models II

## Coordination models and languages today

- After twenty-five years of literature on coordination models and languages. . .
- . . . they are now conceived as the potential sources for the abstractions and the technologies around which complex computational systems can be designed and built
- ? How did this happen?
- A possible explanation in [Omicini and Viroli, 2011], upon which this presentation is based



# Space-based Models I

## Tuple-based models

- Tuple-based models [Rossi et al., 2001] represent the main class of space-based coordination models
- There, communication and coordination occur through a shared data space
  - as in the case of blackboard systems [Corkill, 1991]
- A shared communication space, whose life is independent of the interacting components, is the conceptual basis for *generative communication* [Gelernter, 1985]
- As such, it represents the essential environment abstraction for the support of openness in distributed systems



# Space-based Models II

## Persistent coordination abstraction

- The key idea of generative communication is a coordination abstraction persisting along with the messages exchanged
- This is the essential pre-requisite for a system where components may come and go at run-time. . .
- . . . and provides for time uncoupling, which makes it possible to conceive and design patterns of interaction that could survive the potential erraticism of component behaviour



# Origins of Tuple-based Models I

## LINDA

- The ancestor of all tuple-based models is LINDA
  - In LINDA, [Gelernter, 1985], components communicate and synchronise by exchanging tuples through a shared *tuple space*
  - There, communication and coordination occur through a shared data space
- ! LINDA was first conceived to support parallel computation in closed systems—at least, with no apparent concern for open systems





# Origins of Tuple-based Models II

## From closed to open systems

- LINDA introduces an environment abstraction devoted to the management of the (agent) interaction space
- As a conceptual consequence, computation and *coordination*
  - conceived as the governing of interaction [Wegner, 1997]
- were to be
  - considered as two *orthogonal dimensions* of computer-based systems [Gelernter and Carriero, 1992]
  - handled – that is, analysed, modelled, designed, programmed – in an independent way, by adopting suitable abstractions and mechanisms



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# Basic Features of LINDA-based Models I

## Tuples

- A *tuple* is an ordered collection of possibly-heterogeneous knowledge chunks
- Synchronisation based on the availability of tuples means essentially synchronisation based on the availability of structured knowledge of some sort
- Tuple-based coordination is first of all *knowledge-based coordination*
  - where tuple spaces are possibly interpreted as *knowledge repositories*



# Basic Features of LINDA-based Models II

## Associative access

- Tuple spaces are accessed *associatively*
  - queries specify tuple templates that match tuples based on their structure and the data they contain
- Complete uncoupling in communication
  - information neither on the sender nor on the structure of the share space is required for a message to be received
- Synchronisation possible over a partial representation of knowledge—the tuple *template*
  - a fundamental feature in all the contexts where information is often vague, inaccurate, incomplete, or partially specified—as is typical in knowledge-intensive systems



# Basic Features of LINDA-based Models III

## Logic tuple-space models

- Tuples as first-order logic (FOL) facts
  - Examples
    - Shared Prolog [Brogi and Ciancarini, 1991]
    - ReSpecT [Omicini and Denti, 2001]
  - Components coordinate through FOL tuples
  - Tuple spaces are FOL *theories*
    - the shared communication space can be interpreted as a logic-based knowledge repository used for component coordination
    - each tuple space could be thought as the FOL theory representing some domain element relevant for component coordination
- semantic interpretation of logic tuple space



# Essential Features of LINDA-derived Models I

Two other features characterise tuple-based models as they descend from the original LINDA ancestor

- *distribution* of the coordination abstractions
- *expressiveness* of the coordination abstractions

respectively termed as [Busi et al., 2001]

- reshaping the coordination media
- programming the coordination rules



# Essential Features of LINDA-derived Models II

## Reshaping the coordination media

- Distribution is essential for any complex system
- In the same way as components of a distributed system are spread all over the system topology, multiple tuple spaces fill the system environment, providing for *distributed coordination abstractions*
  - JavaSpaces [Freeman et al., 1999]
  - TSpaces [Wyckoff et al., 1998]
- This paves the way toward pervasive coordination systems
- Also, expressing the environment topology in a distributed setting is essential for the coordination of local interaction as well as of mobile components
  - LIME [Murphy et al., 2006]
  - KLAIM [De Nicola et al., 1998]



# Essential Features of LINDA-derived Models III

## Programming the coordination rules

- The expressiveness of coordination media often needs to be tailored to the complexity and peculiarity of the specific coordinated system
- So, a number of LINDA derivatives, e.g.
  - Law-Governed Interaction [Minsky and Ungureanu, 2000]
  - MARS [Cabri et al., 2000]
  - ReSpecT [Omicini and Denti, 2001]
- focus on the *programmability of the tuple space*, so as to
  - make it possible to explicitly express the rules of coordination
  - embed them within the coordination abstraction
- There, arbitrarily-complex coordination policies can be in principle associated to each of the coordination media, which can be individually programmed so as to embed either global or local coordination policies, as required by the specific coordinated systems



# Essential Features of LINDA-derived Models IV

## One more thing: Situatedness

- The ability to define arbitrarily-complex coordination policies and to embed them within the coordination media should be in principle coupled with the ability to capture and react to *arbitrary environment events*
- Otherwise, environment-based coordination would not be supported directly by the coordination medium
- This provides for the level of situatedness typically required by coordination in pervasive computational environments
  - Situated ReSpecT [Casadei and Omicini, 2009]



# Not Only LINDA: The Case of Gamma I

## Legacy beyond LINDA: Gamma

- The other ancestor of space-based models is Gamma [Banătre et al., 2001]
- Not a derivative of LINDA
- In Gamma, a shared coordination space is ruled by *chemical-like laws* defined by the programmers
  - thus, Gamma reminds the features of programmable tuple space models



# Not Only LINDA: The Case of Gamma II

## Source of inspiration for Gamma

- Analogous to 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
- Gamma is a *nature-inspired* coordination model



# Nature-inspired Coordination Models I

## Nature-inspired computing

- The main idea is to extract models and patterns from natural systems of any sorts, and apply them within computational contexts
  - Nature-inspired models includes neural networks, genetic algorithms, swarm intelligence, ...
  - Strict relationship between coordination and complexity of systems
- nature-inspired models of coordination are of particular interest in the engineering of complex computational systems



# Nature-inspired Coordination Models II

## Nature-inspired coordination

- A whole class of coordination models is inspired by the extraction of patterns from natural and social complex systems
  - *Nature-inspired* coordination models are mostly driven by the idea that
    - working complex systems exist in the real world
    - which we can observe so as
    - to understand their basic principles and mechanisms, to abstract them, and to bring them within our artificial systems
  - Understanding the principles and mechanisms of coordination within complex natural systems
- defining coordination models and technologies for complex artificial systems



# Field-based Coordination Models

## Field-based coordination

- Field-based coordination models are inspired by the way masses and particles move and self-organise according to gravitational/electromagnetic fields [Mamei and Zambonelli, 2006]
- Typically, a pervasive coordination infrastructure generates and maintains computational force fields which are sensed & modified by agents moving through the fields, according to the field intensity and sort



# TOTA

## Field-based coordination in TOTA

- In TOTA [Mamei and Zambonelli, 2004], computational force fields takes the form of *distributed tuples*
- Distributed tuples
  - are generated by both the active components and by the pervasive coordination infrastructure
  - propagate across the environment
  - drive the actions and motion of the component themselves—e.g. allowing two mobile agents to find each other in a dynamic network



# Stigmergic Coordination I

## Origins of nature-inspired coordination models

- Historically, nature-inspired models of coordination are grounded in studies on the behaviour of social insects, like ants or termites
- The key concept there is *stigmergy*, introduced by [Grassé, 1959] as an explanation for the coordination observed in termites societies, where
  - *“The coordination of tasks and the regulation of constructions are not directly dependent from the workers, but from constructions themselves.”*
- Namely, the notion of stigmergy generally refers to a set of coordination mechanisms mediated by the *environment*...
- ... which leads to the emergent behaviours typical of self-organising systems



# Stigmergic Coordination II

## Example: Ants

- In ant colonies, chemical substances – namely *pheromone* – act as environment markers for specific social activities
- Pheromones drive both the individual & the social behaviour of ants
  - by the way, similarly to what happens e.g. in TOTA
- Namely, the notion of stigmergy generally refers to a set of coordination mechanisms mediated by the *environment*



# Environment-based Coordination

## Coordination through the environment

- Most of nature-inspired coordination models are characterised by the active role of the *environment*
- For instance, both field-based and stigmergic coordination are based on some notion of environment affecting the behaviour of coordinated components by shaping the space of component interaction
- Generally speaking, *environment-based coordination* systematically adopts structured abstractions for shaping the environment of system components so as to govern their interactions [Ricci et al., 2005]
- So, environment-based coordination generalises for instance upon both field-based and stigmergic coordination



# Environment-based Coordination through Artifacts

## Coordination artifacts as environment abstractions

- Generally speaking, artifacts work as the basic abstractions to shape the agent environment in MAS [Omicini et al., 2008]
- Complex social behaviour like behavioural implicit communication (BIC) can be built upon *coordination artifacts* [Omicini et al., 2004]
- Coordination artifacts work then as the general-purpose environment abstractions used to inject *social intelligence* within computational systems independently of the intelligence of the individual system components
  - *“artifacts are environment abstractions that mediate agent interaction and enable emergent coordination: as such, they can be used to encapsulate and enact the stigmergic mechanisms and the shared knowledge upon which emergent coordination processes are based.”*  
[Ricci et al., 2005]
- So, environment-based coordination generalises for instance upon both field-based and stigmergic coordination

# Cognitive Stigmergy I

## Beyond stigmergy

- Stigmergy concerns emergent coordination in societies composed by a large amount of ant-like, non-rational agents
- However, stigmergic patterns can be observed also in the context of societies composed by cognitive / rational agents [Omicini et al., 2004]
- *Cognitive stigmergy* is a conceptual (and engineering) framework for exploring the use of stigmergy within societies of cognitive agents, as a means for supporting high-level, knowledge-based social activities [Ricci et al., 2007]



# Cognitive Stigmergy II

## Cognitive stigmergy in MAS

- Cognitive stigmergy is based on the use of artifacts as tools populating and structuring the agent working environment. . .
- . . . which agents perceive, share and rationally use for their individual goals
- Since artifacts are environment abstractions that mediate agent interaction and enable emergent coordination, they can be used to encapsulate and enact the stigmergic mechanisms and the shared knowledge upon which emergent coordination processes are based
- Multiple-level coordination between heterogeneous components
  - ordinary components perceive environment markers as mere signals and react accordingly
  - intelligent components can read them as *signs*, and behave according to their *symbolic interpretation*

# Self-organising Coordination I

## A shared legacy

- Nature-inspired coordination models
  - e.g., chemical, field-based, and stigmergic coordination models
- share a fundamental feature
  - they come from the *core* of complex natural self-organising systems
- As such, they are seemingly the most intuitive sources for abstractions and mechanisms around which self-organising artificial systems could be designed and built



# Self-organising Coordination II

## Towards self-organising coordination

- Generally speaking, *self-organising coordination* can be defined as the management of system interactions featuring self-organising properties
- ... namely, where [Viroli et al., 2009]
  - interactions are local
  - global desired effects of coordination appear by emergence



# Self-organising Coordination III

## The problem of self-organising coordination

- In most classical coordination models the environment is filled with coordination media enacting coordination laws that are
  - typically reactive
  - (essentially) deterministic
  - global
- In self-organising systems coordination
  - patterns typically appear at the global level by emergence
  - from probabilistic, time-dependent coordination laws
  - based on local criteria





# Features of Self-organising Coordination

## Required features of self-organising coordination models

According to [Viroli et al., 2009], the required features of coordination models for self-organising systems are

- Topology & locality
- On-line character
- Time-dependency
- Probabilistic behaviour



# Topology & Locality

## Coordination middleware

- Topology & locality mostly affect the nature of the *coordination middleware*
  - The coordination media provided should
    - be associated to *distributed locations*
    - mostly govern interaction among *local components*
    - *not* be merely *reactive* to interaction
    - instead, be enacted as *always-running services* able to adapt their coordinative behaviour at run time
- as in the case of LIME, ReSpecT and TOTA, among the others



# Time-dependency & Probabilistic Behaviour I

## Classical coordination models

- Apparently classical coordination models apparently address the issues of time-dependency and probabilistic behaviour in some way
- For instance
  - tuple matching templates are returned in a non-deterministic way
  - chemical laws are known to be probabilistic and time-dependent



# Time-dependency & Probabilistic Behaviour II

## Nonetheless...

- On the one hand
  - non-determinism of classical tuple-based model is just a “don’t know” non-determinism
  - non-determinism in self-organising systems is typically stochastic
  - models like TOTA, SwarmLinda [Tolksdorf and Menezes, 2004] and STOKLAIM [Bravetti et al., 2009] have introduced stochastic mechanisms within tuple-based coordination
- On the other hand
  - classical chemical coordination models like Gamma and CHAM do not really reproduce chemical behaviours
  - since they can express neither stochastic behaviours nor time-dependent coordination rules



# Time-dependency & Probabilistic Behaviour III

## Chemical tuple spaces

- As a result, a *chemical tuple-space* model and infrastructure have been defined [Viroli et al., 2010] ...
- ... that embodies all the typical features of self-organisation in natural chemical systems
- There, self-organisation could be achieved in two ways
  - either by means of the behaviour of an individual chemical tuple space (*intra-space self-organisation*)
  - or by means of a suitable pattern of interaction among chemical tuple spaces (*inter-space self-organisation*)



# Tuple-based Models for Self-organising Coordination I

## Extending tuple-based models

- In the overall, suitably-extended tuple-based models provide a promising platform for the design and development of self-organising coordinated systems
- Nonetheless, knowledge-intensive application scenarios pose a huge challenge for tuple-based models
- There, the aforementioned benefits of tuple-based coordination in terms of knowledge-based coordination fade in front of the problems it induces in terms of syntax & (mostly) semantics
  - e.g., two tuples containing the same data may not match due to differences in the tuple structure
  - e.g., two tuples representing the same information may not match based on a different syntax adopted



# Tuple-based Models for Self-organising Coordination II

## Two lines of extension in the literature

- Exploiting tuple-based coordination within a middleware for knowledge intensive environments
  - e.g., [Tolksdorf et al., 2008] experiments with a tuple-based coordination within Semantic Web middleware
  - e.g., [Nixon et al., 2008] survey similar approaches
- Enhancing the tuple space abstraction with a semantic interpretation
  - e.g., [Nardini et al., 2010] extend tuple spaces with a description logic framework so as to equip each tuple, template, and operation over tuple spaces with a well-founded semantic interpretation



# Self-organising Semantic Coordination (SOSC) I

## Adding semantics to tuple spaces

- Generalisation of the basic principles and mechanisms of coordination and self-organisation for application to knowledge-intensive environments
  - Everything still based on tuples and tuple spaces
  - Now equipped with a semantic interpretation
- Definition of the notion of *self-organising semantic coordination*





# Self-organising Semantic Coordination (SOSC) II

## SOSC

- SOSC as the management of interactions in knowledge-intensive systems
- where
  - interactions are local and involve sharing and processing of knowledge
  - the global desired effects of coordination over distributed knowledge appear by emergence and through self-organisation.

Coordination infrastructures – in particular, tuple-based ones – should then be adopted to support self-organising semantic coordination, as in the case of *eternally adaptive service ecosystems* for pervasive computing [Viroli and Zambonelli, 2010].



# The Future of Coordination I

## Impact of coordination models

- Coordination models, languages, technologies and infrastructures are going to deeply impact on the engineering of complex systems
- Also in terms of methodologies and software processes
- and on related research as well

## Challenges for coordination

- A huge number of technical challenges are waiting for the development of coordination middleware and infrastructures
- Such challenges will put the effectiveness of coordination-based approaches to test against many complex, real-world application scenarios



# Challenges for Coordination

## Some of the main issues for coordination in complex systems

- Integration of organisational and security models in the coordination setting
- Full development and testing of nature-inspired coordination models
- Definition of knowledge-oriented coordination models and languages embodying international standards
- Construction of light-weight coordination technologies for pervasive scenarios
- Design of rich coordination frameworks providing developers with tools for the engineering of the interaction space in complex computational systems
- ...



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# Self-aware Pervasive Service Ecosystems

## SAPERE

- European Project FP7 – 2010-2013
- <http://www.sapere-project.eu>
- <http://apice.unibo.it/xwiki/bin/view/SAPERE/>



# Requirements

## Behind the model

- Environment-mediated communication & coordination
- Topology
- Mobility
- Context / Situatedness
- Agent manifestation
- Context representation & awareness
- Self-organising coordination laws



# Natural Inspiration

## Chemical metaphor

- Chemical manifestation—*molecules*
- Chemical environment—*chemical spaces*
- Chemical bonds
- Chemical reaction
- Chemical laws
- Physical/biological diffusion



# Basic Ontology

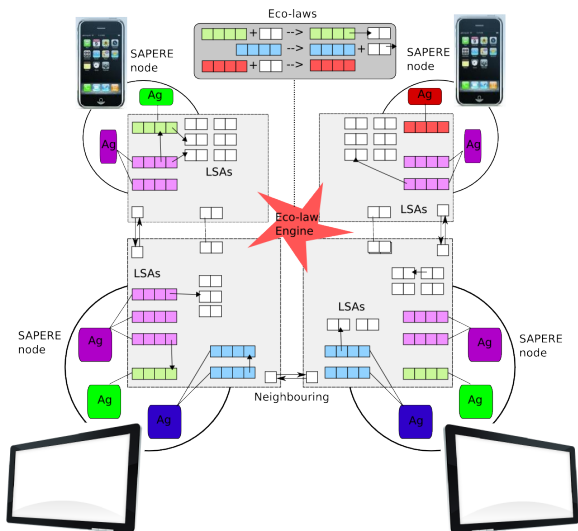
## Main concepts

- LSA (Live Semantic Annotation)
- Shared LSA-space
- Node
- (Local) LSA-space
- Agent
- Bond
- Eco-law





# Basic Architecture



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# KIE & SOS

## Knowledge-Intensive Environments (KIE)

- Application scenarios where data, information, and knowledge storage, search and manipulation play a prominent role
- Many *knowledge-intensive workers*—lawyers, physicians, journalists, researchers, . . .
- Too much knowledge they have to handle and master
- Explicit research is going to be ineffective in a few years
- Mechanisms for *self-organised* diffusion of knowledge are required



## Ecosystems for Self-organising news management

- Architecture

- a self-adapting working environment for journalists, recording actions and adapting to them
- automated and human-made processes for extracting knowledge from knowledge sources
- a pervasive, self-organising infrastructure for knowledge aggregation and diffusion

- Basic elements

- atoms / molecule of knowledge, representing news and articles
- chemical laws for molecule aggregation
- field-based coordination for molecule diffusion and decay
- both explicit and implicit actions on knowledge result in field changes

- Unlike SAPERE, chemical laws are given once and for all

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