From Service-Oriented Architectures to Nature-Inspired

Self-aware Pervasive Service Ecosystems:
The SAPERE Approach

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Outline

- Motivations
- Limitations of SOA
- The Natural Inspiration
- A Reference architecture
- Comparison of Natural Metaphors
- The SAPERE Approach
- Conclusions
The Changing ICT Scenario

- Networks are changing
  - Integration of (increasingly dense) pervasive devices embedded in physical space
  - Convergence of Internet and Telecommunication networks
  - Convergence of social and technical networks
  - High dynamisms and decentralization
- And so management needs are changing
  - Decentralization requires self-management and self-configuration
  - Need to achieve 24/7 availability at limited costs
  - Opportunistic approaches to devices integration
- And service systems have to change accordingly
- Several emerging trends…

AWARE Lecture
New Requirements for Service Systems

- Spatiality and Situatedness
  - Space-dependencies and situation-awareness

- Adaptivity
  - Capable of reacting and re-tuning in response to the dynamics of the pervasive infrastructure
  - Adapting to changing patterns and peculiar users’ needs

- Service Prosumption and Diversity
  - Users also act as producers of data and services (prosumers)
  - Decentralized production models
  - Value Co-creation

- Eternal betas and eternal evolution
  - No service/software components is ever ultimate
  - New components gets on appearing
Limits of “Traditional” SOA

- Too centralized and heavyweight
  - Too many diverse supporting middleware services
  - Inherently centralized

- Hard to meet the identified requirements
  - No spatial concepts
  - Static orchestration of services and devices
  - Limited support for decentralized prosumption,
  - Long-term evolutions constrained by too many assumptions
Decentralized SOA

- Replicate and Distributed Services
  - To support space-dependent activities
  - To localize updates and event notifications
- As a result
  - The distinction between discovery, orchestration, and context services tend to disappear
  - Generally, interactions in the local space
- But
  - What degree of distribution in space?
  - Complex coordination among distributed middleware services
Let’s Take it Radically

- No more distinction between discovery, orchestration, context, etc.
  - A single (and minimal) interaction space to handle data, interactions, context, orchestration
  - Based on a limited set of general “interaction laws”
- Adaptivity by self-organization
  - Based on the set of laws and relying on spatial locations, without pre-defined orchestration patterns
- No “distributed” architecture but “continuous” one
  - Abstract a spatial continuum over the network
  - Build over the dynamic infrastructure of devices
  - Inherently open to decentralized contribution
- Isn’t this resembling of natural systems?
Nature-inspired Service Ecosystems

- In natural systems (and whether you think at physics, chemistry, biology, or ecology)
  - Spatiality is there by construction
  - Self-adaptation, self-configuration, self-management, are inherent part of their everyday life and self-organizing dynamics
  - Inherently open to new and increasingly diverse species
  - The infrastructure is eternal and does not change, although their components may naturally evolve
- So we can get inspiration from nature to realize “Nature-inspired Pervasive Service Ecosystems”
- But what kinds of natural systems are we talking about?
Natural Metaphors

- When modeling nature-inspired pervasive service ecosystems
  - How should its components, laws, world, be modelled?
  - What form should they take in implementation terms?
- Several possible natural metaphors can be adopted
  - Physical, chemical, biological, social
  - Corresponding at different “levels of observation”
  - Based on different mechanisms for laws and on different components behaviours
  - And in which features, of adaptability, evolvability, and the capability of controlling decentralized control are differently expressed
- But how can we comparatively reason among such apparently diverse metaphors?
The Reference Architecture

- It abstracts from any specific nature-inspired metaphor
- Shows how general ecosystem concepts can be framed in a uniform way
- Useful to turn the architecture into an actual middleware infrastructure
The Pervasive Computing Continuum

- Shaping the hardware ground on which the actual ecosystem will live and execute
  - Pervasive sensing and actuating devices very densely deployed in space
  - Personal computer-based systems
  - Wireless communications
- Feeding the ecosystem with data about nearly every facts of the world
  - Also via Web information
Users, Consumers, and Prosumers

- They can “observe”, i.e., query, the ecosystem and its components
  - To obtain data, or results of computations
  - In a fully decentralized way
- They can “extract” components
  - To consume data and service
- They can “inject” new components and data items
  - To personalize the network
  - To deliver own services
  - To enforce control
The World

- A very minimal middleware substrate
  - No “smart” middleware services
  - Networked reactive tuple spaces
- Key goals
  - Supporting the spatial lifecycle of components over a dynamic substrate
  - Enabling and enforcing interactions across components
  - According to the “laws of nature” of the ecosystem
The Eco-Laws

- Ruling interactions and the overall dynamics and self-* behaviour of the system
  - How components should interact and when
  - How components should compose/aggregate
  - When component should die/clone/reproduce
- They are eternal
  - Species of components can change, laws can’t
  - Laws apply to all components
  - Different species may react to laws in differentiated ways

[Diagram showing layers of "Users/Consumers/Producers", "Species" (service components), "Laws" (fundamental interaction rules), "World" (middleware substrate for the ecology), and "Pervasive Computing Continuum" (pervasive devices and Web information).]
Species

- The software/digital components of the ecosystem
  - Software agents in the end
- May be of different nature
  - “Passive” data items
  - “Active” computational entities
  - Decentralized production
- Are all subject to the laws
  - But different components can react differently to laws
  - Based on internal characteristics and external interfaces
The Ecosystem Dynamics

- **Species**
  - Living in a region of “World”
  - Moving, acting, composing, as determined by laws
  - Not self-aware in themselves

- **Laws**
  - Impact on the local activities and interactions
  - Apply based on state of local components (feedback loops)

- **World**
  - The shape of space influence (and is influenced by) the above

- **Dynamics**
  - Seemingly self-aware adaptability/evolvability at the system level
Where is Self-awareness?

- Self-awareness is not at the level of individual components
  - None of them is aware of something
  - They can only perceive and react to specific aspects of local spatial situation
- Self-awareness is a systemic, observable property of the ecosystem
  - Upon changes in a situation
  - There are spontaneous reactions in the ecosystems
  - As if it were aware of what’s happening
Which Natural Metaphor?

- Beside the abstract reference architecture of the ecosystem
  - How should its components, laws, world, be modelled?
  - What form should they actually take in implementation terms?

- Several possible natural metaphors can be adopted
  - Corresponding at different “levels of observation” of natural systems
  - Based on different mechanisms for laws and on different components behaviours
  - And in all of which self-* features, adaptability, and evolvability, are (to different extents) inherently expressed

- It is worth outlining that such metaphors, so far, have been mostly exploited for specific solutions, applications, and/or algorithms (e.g., in autonomic communications research) but never as a comprehensive approach
# Metaphors

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<td>The Universe (a network), as shaped by waves and particles.</td>
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The TOTA Middleware (Mamei Zambonelli, 2004)

The Proto Language (Beal, 2004)
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**The Gamma Coordination Language (Banatre, 1990)**

**Computational Biology and DNA Computing**
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**Ant Colonies**

(Parunak 2007; Babaoglu 2006)
Metaphors

Computational Societies of agents (Jennings, 2003)

Trophic Networks (Agha, 2008; Zambonelli 2008)

Ecological (Social)
Organisms (Agents) and Species (Classes) and Resources (Data)

Survive (goal-orientation), eat, produce, and reproduce
Niches (Pervasive computing environments)
# Metaphors

This table illustrates various metaphors across different domains. The highlighted text indicates a question mark, suggesting an exploration of how these metaphors can be extended or reinterpreted in other contexts.

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Comparative Analysis

- Are these metaphor equally suitable to address the needs of future service ecosystems?
  - NO!
  - But it depends on what you want to achieve

- Let’s analyse according to three dimensions:
  - **Space**: the capability of facilitating self-organization and self-adaptation of functional distributed patterns of activity
  - **Time**: the capability of tolerating evolution and increasing diversity
  - **Control**: the capability of being easy to understand, design, and control in a decentralized way
Pros and Cons

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<td>(global self-organizing spatial structures)</td>
<td>(no new components, always same behaviours)</td>
<td>(we know well how to build and control specific structures in physic)</td>
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<td>(mostly local self-organizing structures, sometimes global too, as in crystals)</td>
<td>(several new components can be generated under the same basic laws)</td>
<td>(reactants and catalysts can exert control over the dynamics and structure of reactions)</td>
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<td>(local, morphogenesis of local shapes)</td>
<td>(limited number of new “shapes”, and only local changes)</td>
<td>(mechanisms of morphogenesis not fully understood)</td>
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<td>(local structures mostly, although sometimes leading to more global patterns)</td>
<td>(several new species and same laws)</td>
<td>(difficult to understand how to enforce control over ecologies of many species, at most only local centralized control)</td>
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Summary

- Self-organization and self-adaptation
  - Physical and biological metaphors are well understood and extensively studied in several computational scenarios
  - Chemical and ecological metaphors could work equally well
- Diversity and evolution
  - Physical and biological metaphors are not directly suitable
  - Chemical and biological metaphors accommodate them
- Control
  - Physical and chemical systems are well understood, and tools exists to control them
  - Less control and understanding of bio/ecological dynamics
- None of the metaphors fully support the requirements
  - A new synthesis may be needed
The SAPERE Approach

- SAPERE “Self-aware Pervasive Service Ecosystems”
  - EU FP7 FET Project Funded in the “Self-awareness in autonomic systems” initiatives
  - Starting October 1st 2010, lasting 3 years
  - UNIMORE (Coordinator), UNIBO, UniGeneve, UniStAndrews, UniLinz
  - Funding: 2.3M Euro

- Starts from the proposed reference architecture
  - To define and implement a fully-fledged framework for nature-inspired pervasive service ecosystems
  - Trying to define a new general-purpose synthesis out of existing natural metaphors
SAPERE Specific Objectives

- Both of a scientific and technological nature
- All of which revolving around the unifying reference architecture
Key Expected Results of SAPERE

- A novel model and methodology to support the development of complex nature-inspired service ecosystems in open and dynamic pervasive scenarios
  - Centered around a new nature-inspired synthesis
  - Chemical + elements of bio- and physically inspired metaphors
- Release of a uniform set of:
  - Self-* algorithms for service/data composition and aggregation (in the form of libraries)
  - Algorithms and tools for distributed management of contextual-knowledge, to enforce present- and future-adaptability in the ecosystem
- A novel middleware for pervasive computing scenarios (Open Source)
  - Integrating the stated algorithms in the form of libraries
- A set of released innovative applications:
  - Showcased on the “Ecosystem of Displays” testbed
Key Envisioned Impacts

- **Scientific**
  - New foundation for distributed pervasive service systems
  - New approach to autonomic → from feedback loops to inherent systemic self-awareness and holistic adaptivity
- **Technological**
  - Deconstructing middleware
  - New basis for open and dynamic service platforms
- **Social**
  - Innovative for-all and fitted-to-everybody pervasive services
  - Much easier to be deployed and used
  - New light into the idea of “collective intelligence”
- **Economic**
  - Easier for small actors to enter the ecosystem with highest values
  - Lower management costs for services and devices
  - Better exploitation of resources due to self-adaptivity and self-awareness
  - Towards “eternally adaptive pervasive service ecosystems”
Conclusions

- Nature-inspired service ecosystem have the potential to represent a sound approach to face, once and for all, several technical and social challenges for future and emerging network and service scenario
  - i.e., for the realization of self-aware adaptive service ecosystems
- However, there is still a lot of foundational and experimental research to do before even understanding if such an approach can be applicable and effective
- SAPERE will experience this at the level of models, algorithms, middleware, and applications, and relying on a sound reference architecture