From Coordination to Semantic Self-Organisation
A Perspective on the Engineering of Complex Systems

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Abstract

After briefly recapitulating the classical lines of the literature on coordination models, we discuss the new lines of research that aim at addressing the coordination of complex systems, then focus on mechanisms and patterns of coordination for self-organising systems. The notions of semantic coordination and self-organising coordination are defined and shortly discussed, then a vision of SOSC (self-organising semantic coordination) is presented, along with some insights over available technologies and possible scenarios for SOSC.

1. Coordination: Background
   - Coordination Models: An Overview
   - On the Expressiveness of Coordination Models
2. Self-Organisation & Coordination
   - Self-Organisation
   - Stigmergy
   - Cognitive Stigmergy
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Coordination in Distributed Systems

Coordination model as a glue

A coordination model is the glue that binds separate activities into an ensemble [Gelernter and Carriero, 1992]

Coordination model as an agent interaction framework

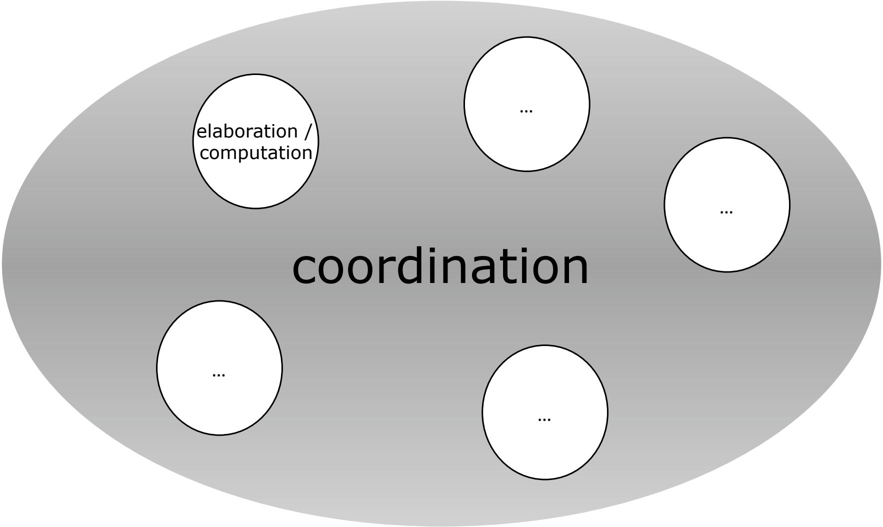
A coordination model provides a framework in which the interaction of active and independent entities called agents can be expressed [Ciancarini, 1996]

Issues for a coordination model

A coordination model should cover the issues of $creation$ and $destruction$ of agents, $communication$ among agents, and spatial $distribution$ of agents, as well as $synchronization$ and $distribution$ of their $actions$ over time [Ciancarini, 1996]

What is Coordination?

Ruling the space of interaction



New Perspective on Computational Systems

Programming languages

- Interaction as an orthogonal dimension
- Languages for interaction / coordination

Software engineering

- Interaction as an independent design dimension
- Coordination patterns

Artificial intelligence

- Interaction as a new source for intelligence
- Social intelligence

Coordination: A Simple Meta-model [Ciancarini, 1996] I

A constructive approach

Which are the components of a coordination system?

Coordination entities Entities whose mutual interaction is ruled by the model, also called the *coordinables*

Coordination media Abstractions enabling and ruling agent interactions

Coordination laws Rules that govern the space of interaction—ruling the observable behaviour of coordinables, and the computationa behaviour of coordination media

Two Classes for Coordination Models

Control-driven vs. data-driven Models

— Control-driven vs. Data-driven Models [Papadopoulos and Arbab, 1998]

Control-driven Focus on the *acts* of communication

Data-driven Focus on the *information* exchanged during communication

— Several surveys, no time enough here

— Are these really *classes*?

- actually, better to take this as a criterion to observe coordination models, rather than to separate them

Data-driven Models I

Communication channel

- Shared memory abstraction
- Stateful channel

Processes

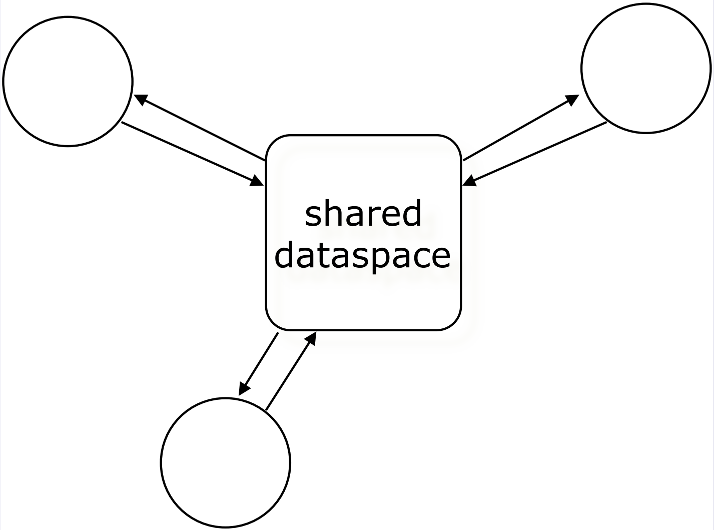
- Emitting / receiving data / information

Coordination

- Access / change / synchronise on shared data

Data-driven Models II

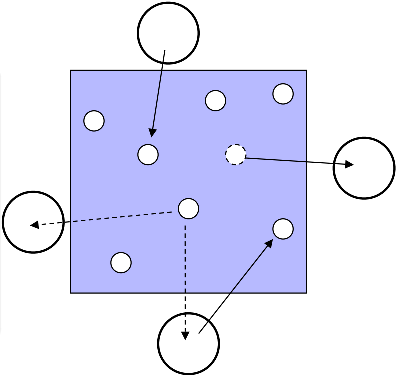
Shared dataspace: constraint on communication



The Tuple-space Meta-model

The basics

- *Coordinables* synchronise, cooperate, compete
  - based on *tuples*
  - available in the *tuple space*
  - by *associatively* accessing, consuming and producing tuples



Hybrid Coordination Models

- Generally speaking, control-driven coordination does not fit so well information-driven contexts, like agent-based ones
  - control-driven models like Reo [Arbab, 2004] need to be adapted to agent-based contexts, mainly to deal with the issue of agent autonomy [Dastani et al., 2005]
  - no coordination medium could say "do this, do that" to a coordinated entity, when a coordinable is an agent
- Knowledge-intensive systems mandate for data-driven (or, knowledge-oriented) models—especially, space-based ones
- Pervasive systems require event-driven coordination, typical of control-driven models—e.g., for handling openness & situatedness
- We need features of both approaches to coordination
  - *hybrid* coordination models
  - adding for instance a control-driven layer to a space-based one

A Hybrid Model: ReSpecT Tuple Centres

Reaction Specification Tuples [Omicini and Denti, 2001]

`reaction(Event, Guard, Body)`

- Coordination as *reactive behaviour*
  - of coordination abstractions
  - in response to events / actions

  ⇒ When an event ϵ matching `Event` occurs in the tuple centre, and the `Guard` succeeds over ϵ properties, then reaction $(\epsilon, \texttt{Body})$ is triggered and executed

- Coordination specified via (FOL) specification tuples
  - tuple space + specification space = tuple centre
  - theory of communication + theory of coordination = theory of interaction
  - declarative vs. procedural language

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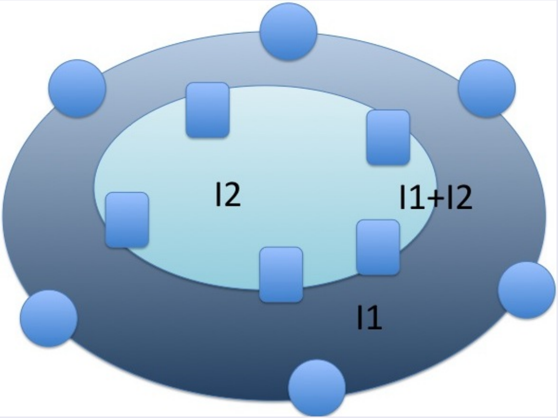
Expressiveness of Coordination I

Spaces of interaction



Expressiveness of Coordination II

Spaces of interaction for coordination

- **I1** Mostly from the observable behaviour of coordinables, the space of coordinable interaction
- **I2** Mostly from the behaviour of coordinators, the space of coordination media
- **I1+I2** The overall space of interaction, where the full acceptation of coordination is enforced

Expressiveness of Coordination III

Turing equivalence & the spaces of interaction

I1 Interactions alone – with minimal assumptions on the computational abilities of coordination media – may / may not produce a Turing-equivalent system

- e.g., Linda with synchronous out is Turing-equivalent—whereas Linda with asynchronous out is not [Busi et al., 2000]

I2 Coordination media alone – with no assumption on the observable behaviour of coordinables

- e.g., ReSpecT tuple centres are Turing-equivalent [Denti et al., 1998]

I1+I2 Anything more / beyond?

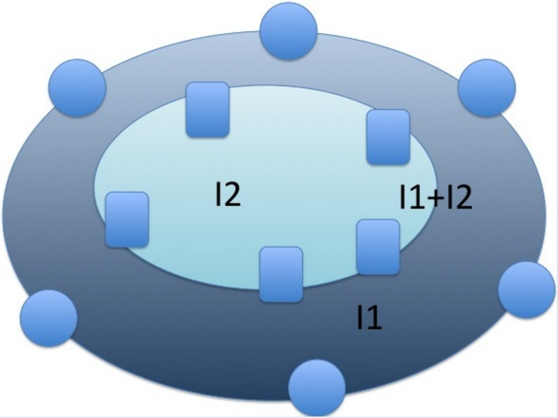
- complex coordination policies could be charged in principle upon the most suited abstractions

Placing Coordination I

- Having three conceptual spaces for Turing equivalence – coordinables, I1, I2 – does not necessarily make you overcome Turing machines: however, it gives you a lot of freedom in organising systems
- Engineers may choose where to put properties of a system – like, say, intelligence, or self-org mechanisms
- This draws the line that brings to hybrid coordination models: data-driven (with full Turing equivalence from coordination primitives) with enough computational power in the coordination media, and the ability to handle event-driven coordination policies
- Also, this paves the way towards self-* patterns of coordination, where self-* mechanisms can be embedded wherever needed

Placing Coordination II

Spaces of coordination



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Intuitive Idea of Self-Organisation

- Self-organisation generally refers to the internal process leading to an increasing level of organisation
- *Organisation* stands for relations between parts in term of structure and interactions
- *Self* means that the driving force must be internal, specifically, distributed among components

Elements of Self-Organisation

Increasing order — due to the increasing organisation

Autonomy — interaction with external world is allowed as long as the control is not delegated

Adaptive — suitably responds to external changes

Dynamic — it is a process not a final state

Definition of Self-Organisation

- For instance, the widespread definition of Self-Organisation from [Camazine et al., 2001]

  Self-organisation is a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern.

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Insects Colonies

- Behaviours displayed by social insects have always puzzled entomologist
- Behaviours such as nest building, sorting, routing were considered requiring elaborated skills
- For instance, termites and ants build very complex nests, whose building criteria are far than trivial, such as inner temperature, humidity and oxygen concentration

Definition of Stigmergy

- In [Grassé, 1959], Grassé proposed an explanation for the coordination observed in termites societies

  The coordination of tasks and the regulation of constructions are not directly dependent from the workers, but from constructions themselves. The worker does not direct its own work, he is driven by it. We name this particular stimulation stigmergy.

- From the very beginning, the study of self-organising patterns has been linked to coordination of complex systems

Elements of Stigmergy

- Nowadays, stigmergy refers to a set of coordination mechanisms mediated by the environment
- For instance in ant colonies, chemical substances, namely *pheromone*, act as markers for specific activities
- E.g. the ant trails between food source and nest reflect the spatial concentration of pheromone in the environment
- Coordination models like TOTA [Mamei and Zambonelli, 2004] exploits a pheromone-like mechanism of coordination

Stigmergy and the Environment

- In stigmergy, the environment play a fundamental roles, collecting and evaporating pheromone
- In its famous book [Resnick, 1997], Resnick stressed the role of the environment

  The hills are alive. The environment is an active process that impacts the behavior of the system, not just a passive communication channel between agents.

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Environment-based Coordination I

Environment in coordination [Omicini et al., 2004]

- In the context of human organisations, environment plays a fundamental role for supporting cooperative work and, more generally, complex coordination activities
- Support is realised through services, tools, artifacts shared and exploited by the collectivity of individuals for achieving individual as well as global objectives

Environment-based Coordination II

Coordination artifacts [Ricci et al., 2005]

- Coordination artifacts are the entities used to instrument the environment so as to fruitfully support cooperative and social activities
- Infrastructures play a key role by providing services for artifact use and management

Environment engineering with coordination artifacts

- Environment should be treated as a first-class entity in the engineering of complex distributed systems [Weyns et al., 2007]
- Coordination artifacts can be used for shaping the environment / engineering the environment [Ricci and Viroli, 2005]

Stigmergy & Coordination

Cognitive stigmergy [Ricci et al., 2007]

- More articulated forms of *environment-based coordination* are possible, where artifacts give structure to the environment by encapsulating and promoting the mechanisms for stigmergic coordination
- For instance, when signals (e.g., pheromones) are read as signs and given a symbolic interpretation by rational agents
- Stigmergy & cognitive stigmergy for emergent coordination. . .
- . . . where both reactive and intelligent agents can fruitfully participate in an emergently-coordinated activity. . .
- . . . even though with different level of understanding of the coordinating environment

From Hybrid Coordination to Cognitive Stigmergy via ReSpecT Tuple Centres

From coordination media to coordination artifacts [Omicini et al., 2004]

⇒ ReSpecT tuple centres can be used as coordination artifacts for MAS, encapsulating the rules for MAS coordination expressed in terms of ReSpecT reactions

Coordination as a service [Viroli and Omicini, 2006]

⇒ ReSpecT tuple centres can be used to provide MAS with coordination services, with coordination policies possibly inspectable by agents as FOL theories

Cognitive stigmergy [Ricci et al., 2007]

⇒ ReSpecT tuple centres can be used to build up structured environments for self-organising MAS based on cognitive stigmergy

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Re-considering Environment-based Coordination I

An observation

- In a coordinated system, the environment is filled with coordination media – e.g. tuple spaces or ReSpecT tuple centres – enacting coordination laws that are typically *reactive*, *deterministic*, and *global*—in most models. . .
- In self-organising systems – as well as in few emerging works in coordination –, coordination services with interesting global properties appear by emergence from probabilistic coordination laws, based on *local* criteria, and time-reactive

Re-considering Environment-based Coordination II

Most coordination models are old-style

- Deterministic in most essential meanings, typically time-independent, usually global in effect
- TOTA [Mamei and Zambonelli, 2004], SwarmLinda [Tolksdorf and Menezes, 2004], stoKLAIM [Bravetti et al., 2009] are few examples of attempting new paths
- A good mixture of old and new features is required for self-organising coordination

A Framework for Self-organising Coordination I

Essential features of self-organising coordination [Casadei and Viroli, 2008]

- Topology
- Locality
- On-line character
- Time
- Probability

Topology

- The application is deployed over a topologically-structured distributed system
- Coordination media and agents are deployed over locations

A Framework for Self-organising Coordination II

Locality

- Topology is strictly tight with the *scope* of interactions
- A coordinated system features two (relevant) kinds of interaction: between an agent and a coordination medium, and between coordination media
- Both kinds of interaction should occur *locally*—that is, either across the same location, or across two neighboring locations as defined by topology

A Framework for Self-organising Coordination III

On-line character

- Coordination media should not be merely reactive—reactive to interaction, affecting interaction
- Instead, they should behave with an on-line coordination behaviour, enacted as an *always-running service*
- For instance, in order to work properly, the fading mechanism should not be completely defined at design time, but rather adapt on-line to the rate at which agents move

Time

- Coordination (policies) should depend on time
  - a self-organising coordination service should be given at a certain “rate”
  - some coordination primitive could be time-dependent—e.g., timeout

A Framework for Self-organising Coordination IV

Probability

- Space-based non-determinism is essentially delegation to implementation
  - It is not the same as "natural" non-determinism...
- Effects of actions are not deterministic in nature: stochastic distribution is typical
- It should then be possible to express stochastic (coordination) behaviours within coordination media

Self-organising Coordination

A definition [Viroli et al., 2009]

- Self-organising coordination is the management of system interactions featuring self-organising properties, namely, where interactions are local, and *global desired effects of coordination appear by emergence*
- Constructively, self-organising coordination is achieved through *coordination media spread over the topological environment*, enacting *probabilistic and time-dependent coordination rules*

Self-organising Coordination with ReSpecT & TuCSoN I

TuCSoN [Omicini and Zambonelli, 1999]

- A coordination infrastructure providing ReSpecT tuple centres as its coordination media
- For instance, just the TuCSoN distributed topology is required

Topology

- Assuming the network is organised in a topologically structured distributed system, TuCSoN allows one or more tuple centres to be created locally to a specific node
- For instance, coordinating (Java) agents, too, are supposed to be localised in a node of the network

Self-organising Coordination with ReSpecT & TuCSoN II

Locality

- TuCSoN agents and tuple centres should be aware of locality: they should just know the list of tuple centre identifiers in the neighbourhood
- For a tuple centre, e.g., this simply means a tuple `neighbour(tc)` occurs in the space if tuple centre `tc` is in the neighbourhood

Self-organising Coordination with ReSpecT & TuCSoN III

On-line charachter & Time

- ReSpecT support timed reactions: when the tuple centre time (expressed as Java milliseconds) reaches `T`, the corresponding reaction is fired
- Moreover, a reaction goal can be of the kind `out_s(reaction(time(T),G,R))`, which inserts tuple `reaction(time(T),G,R)` in the space, thus triggering a new reaction—and essentially, self-modifying itself
- These mechanisms can be used to realise either an on-line service that keeps transforming tuples as time passes, or time-dependent coordination primitives

Self-organising Coordination: Examples

Two examples [Viroli et al., 2009]

- Adaptive tuple distribution – self-organisation through interaction *between* coordination media
- Chemical coordination – self-organisation through interaction (of tuples) *inside* a coordination medium

Adaptive Tuple Distribution

Tuple clustering: Sketched

- Like corpse clustering by ants
- Tuples carrying information of the same class should be aggregated...
- ...thus forming clusters of similar tuples across the network
- ReSpecT tuple centres react and interact with each other to adaptively distribute tuples

Chemical-like Coordination I

A biologically-inspired coordination model

- Chemical-like coordination laws embedded in the coordination medium
- In ReSpecT tuple centres, built as ReSpecT reactions

A sketch

- Tuples in a tuple centre behave like chemical components
- Chemical laws are expressed as ReSpecT reactions

More in [Viroli et al., 2009]

- Where coordination laws like decay, Lotka reactions, Oregonator, . . . , are described and discussed
- as well as implemented in ReSpecT and experimented

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The Issue of Semantics in Coordination

Semantics for space-based coordination

- data-driven / knowledge-oriented coordination models fit well the scope of Knowledge-intensive systems (KIS)—in particular space-based ones
- the main issue there is that coordination occurs in a merely syntactic fashion: no semantics is associated to the information exchanged
- so, no coordination policies can be in principle based on semantics

Ongoing work [Nardini et al., 2010]

- associating semantics to tuple spaces
- adding a space for ontology
- and suitably extending the matching mechanism

TBox for Semantic Tuple Centres

TBox

- TBox consists of concept descriptions, which denote sets of objects called individuals, and role descriptions, which denote binary relationships between individuals
- Each ReSpecT tuple centre is associated to a specific TBox describing the stored information
- Tuple centres sharing the same node may or may not share a TBox
- For the TBox definition in ReSpecT tuple centres, a SHOIN(D)-like description language is adopted: OWL-DL ontology description language

ABox for Semantic Tuple Centres

ABox

- ABox consists of the assertions about the individuals and roles, in terms of the terminology defined via TBox
- Each tuple stored in a tuple centre can be seen as an object belonging to the application domain, with the set of relationship in which it is involved

→ A tuple represents an ABox individual

→ The set of tuples stored in a tuple centre can be written with an ABox language

- In order to describe tuples as ABox individuals so they can be interpreted in a semantic way by means of a TBox, we need a SHOIN(D) description language-like to specify
  - the name of the individual we mean to describe
  - the concept to which the individual belongs
  - the set of roles in which the individual is involved

Semantic Tuple Templates

Templates

- A tuple template represents a specification of a set of tuples. Adopting a semantic viewpoint, a tuple template can be seen as a specification of a set of domain individuals described through the domain ontology.

→ A specification of a set of ABox individuals described through a TBox

- The matching mechanism could be then extended though a SHOIN(D)-like description language for semantic tuple templates

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Self-organising Semantic Coordination (SOSC)

Self-organising semantic coordination is the management of KIS interactions, which are local and involve sharing and processing of knowledge: global desired effects of coordination over distributed knowledge appear by emergence and through self-organisation.

Self-* & Coordination for KIS

- The conceptual framework of self-organising semantic coordination (SOSC) generalises the basic principles and mechanisms of coordination and self-organisation for application to knowledge-intensive environments (KIS)
- Within KIS, knowledge moves and organises itself autonomously to create rich and dynamic application scenarios
- The conceptual framework of SOSC suitably generalises the basic principles and mechanisms of coordination and self-organisation, to apply them to knowledge-intensive environments. Coordination infrastructures could then be adopted to support KIS, as for eternally adaptive service ecosystems [Viroli and Zambonelli, 2010].

Vision

Impact of SOSC mechanisms & infrastructures

- Every piece of information made available in a knowledge-intensive system can trigger self-organising mechanisms. . .
- . . . where chunks of knowledge interact with each other and coordinate to form semantic clouds
- SOSC promotes a view of knowledge-intensive environments where a multiplicity of applications coexist and share information through both explicit and implicit mechanisms.
- The contribution of each knowledge source is no longer limited to the scope where it is originally designed, but potentially spans over any relevant knowledge-based environment
- Fruition of knowledge is then no longer limited by the standard knowledge-access mechanisms, but is instead actively promoted by SOSC mechanisms
- So, as a result of the diffusion of SOSC infrastructures, knowledge will possibly spread from the original sources across the network, autonomously relate with other independently-generated knowledge, and be accessible in form of spontaneously-aggregated semantic clouds independently of the original application boundaries

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