

# Self-Organisation & Autonomy

## An Introduction

### Autonomous Systems

Sistemi Autonomi

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- 1 Basic Concepts & History
  - Self-Organisation
  - Emergence
  - Self-Organisation vs. Emergence
  
- 2 Self-Organisation and Emergence in Natural Systems
  - Physical Systems
  - Biological Systems
  - Social Systems
  
- 3 Self-Organisation and Emergence in Artificial Systems
  - Algorithms and Computing
  - Robotics and Automated Vehicles
  
- 4 Self-Organising Systems & Autonomy: Issues



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  - Self-Organisation
    - Emergence
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- 2 Self-Organisation and Emergence in Natural Systems
  - Physical Systems
  - Biological Systems
  - Social Systems
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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

# History of Self-Organisation

- The idea of the spontaneous creation of organisation can be traced back to René Descartes
- According to the literature, the first occurrence of the term Self-Organisation is due to a 1947 paper by W. Ross Ashby [Ashby, 1947]
- Ashby defined a system to be self-organising if it changed its own organisation, rather being changed from an external entity

# 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



# Self-Organisation in Sciences

- Initially ignored, the concept of self-organisation is present in almost every science of complexity, including
  - Physics
  - Chemistry
  - Biology and Ecology
  - Economics
  - Artificial Intelligence
  - Computer Science



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  - **Emergence**
  - Self-Organisation vs. Emergence
- 2 Self-Organisation and Emergence in Natural Systems
  - Physical Systems
  - Biological Systems
  - Social Systems
- 3 Self-Organisation and Emergence in Artificial Systems
  - Algorithms and Computing
  - Robotics and Automated Vehicles
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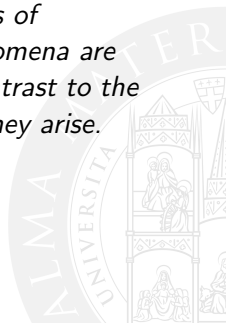
# History of Emergence

- Emergence is generally referred as the phenomenon involving global behaviours arising from local components interactions
- Although the origin of the term emergence can be traced back to Greeks, the modern meaning is due to the English philosopher G.H. Lewes (1875)
- With respect to chemical reactions, Lewes distinguished between *resultants* and *emergents*
  - Resultants are characterised only by their components, i.e. they are reducible
  - Conversely, emergents cannot be described in terms of their components

# Definition of Emergence

- We adopt the definition of emergence provided in [Goldstein, 1999]

*Emergence [..] refers to the arising of novel and coherent structures, patterns, and properties during the process of self-organisation in complex systems. Emergent phenomena are conceptualised as occurring on the macro level, in contrast to the micro-level components and processes out of which they arise.*



# Emergence vs. Holism

- Emergence is often, and imprecisely, explained resorting to *holism*
- Holism is a theory summarisable by the sentence *the whole is more than the sum of the parts*
- While it is true that an emergent pattern cannot be reduced to the behaviour of the individual components, emergence is a more comprehensive concept



# Properties of Emergent Phenomena

**Novelty** — unpredictability from low-level components

**Coherence** — a sense of identity maintained over time

**Macro-level** — emergence happens at an higher-level w.r.t. to components

**Dynamism** — arise over time, not pre-given

**Ostensive** — recognised by its manifestation



# Requirements for Emergency

Emergence can be exhibited by systems meeting the following requirements

**Non-linearity** — interactions should be non-linear and are typically represented as feedback-loops

**Self-organisation** — the ability to self-regulate and adapt the behaviour

**Beyond equilibrium** — non interested in a final state but on system dynamics

**Attractors** — dynamically stable working state



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# Definition of Self-Organisation

## Widespread definition of Self-Organisation by [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.

- It is evident that the authors conceive self-organisation as the source of emergence
- This tendency of combining emergence and self-organisation is quite common in biological sciences
- In the literature there is plenty of misleading definitions of self-organisation and emergence [De Wolf and Holvoet, 2005]

# Natural Systems

- Natural systems can be broadly as [Di Marzo Serugendo et al., 2011]
  - Physical systems
  - Biological systems
  - Social systems





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  - Robotics and Automated Vehicles
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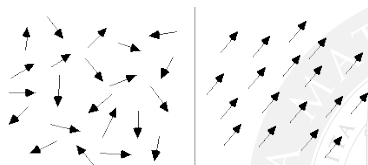
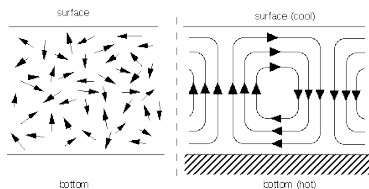


# Physics and Chemistry

- Theory of self-organisation were originally developed within Physics and Chemistry
- Most typical features included
  - when the system reaches a *critical threshold*, an immediate change occurs
  - self-organisation can be observed *globally*

# Self-Organisation of Matter

- Self-organisation of matter happens in several fashion
- In magnetisation, spins spontaneously align themselves in order to repel each other, producing an overall strong field
- Bénard cells is a phenomena of convection where molecules arrange themselves in regular patterns because of the temperature gradient

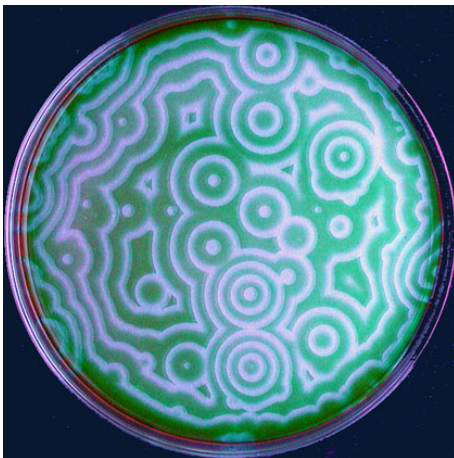


*The left hand side picture displays Bénard cells.  
The right hand side picture displays magnetisation.*

# Belousov-Zhabotinsky Reaction I

- Discovered by Belousov in the 1950s and later refined by Zhabotinsky, BZ reactions are a typical example of far-from-equilibrium system
- Mixing chemical reactants in proper quantities, the solution colour or patterns tend to oscillate
- These solutions are referred as *chemical oscillators*
- There have been discovered several reactions behaving as oscillators

# Belousov-Zhabotinsky Reaction II



A snapshot of the Belousov-Zhabotinsky reaction.

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  - Physical Systems
  - **Biological Systems**
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# Living Organisms

- Self-organisation is a common phenomenon in subsystems of living organisms
- An important field in biological research is the determination of invariants in the evolution of living organisms
  - in particular the spontaneous appearance of order in living complex systems due to self-organisation
- In biological research, self-organisation essentially means the global emergence of a particular behaviour or feature that cannot be reduced to the properties of individual system's components—such as molecules and cells

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# Prey-Predator Systems

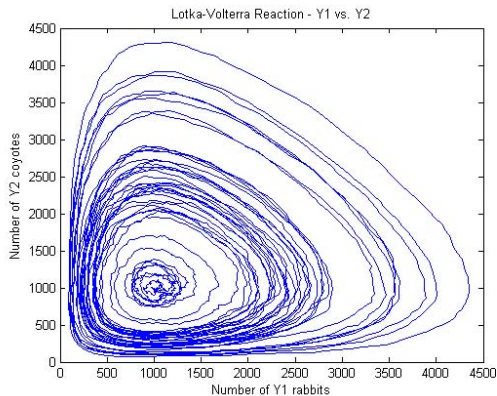
- The evolution of a prey-predator systems leads to interesting dynamics
- These dynamics have been encoded in the Lotka-Volterra equation [Solé and Bascompte, 2006]
- Depending on the parameters values the system may evolve either to overpopulation, extinction or periodical evolution
- The Lotka-Volterra equation:

$$\frac{dx}{dt} = x(\alpha - \beta y)$$

$$\frac{dy}{dt} = -y(\gamma - \delta x)$$



# Lotka-Volterra Equation



A chart depicting the state space defined by the Lotka-Volterra equation.

# Synchronised Flashing in Fireflies I

- Some species of fireflies have been reported of being able to synchronise their flashing [Camazine et al., 2001]
- Synchronous flashing is produced by male during mating
- This synchronisation behaviour is reproducible using simple rules
  - Start counting cyclically
  - When perceive a flash, flash and restart counting

## Synchronised Flashing in Fireflies II



A photo of fireflies flashing synchronously.



# Schools of Fishes



School of fishes exhibit coordinated swimming: this behaviour can be simulated based on speed, orientation, and distance perception [Camazine et al., 2001].

# Flocks of Birds



The picture displays a flock of geese: this behaviour can be simulated based on speed, orientation, and distance perception [Camazine et al., 2001].

# 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

# Termites Nest in South Africa



The picture displays the *Macrotermes michealseni* termite mound of southern Africa.



# Stigmergy

- In a famous 1959 paper [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.*

# Elements of Stigmergy

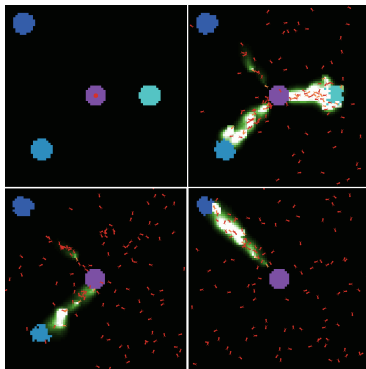
- Nowadays, stigmergy refers to a set of coordination mechanisms mediated by the environment
- For instance in ant colonies, chemical substances, namely *pheromone*, act as markers for specific activities
- E.g. the ant trails between food source and nest reflect the spatial concentration of pheromone in the environment

# Trail Formation in Ant Colonies



The picture food foraging ants. When carrying food, ants lay pheromone, adaptively establishing a path between food source and the nest. When sensing pheromone, ants follow the trail to reach the food source.

# Simulating Food Foraging

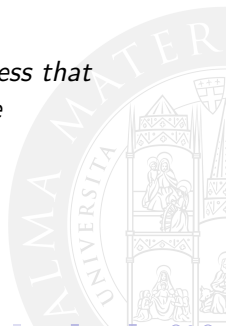


The snapshots display a simulation of food foraging ants featuring a nest and three food sources. Ants find the shortest path to each source and consume first the closer sources. When no longer reinforced, the pheromone eventually evaporates.

# 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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  - Biological Systems
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# Swarm Intelligence

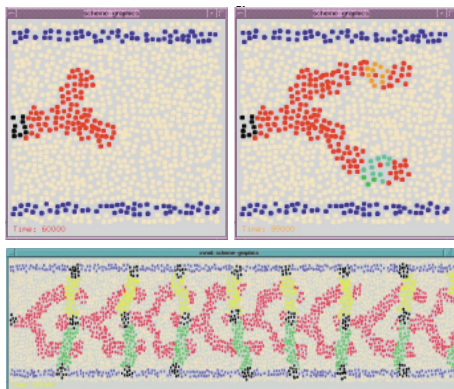
- *Swarm intelligence* is a problem solving approach inspired by collective behaviours displayed by social insects [Bonabeau et al., 1999, Bonabeau and Théraulaz, 2000]
- It is not a uniform theory, rather a collection of mechanisms found in natural systems having applications to artificial systems
- Applications of Swarm Intelligence include a variety of problems such as task allocation, routing, synchronisation, sorting
- In Swarm Intelligence, the most successful initiative is Ant Colony Optimisation

# ACO: Ant Colony Optimisation

- ACO [Dorigo and Stützle, 2004] is a population-based metaheuristic that can be used to find approximate solutions to difficult optimisation problems
- A set of software agents called artificial ants search for good solutions to a given optimisation problem
- To apply ACO, the optimisation problem is transformed into the problem of finding the best path on a weighted graph
- ACO provided solutions to problems such as VRP-Vehicle Routing Problem, TSP-Travelling Salesman Problem and packet routing in telecommunication networks



# Amorphous Computing



An amorphous computing [Abelson et al., 2000] medium is a system of irregularly placed, asynchronous, locally interacting identical computing elements.

# Autonomic Computing

- An industry driven research field initiated by IBM [Kephart and Chess, 2003], mostly motivated by increasing costs in systems maintenance
- Basic idea: applying self-organising mechanisms found in human nervous system to develop more robust and adaptive systems
- Applications range from a variety of problems such as power saving, security, load balancing

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- 2 Self-Organisation and Emergence in Natural Systems
  - Physical Systems
  - Biological Systems
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# Robocup I

*By the year 2050, develop a team of fully autonomous humanoid robots that can win against the human world soccer champion team.*

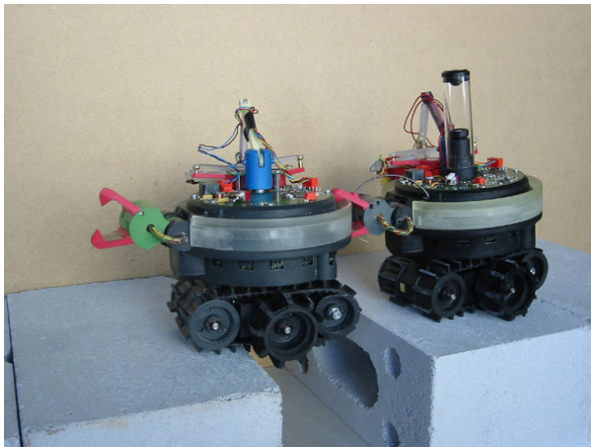
- Robocup objective consists in pushing robotics research applying the techniques developed to eventually win soccer match
- Robocup matches are organised in leagues reflecting different robot capabilities
- Self-organising techniques are extensively applied since the robots have to be autonomous rather than remotely controlled

# Robocup II



A few robots participating to Robocup 2006

# SWARM-BOTS



SWARM-BOTS [Dorigo et al., 2005] was a project funded by European Community tailored to the study of self-organisation and self-assembly of modular robots.

# AGV – Automated Guided Vehicles

- Stigmergy has been successfully applied to several deployments of Automated Guided Vehicles [Weyns et al., 2005, Sauter et al., 2005]
- Basically, the AGVs are driven by digital pheromones fields in the same way ants perform food-foraging



Various pictures of AGVs.

# Are SOS Autonomous?

- They are *adaptive*, in that they properly respond to external stimuli
- So their autonomy from the environment is *partial*
- At the same time, they are *self-governed*, in that their evolution is self-driven, in some essential sense
- So, their autonomy is evident, as well



# How Much Autonomy?

- Good design of a SOS provides the goals to be achieved, and the means to self-organise the system structure accordingly
- How much autonomy in that?
- How much autonomy from the designer, from the user, from the environment, overall?

# Autonomy of SOS Depends on...

- The models, mechanisms, and technologies adopted for implementing computational SOS
- We will explore *agents*, *MAS*, and *coordination*



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  - Physical Systems
  - Biological Systems
  - Social Systems
- 3 Self-Organisation and Emergence in Artificial Systems
  - Algorithms and Computing
  - Robotics and Automated Vehicles
- 4 Self-Organising Systems & Autonomy: Issues



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