Multi-Agent Coordination

– Introduction to Multi-Agent Systems –

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Outline

Ongoing trends in Digital World

Context

- **Ubiquity**
  - Continual reduction in cost of computing capability introduces processing power into places and devices that would have once been uneconomic
  - **How to deal with systems composed of 10^{10} processors?**
- **Interconnection**
  - Computer systems today no longer stand alone, but are networked into large distributed systems
  - **How to consider computing as primarily a process of interaction?**
- **Intelligence**
  - Tasks that are automated and executed by computers are becoming even more complex, addressing more and more cognitive levels
  - **How to use Artificial Intelligence models and techniques within Ubiquitous and Interconnected systems?**
- **Delegation – Authority sharing**
  - Control is delegated partly or totally to computers, even in safety critical tasks
  - **How to ensure the behavior of systems with or without humans in the decision loop?**

Applications

Context

Modern software applications have to deal with:

- an increasing level of **autonomy** of **interconnected** software systems
- the **integration** of countless systems that are not known in advance
- complex scenarios in which **adaptive** and **open** teams of intelligent autonomous entities and robots will interact with humans and everyday objects, all interconnected

Applications

Context

- Strong inter-connection of physical, digital and social worlds
- Increasing automation of socio-cognitive tasks
- to build long-lived socio-technical and cognitive systems
- Openness, distribution, no centralization, intensive use of knowledge

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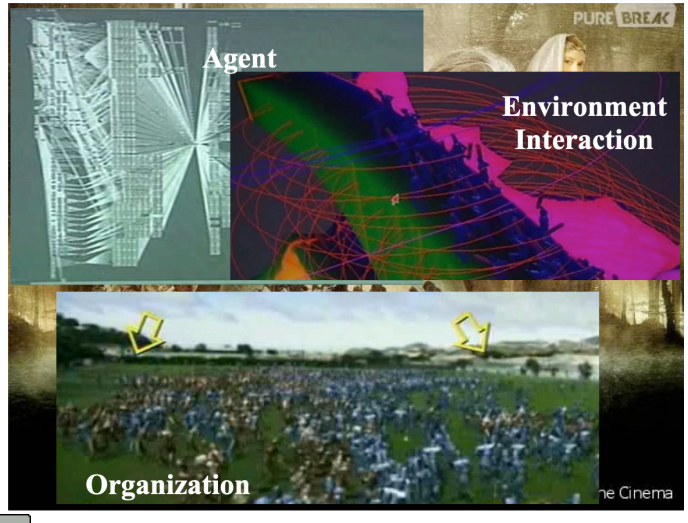

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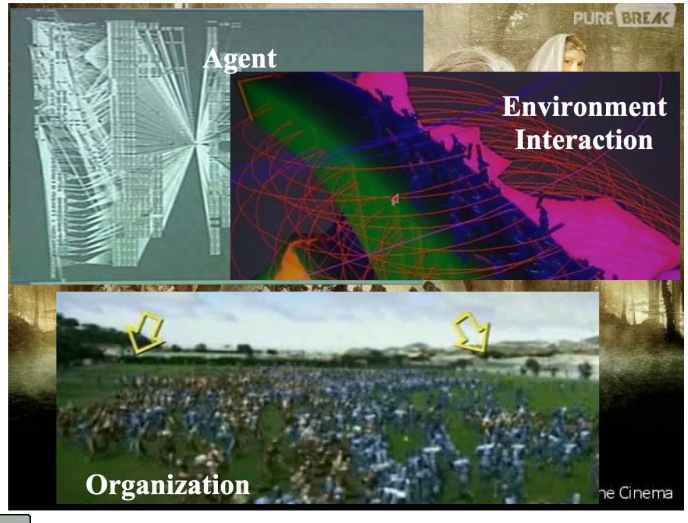

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Outline

Autonomy

Challenges

- In the Artificial Intelligence context considered in this course, **autonomy** is the property of a system that is:
  - embedding and enacting some **decision making**
  - in order to perform tasks for which it has been designed
  - by interacting with some environment and adapting to it
- An autonomous system is able to act without human intervention even if their task could involve assisting and interacting with human users

Distribution & Heterogeneity

Challenges

- Complex systems are generally **distributed** over multiple computing hosts and devices
- They do not share memory, and typically communicate through the internet

- Being defined by different developers, in different contexts, these systems are also **heterogeneous**
  - Different components can have different characteristics and capabilities, and can run on various hardware and software stacks
  - Representation and reasoning on various types of knowledge (e.g. expert knowledge, policy/norms, legal knowledge)
- **Interoperability** is a mandatory requirement for such systems

Decentralization

Challenges

- Complex systems cannot be designed as a single entity centralizing all the decision making
  - Impossibility or impracticability of conveying in a single point all the information needed for the decision making,
  - Impossibility of processing them in an effective way using a single decision maker,
  - Need to apply different decisions concurrently in different parts of a distributed environment.
- Such systems require to adopt a full **decentralization** of both **data** and **control** with multiple loci of control and decision making, each one dealing with a portion of the whole environment and problem.
- **Coordination** strategies are then needed to manage the dependencies among the **loosely coupled** decision makers in order to achieve the objectives of the system as a whole.

Openness & Long Liveness

Challenges

- A full model of the structure and dynamics of complex systems cannot be defined at design time.
  - the set of their elements is highly dynamic (i.e., the participants, whether humans or software entities, may enter and leave the system while it runs)
  - the number and behaviors of their components cannot be controlled at design time
  - the full business logic to be executed at runtime cannot be fully specified at design time.
- Being **open** and **long-running** systems, **situated** in contexts that evolve over time, **flexibility** and **adaptation** are mandatory properties.

Interpretability & Explainability

Challenges

- **Interpretability** aims at describing the internals of the elements of a system for humans in an understandable way.
- **Explainability** should explain the models that are already understandable, in order to obtain the trust of users or to generate new insights about the reasons for their decisions, subsequently answering the question of why a specific decision has been made by the model.
- Interpretability and explainability are considered as critical factors contributing to humans' trust in complex autonomous systems.
- Just like autonomy, they can be defined at different levels, spanning from designers to programmers, and users.

Outline

Multi-Agent System

- A suitable paradigm for modeling and engineering such complex systems while tackling with their challenges
- A multi-agent system is an organized ensemble of autonomous goal-oriented entities called **agents**, communicating with each other and **interacting** within an **environment**.
  - At the individual level, each agent can have its own goals and tasks to pursue autonomously by deciding what actions to do.
  - As an ensemble, agents typically need to coordinate, cooperate and regulate in order to achieve the global objective of the MAS as a whole, as an **organization**.

Multi-Agent System

Definitions

An organisation of autonomous agents interacting with each other within a shared environment

- **Agents**: autonomous entities able to react to events while pro-actively defining goals and directing actions to achieve them
  $\rightsquigarrow$ (soft/hard)ware, (coarse/small)-grain, (hetero/homo)geneous,
- **Environment**: shared medium providing the surrounding conditions for agents to exist and act (e.g. comm. and coord. infra., topology of spatial domain, support of an action model)
  $\rightsquigarrow$ virtual/physical, passive/active, deterministic or not, ...
- **Interaction**: motor of dynamic and interoperability in the MAS
  $\rightsquigarrow$ direct communicative / indirect actions through the environment
- **Organisation**: abstractions to declare and make accessible to agents their expected collective structure and functioning in a shared environment (e.g. coordination and regulation activities)
  $\rightsquigarrow$ pre-defined/emergent, static/adaptive, open/closed, ...

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MAS **is more than** a simple set of agents

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Principles

Definitions

Multi-agent system principles

- **Distribution** of knowledge, resources, reasoning/decision capabilities
- **Decentralisation** of control, authority (loosely coupled agents)
- **Coordination** & **Regulation** models and mechanisms to install coordination & regulate the autonomous agents
- Flexible interlacement of **emergent**, **social order**, **normative** functioning

Agent principles

- **Situated**, **Reactive**, **Pro-Active**, **Social** & **Organization-aware** entities
- **Autonomy**: agents may exhibit activities that are not the one expected by the other agents in the system
- **Delegation**: agents may receive some control over their activities

Outline

Short History

Positioning

- 1973 – **Distributed Artificial Intelligence** (DAI)
  - *Hearsay II* (1973) – blackboard architecture for speech recognition –, *Actor Languages* (1973) – messages as control structures –, *Beings* (1975), *Society of Minds* (1978)
- 1980 – **Agents in the Artificial Intelligence Area**
  - *Contract Net* (1980) – interaction protocol for delegation –, *DVMT* (1984) – Distributed Interpretation –, *Subsumption architecture* (1986) – Reactive Robots –, *MACE* (1987) – multi-agent platforms –
- 1990 – **Autonomous Agents & Multi-Agent Systems**
  - Agents in other domains: Personal Assistants, Avatars, Mobile Agents, Reactive Agents, ..., Artificial Life, Economic Agents, ...
  - Self-organisation, Emergence, Agent Oriented Software Engineering,
  - **1st ICMAS Conference in 1996**
- 2000 – **Agents in the large**
  - Application domains addressing Web, Ambient Computing, Internet of Things, ...
  - Interactions, Organisations, Environment, Reputation & trust, Game Theory, ...
  - **Since 2002, AAMAS Conferences**

Inter-disciplinary Domain

Positioning

- Direct Inheritance from:
  - Programming, Object Oriented Programming (e.g. encapsulation, modularity, reusability)
  - Artificial Intelligence (e.g. symbolic reasoning, logic)
  - Distributed Systems, Parallelism, Concurrent Programming
- and from:
  - Complex System (physics, ..., ethology, ecology, ...)
  - Artificial Life, Neural networks, ...,
  - Social Psychology, Sociology, Activity Theory, Economy, ...

Multi-Agent System vs Objects System

Positioning

- An agent, as an object, encapsulates a state and behaviors

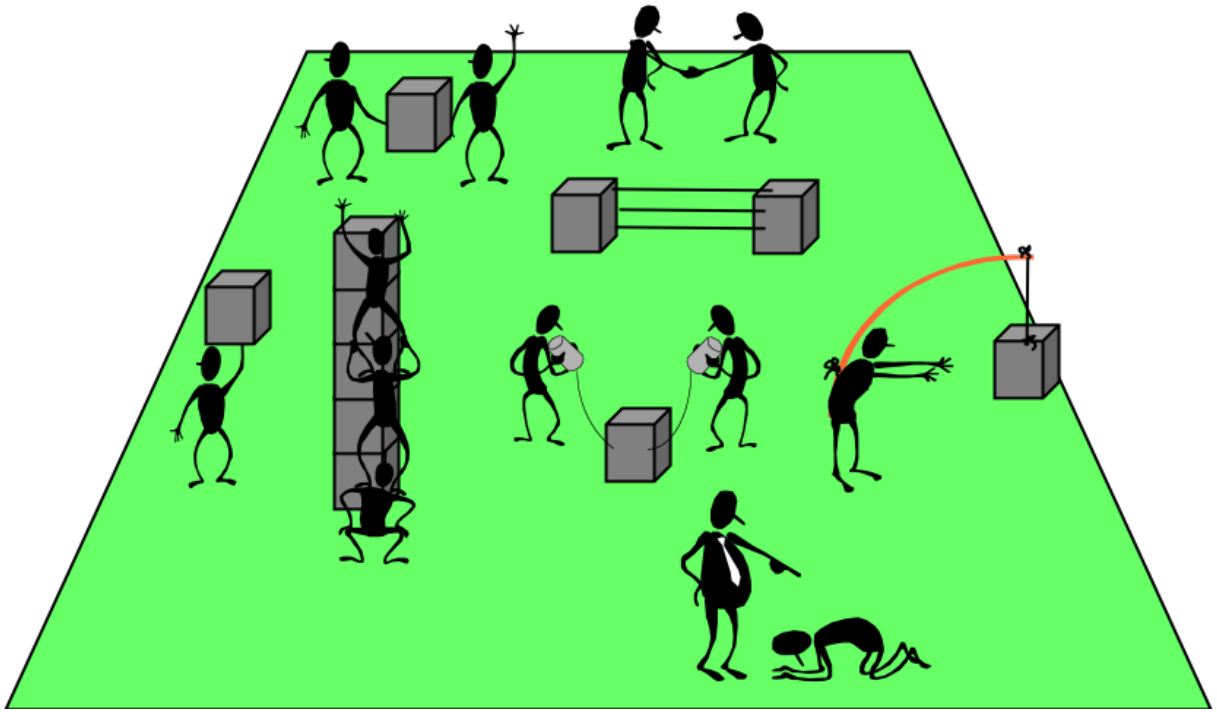
BUT

- An agent encapsulates its control over its behaviors; an object has only control over its state
- Interactions among agents have a broader scope than the method calls between objects
- Interactions consist in goals, plans, actions, hypothesis exchanges
- An agent may have different control cycles (data-directed, goal-directed, interaction-directed, ...)
- A MAS has several control flows. An Object system has, a priori, only one control flow

Autonomous Agents in a Multi-Agent World vs Artificial Intelligence Program

Positioning

- **Mono-Agent** perspective of AI is pushed away
- Agents are **situated** in a dynamic world and **interact** with other agents
- Knowledge, Goals, Actions gain a **social** dimension



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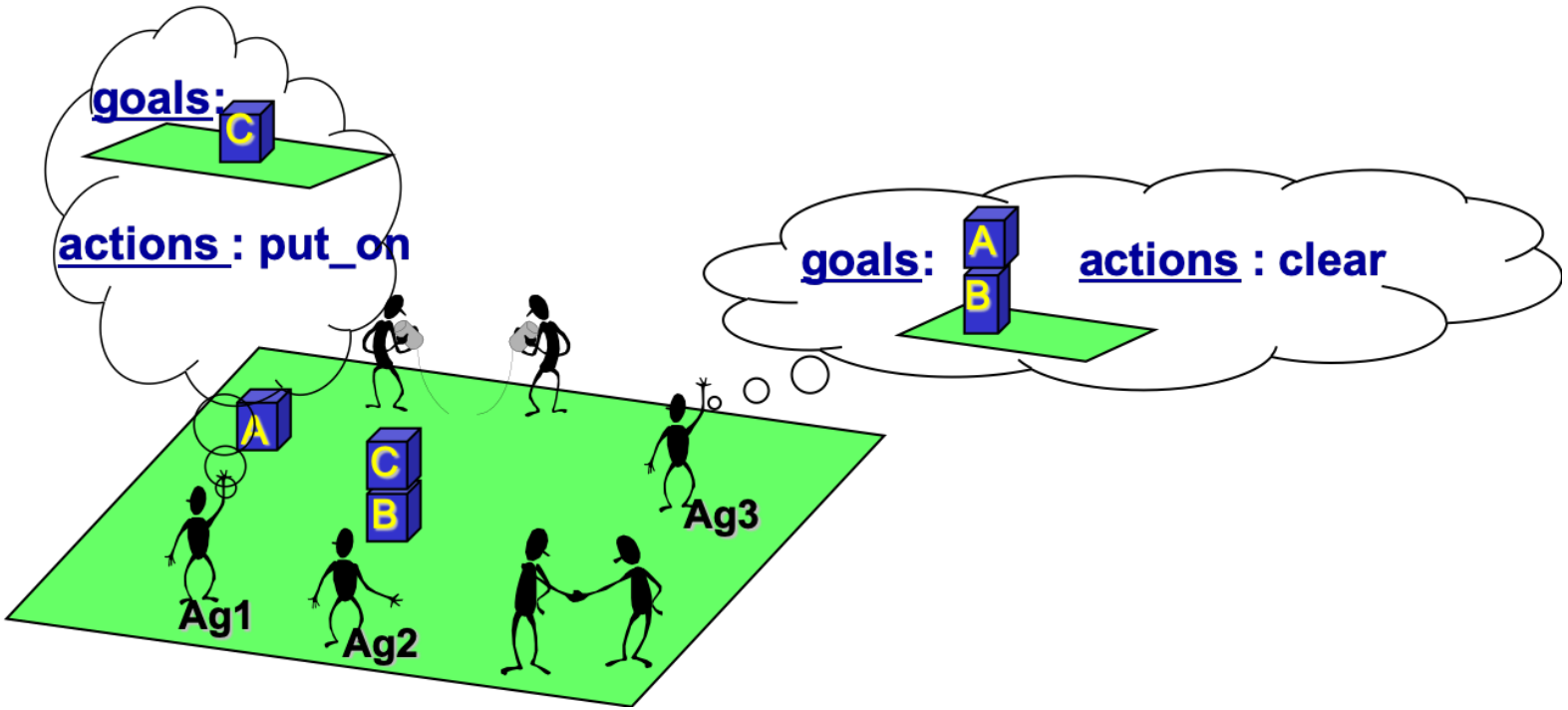

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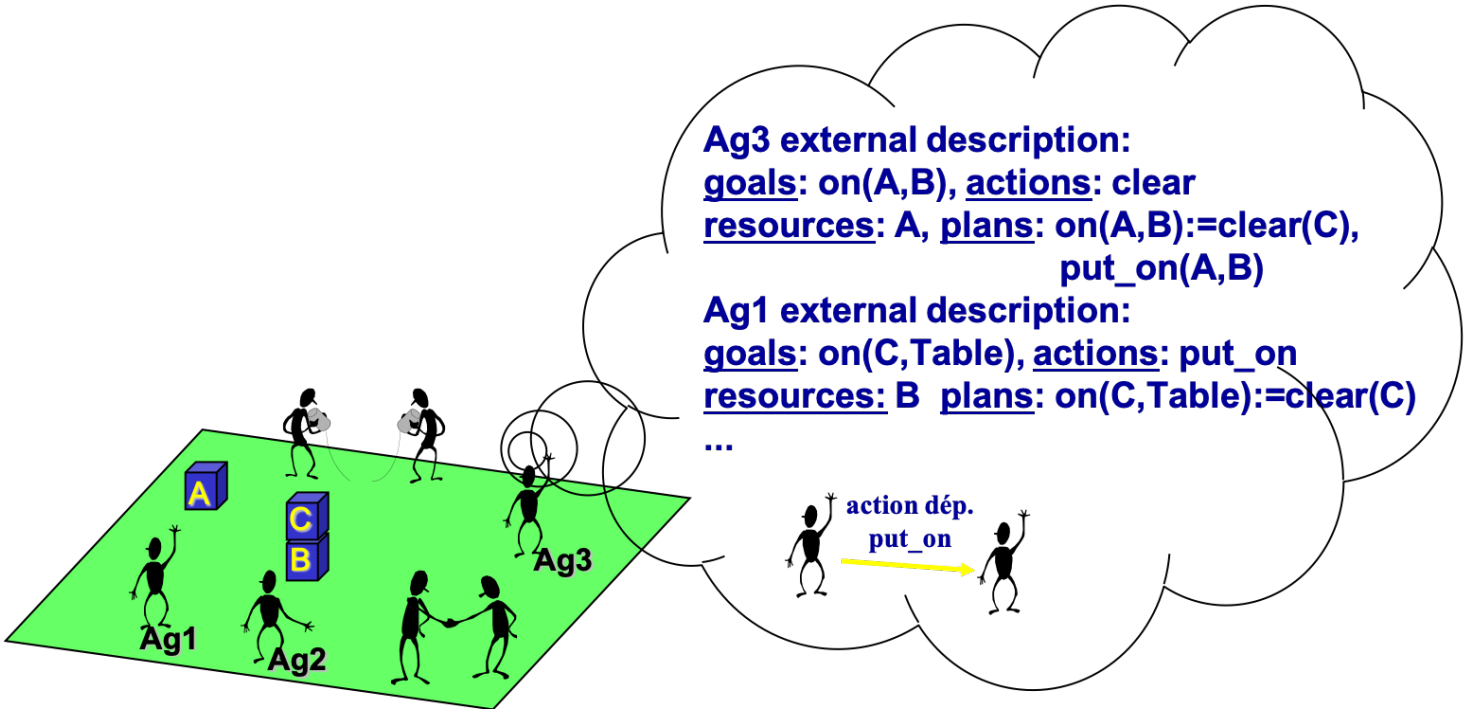

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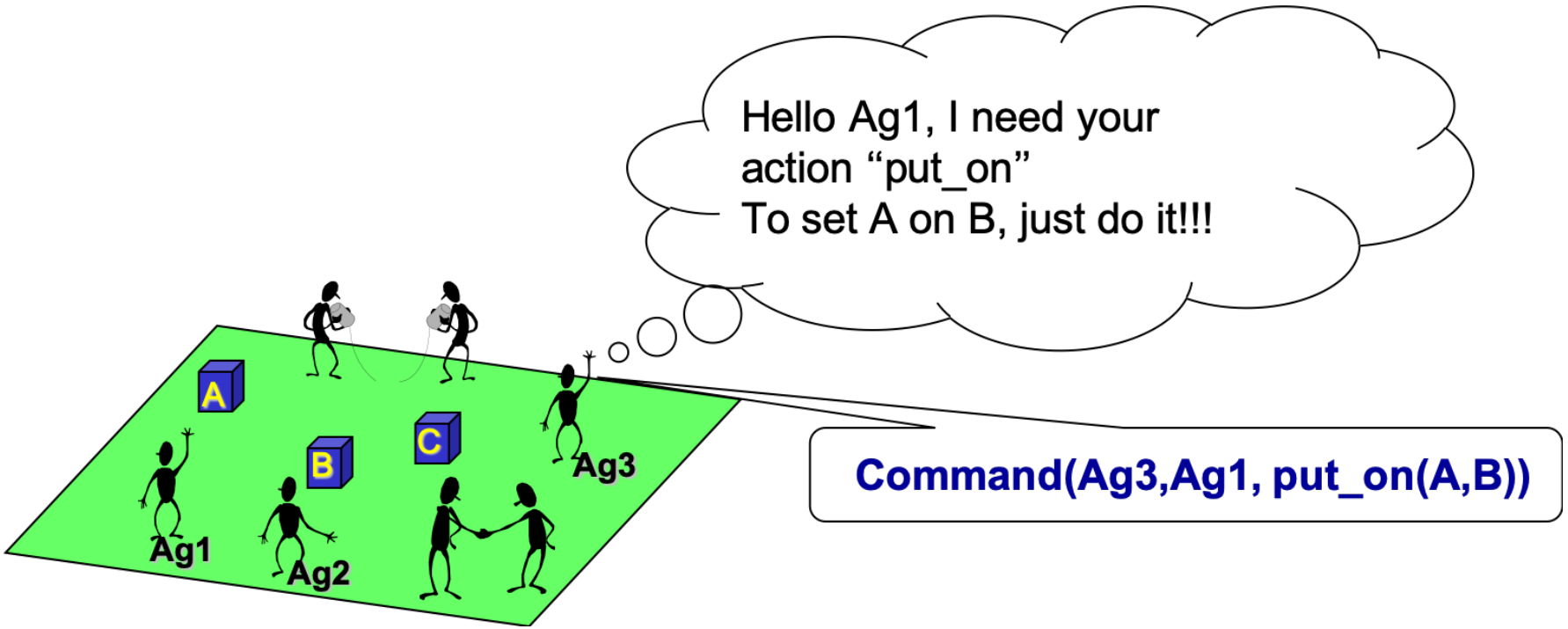


Multi-Agent System vs Distributed System

Positioning

- Both take into account interconnection and distribution

BUT

- In MAS, Interconnection and Distribution are concerned by:
  - The requirement of taking into account the agent autonomy, of developing synchronization and coordination mechanisms to coordinate their activities
  - The requirement to represent and take into account the user interests
  - The requirement to cooperate and to achieve agreements (or even compete) with other systems aiming at achieving their own interests

Topics of Interests

Positioning

- **Agent Theories and Models**: Belief-Desire-Intention theories and models, Cognitive models, Models of emotions, ...
- **Communication and Argumentation**: Commitments, Communication languages and protocols, Speech act theory, Argumentation-based dialogue and protocols, ...
- **Agent Cooperation**: Biologically-inspired approaches and methods, Collective intelligence, Distributed problem solving, Teamwork, team formation, teamwork analysis, Coalition formation, ...
- **Knowledge Representation and Reasoning**: Ontologies for agents, Reasoning in agent-based systems, Single and multi-agent planning and scheduling, Reasoning about action, plans and change, Reasoning about knowledge, beliefs, goals and norms, ...
- **Agent Societies and Societal issues**: Organizations and institutions, Social networks, Socio-technical systems, Normative systems, Values in MAS (privacy, safety, security, transparency, ...), Coordination and control models for multiagent systems, Trust and reputation, Policy, regulation and legislation, Self-organization
- ...

$\rightsquigarrow$ large set of concepts and approaches have been produced in the domain

Outline

Action Domains

- **Integration and Engineering of Intelligent Systems**
  - Integration of intelligent applications, with humans, organizations and the physical world
  - Making them interoperate, interact, cooperate in a flexible and consistent manner with each other
- **Problem Solving**
  - Modeling and solving problems by cooperation between local solvers
  - Installing top-down and/or bottom-up (emergent) solving process
- **Multi-Agent Based Simulation**
  - Modeling and reproducing complex phenomena of interacting entities in the real world in order to understand or to explain their behavior

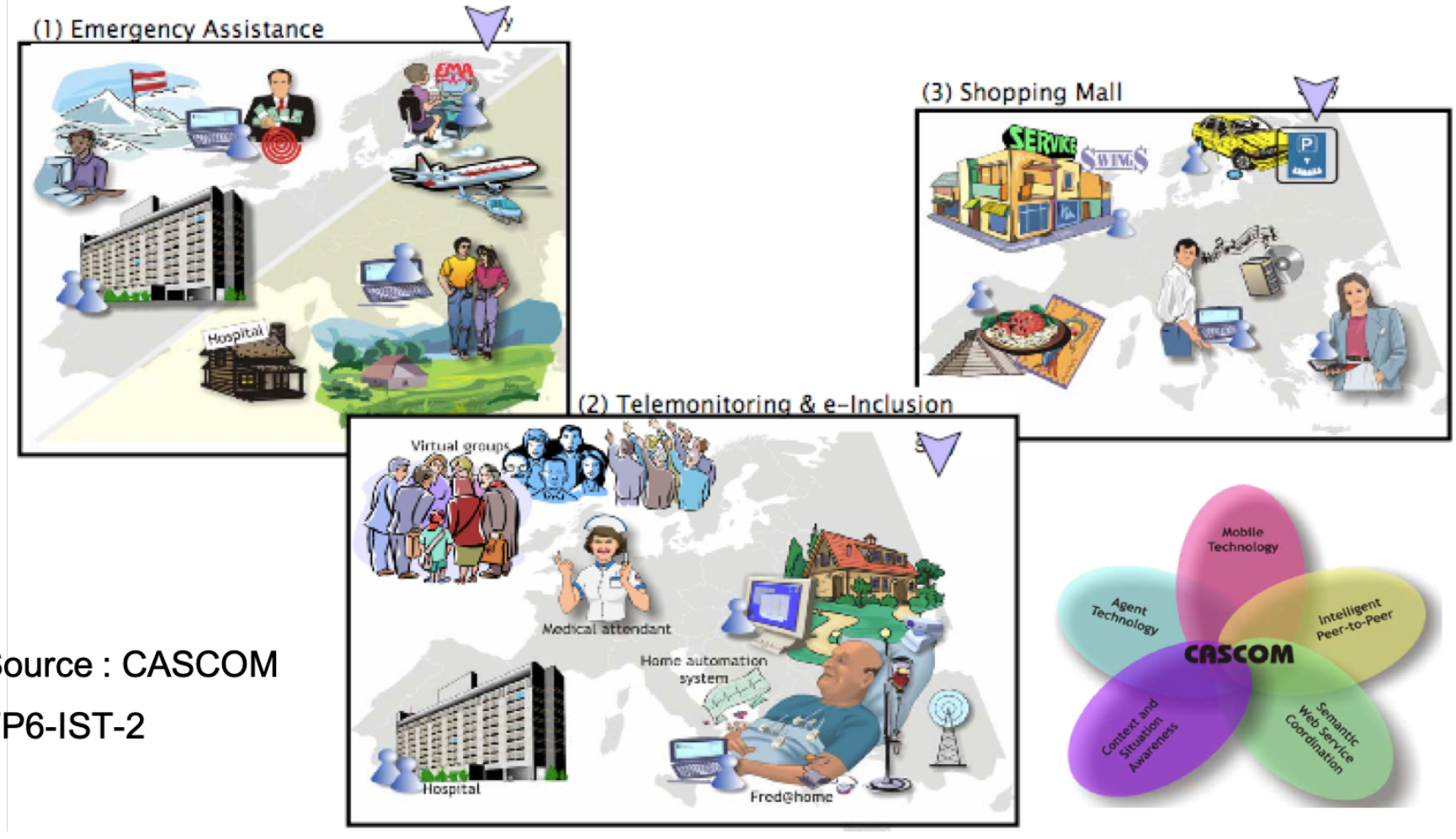
Integration and Engineering of Intelligent Systems

Action Domains

- Properties of the targeted applications:
  - Absence of monolithic vision
  - Incremental development, by different teams
  - Multi-* (sites, expertise, domains, points of view, decisions, goals, motivations, . . .)
  - Continuous execution and adaptation
  - Human-Centred
- Main requirements:
  - Openness, permeability, scalability in size or structure
  - Distribution, no central control, control and interaction are local
  - Autonomous Interacting entities loosely coupled with others or applications
  - Knowledge Intensive processing and sharing
  - Users may delegate their decisions to the application

Open and Decentralized AI Systems

Action Domains– Integration and Engineering of Intelligent Systems



Source : CASCOM

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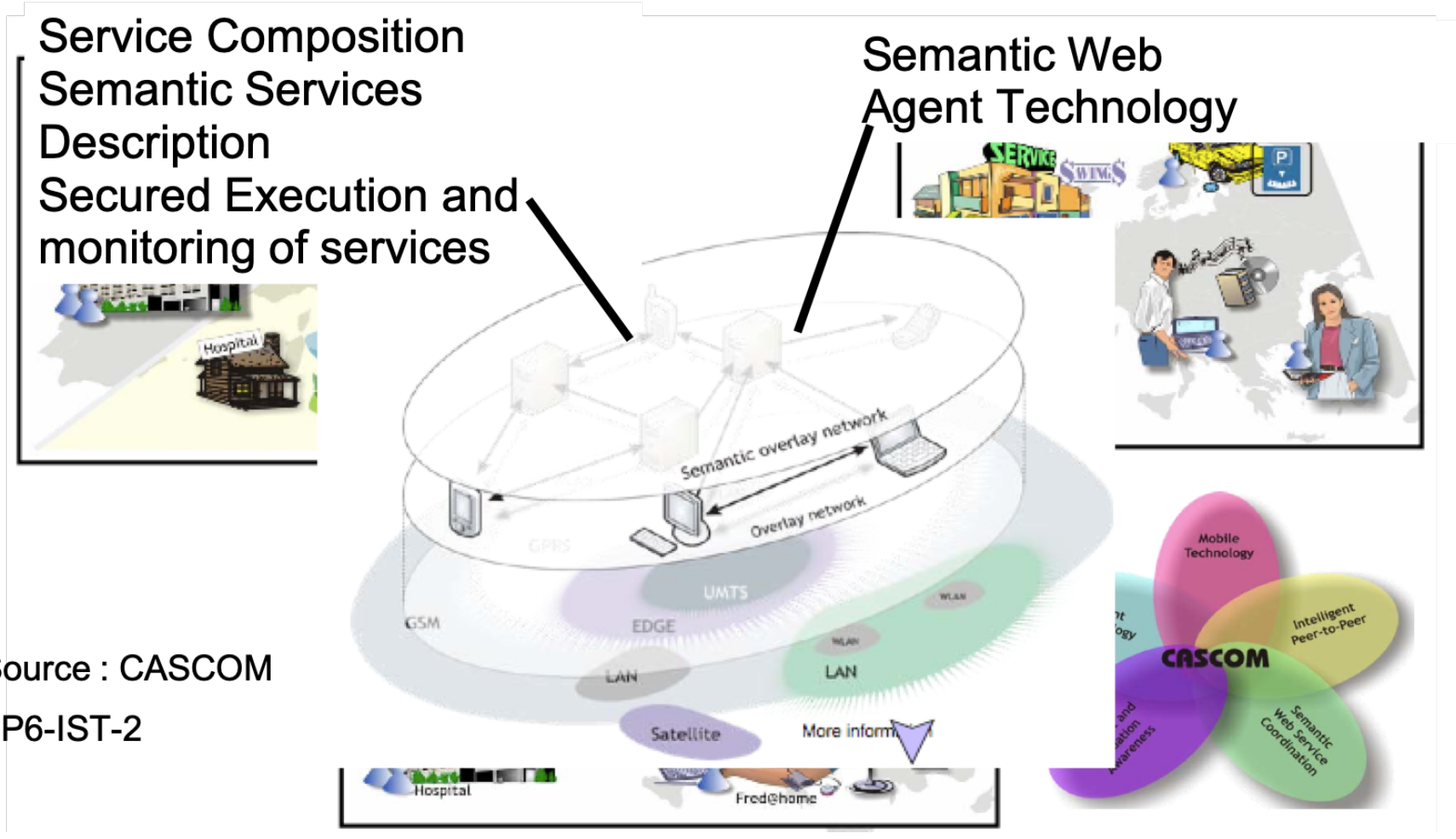
Open and Decentralized AI Systems

Action Domains– Integration and Engineering of Intelligent Systems



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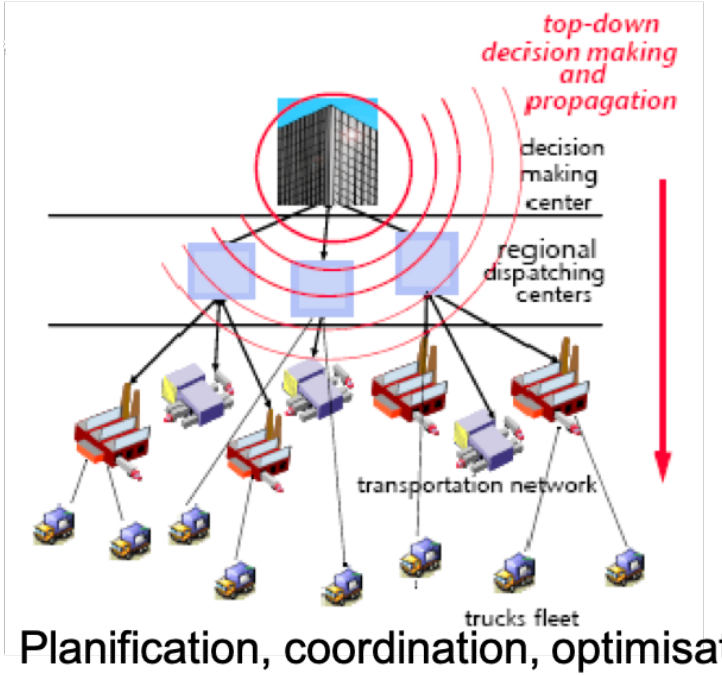
Logistics

Action Domains– Integration and Engineering of Intelligent Systems



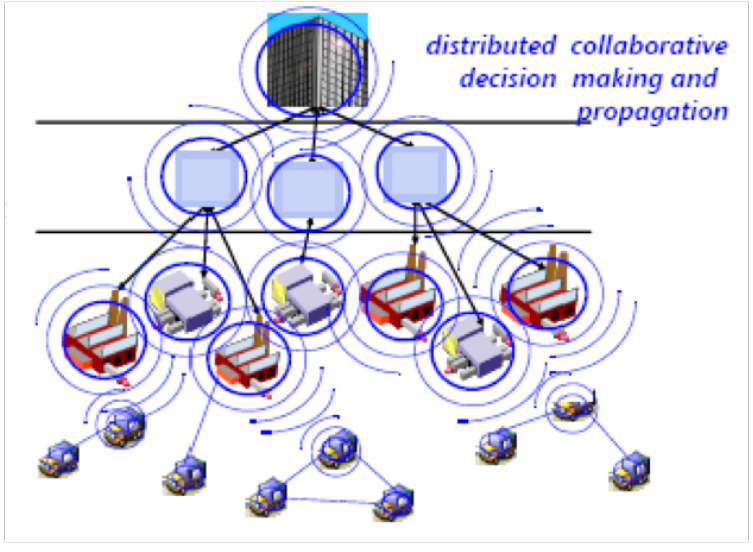
Planification, coordination, optimisation along a top-down approach *:*

- *Centralised collect and processing of informations and events*
- Propagation of plans & decisions
- No realtime decision.

Source Whitestein Agent Technology Conference 2004

Planification, coordination, optimisation along a bottom-up approach

- Responsibility Delegation
- Communication between the nodes
- Real time detection & reaction to changes
- Adaptation to changes & continuous optimisatio



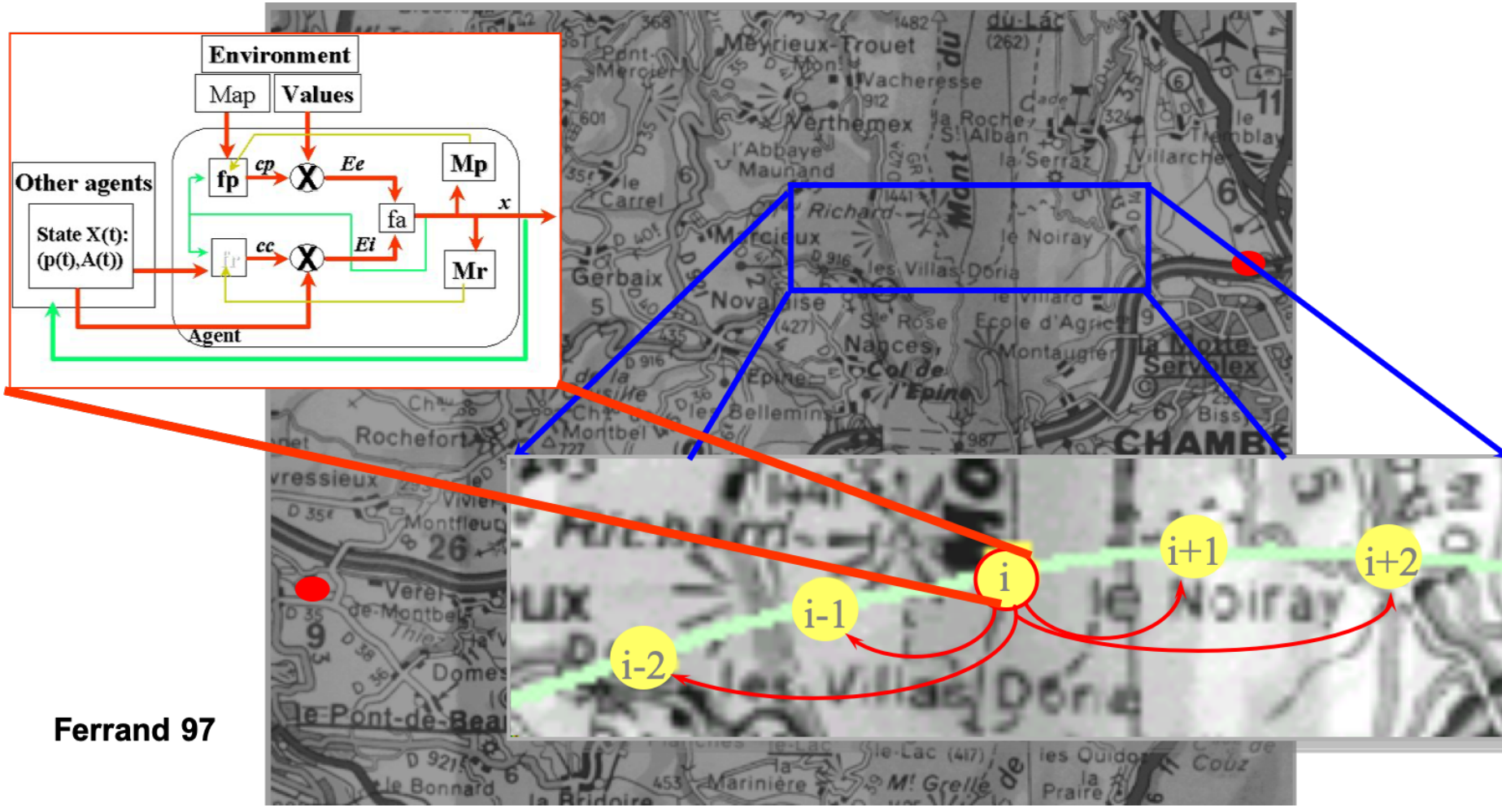
Problem Solving

Action Domains

- Properties of the targeted applications:
  - Absence of global strategies, of global solving method
  - Interaction between local strategies, between local solving methods
  - Solution is the result of the interaction between local processes (points of view, decisions, goals, motivations, . . .)
  - Continuous functioning and evolution
- Main requirements:
  - Decentralisation, local control, interactions
  - Openness, permeability, scalability in size or structure
  - Shared and dynamic environment
  - Emergence of the solution

Territory Aided Management

Action Domains– Problem Solving

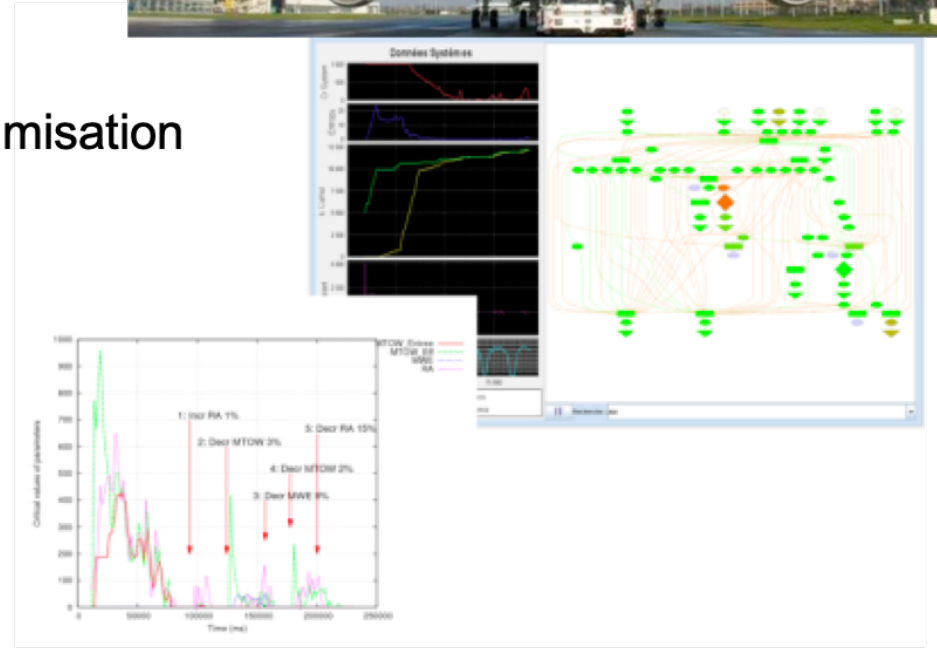


Ferrand 97

Complex System Aided Design

Action Domains– Problem Solving

- Multi-Disciplinary Simulation & optimisation (ID4CS)
- Design of complex system :
  - Multi-level, Multi-disciplinary
  - Multi-methods
  - Multi-objectives, Multi-attributes
  - Uncertainty
- Cooperation methods between optimisation technics,
- Management of uncertainty



- Multi-* problem solving
- Emergence

Multi-Agent Based Simulation

Action Domains

- Properties of the targeted applications:
  - Individu centred, absence of global strategies, of global model
  - Interaction between local models, local strategies
  - Global behaviour is the result of the interaction between local processes (points of view, decisions, goals, motivations, . . .)
  - Continuous functioning and evolution
- Main requirements:
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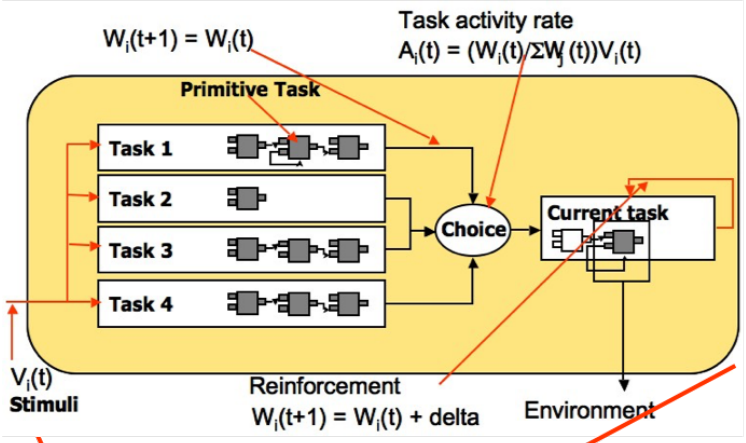
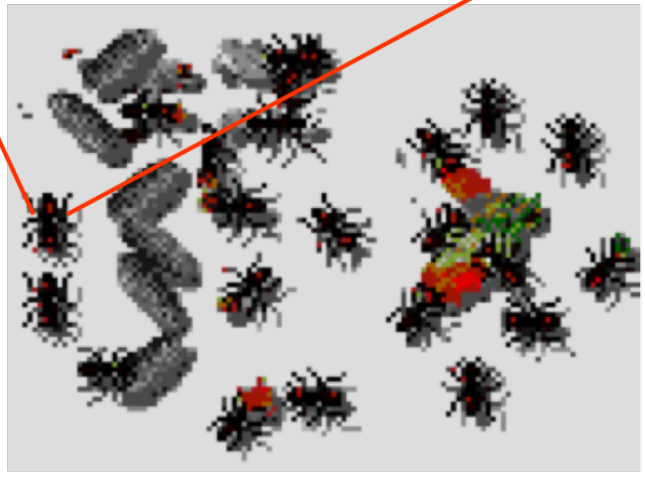
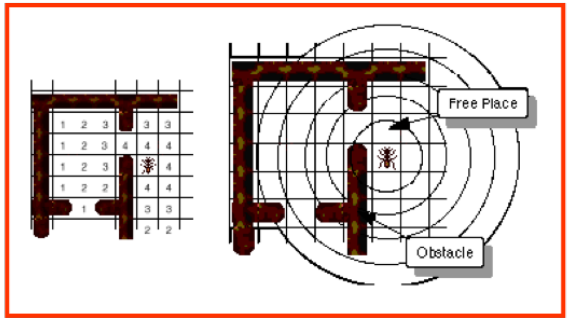
Social Ant Simulation

Action Domains– Multi-Agent Based Simulation







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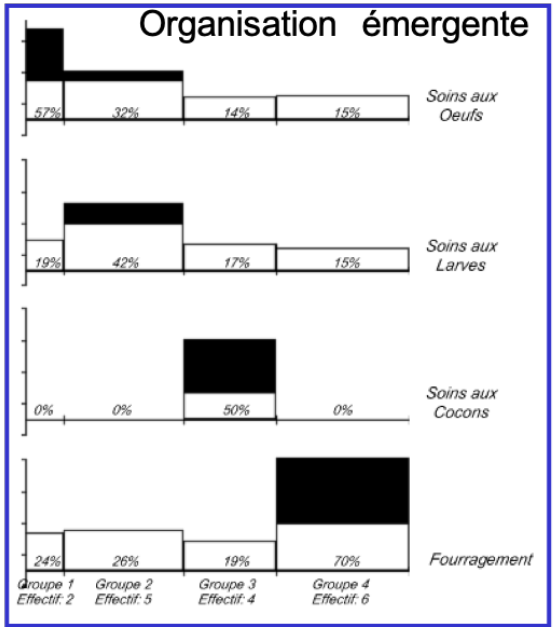
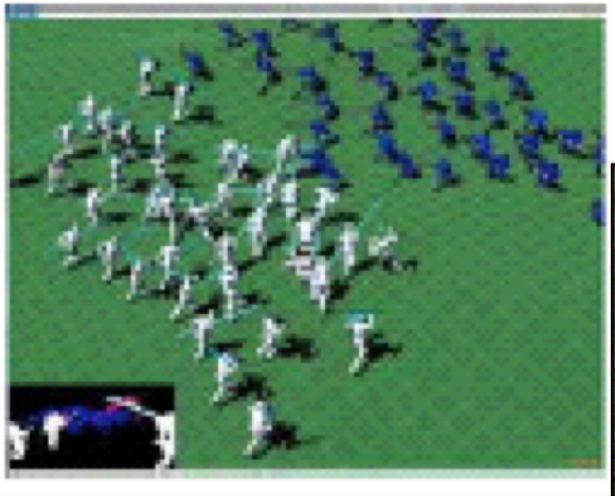


Entertainment

Action Domains– Multi-Agent Based Simulation

http://www.massivesoftware.com/

The Return of the King (2003)
The Two Towers (2002)
The Fellowship of the Ring (2001)



I, Robot (2004)

Ratatouille (2007)

…, Entertainment

Conversational Zeno Robot
http://hansonrobotics.com/

Outline

Conclusion

How to **engineer** such systems?

How to **coordinate** such systems?