Paradigms, Models and Technologies for Building and Simulating Self-Organising Systems

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Outline

1. Basic Concepts
2. Examples of Self-Organising Systems
3. Stigmergy & Pheromone Based Coordination
4. Related Paradigms and Scenarios
5. Methodologies & Tools
6. Conclusions

Prerequisites

- I assume you're familiar with the agent paradigm, specifically
  – the notion of agent
  – the notion of environment
  – Multi-Agent Systems related topics

Self-Organization

Basic Concepts

Intuitive Notion of Self-Organization

- *Organization* refers to relations between system parts in terms of
  - structure
  - interaction
- *Self*
  - performed by 1+ system parts
  - i.e. not imposed from external agents

Refining the Notion of Self-Organization

- Self-Organizing System
  - spontaneously increases its inner organization as the result of interaction between its parts
  - maintains its internal organization despite environment perturbations
- When driven by a single entity it is sometimes referred as *apparent* or *weak*

Self-Organization Principle

- First occurrence of the term "Self-Organization" by the psychiatrist and engineer W. Ross Ashby (1947)

"A system shows self-organization, if its behavior shows increasing redundancy with increasing length of the protocol."

- W. Ross Ashby. "Principles of the Self-Organizing Dynamic System", Journal of General Psychology (1947), #37, pages 125–128

History

- The idea of self-organization is not recent, see Descartes *Discourse on the Method* and *Le Monde* (XVII century)
- The first formulation was provided by Ashby (1947), but has been ignored for a while
- It started to spread in the 1970s when adopted by physicists
- In the meanwhile, several sciences including chemistry, biology, ecology, sociology, economy showed the existence of related phenomena

The notion of emergence

- Sometimes self-organizing systems exhibit global properties that are not *reducible* to properties of the parts
- These properties arise as the intrinsic result of the local dynamics of the system
- These properties are called emergent

Vision

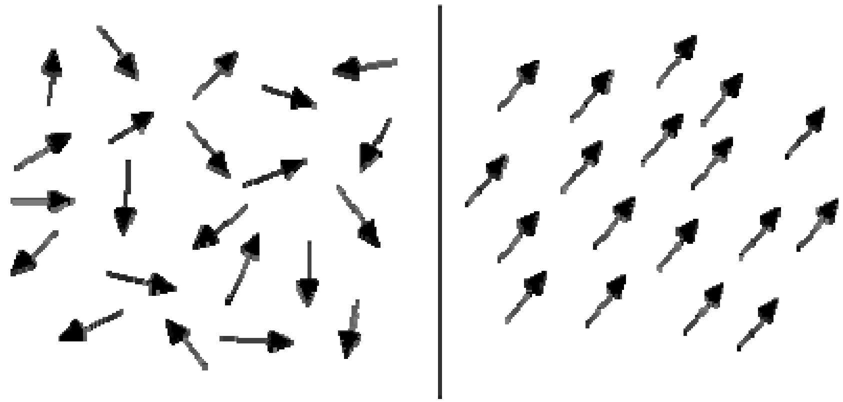
- *Every* self-organizing systems are regulated by the same set of principles and mechanisms
- The objective of the self-organization theory is
  - to find such principles!
  - understand how emergence works

Self-Organization

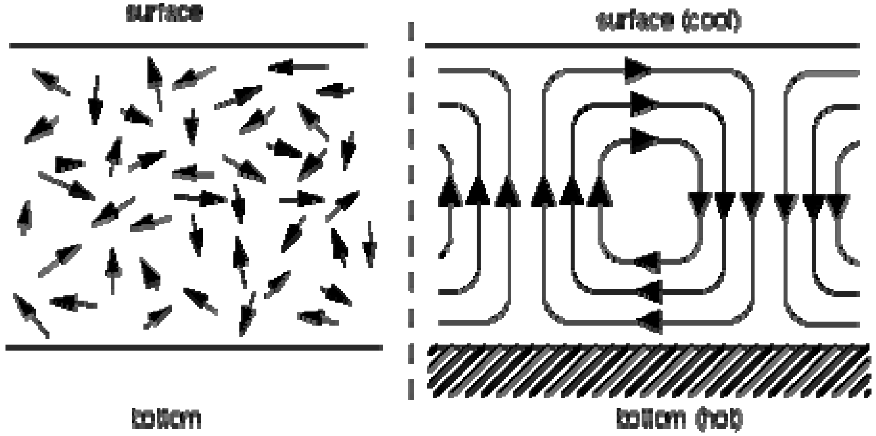
Examples of Systems

Physics: Magnetization & Bérnard Rolls

- Magnetization – spins align to external magnetic field

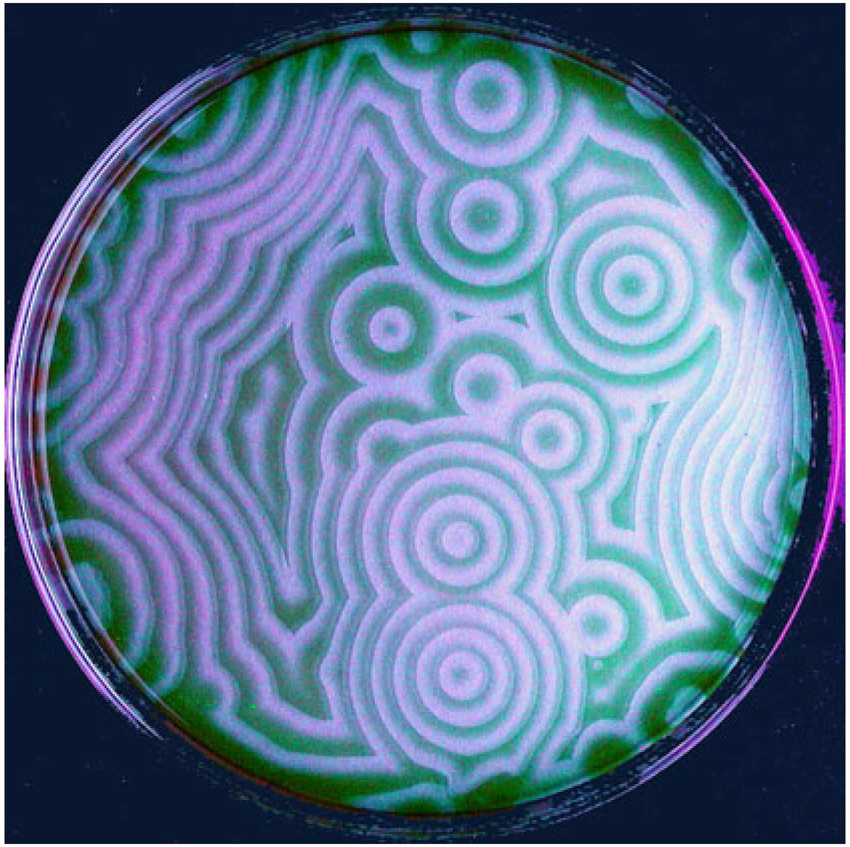


- Bérnard Rolls – molecules flow in cells due to the temperature gradient (convection)

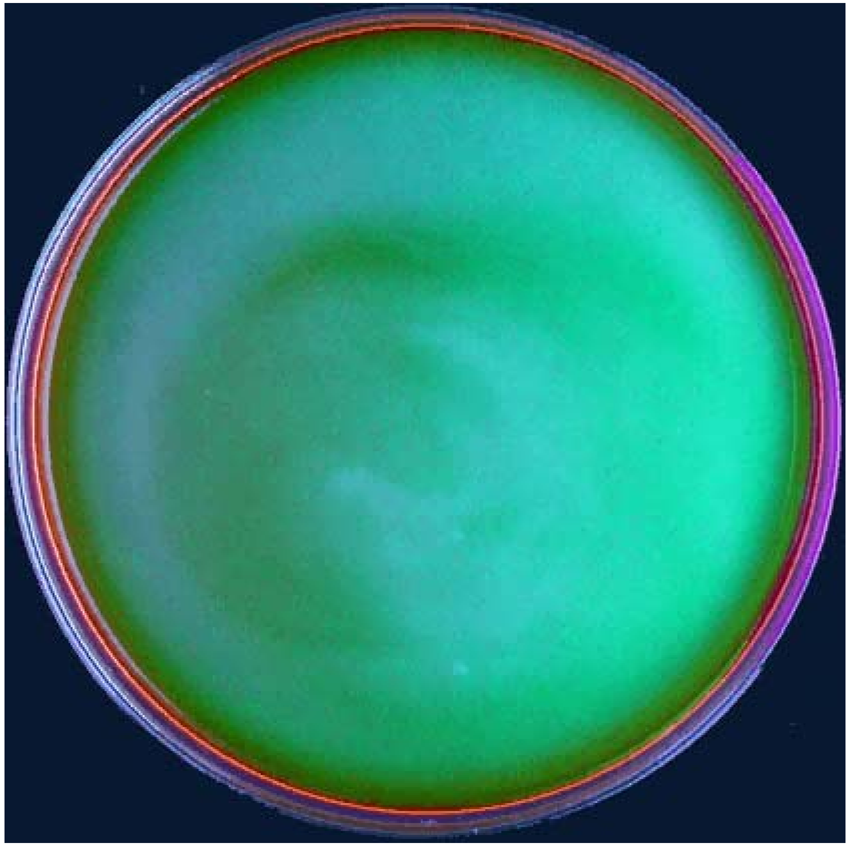


Chemistry: Belousov-Zhabotinski Reaction

- Discovered by Belousov in 1950s
- Later refined by Zhabotinski
- Chemical-oscillator
- There are several reactions showing these patterns



Chemistry: Belousov-Zhabotinski Reaction

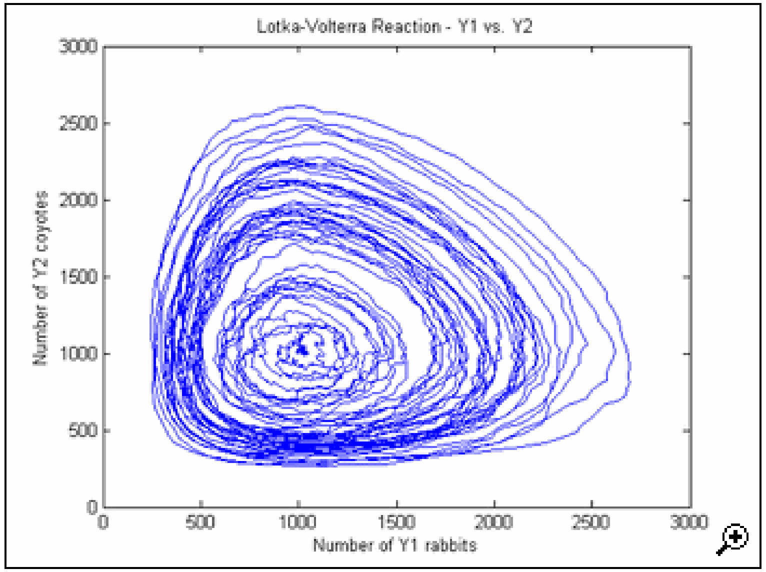


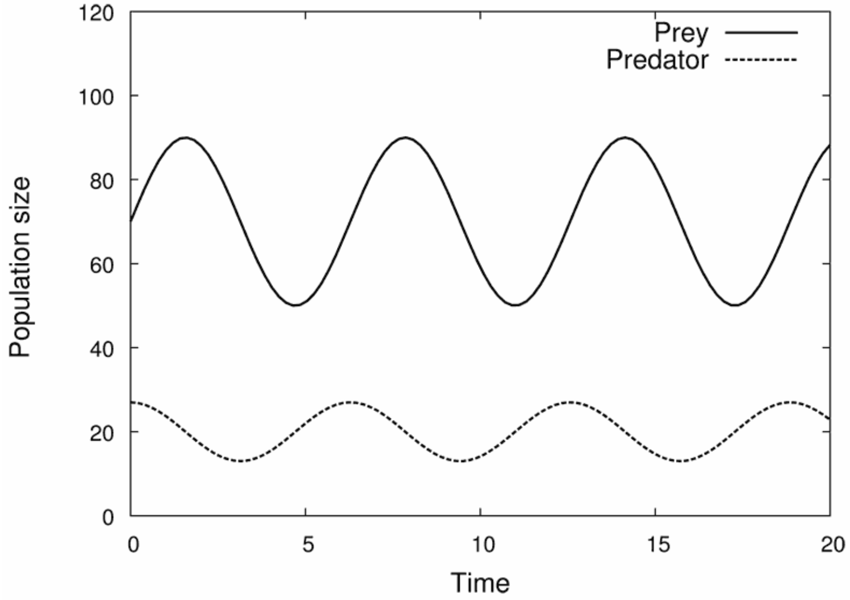
Economy: Market Equilibrium

- In free market the interaction between consumers and supplier, in terms of demand and supply, regulates prices
- Classical economy perspective, see Adam Smith
- This doesn’t apply when
  – there is an entity acting as a controller – e.g. government (external), monopoly (internal)
  – famous brands, e.g. Ferrari

Ecology: Prey-Predator System

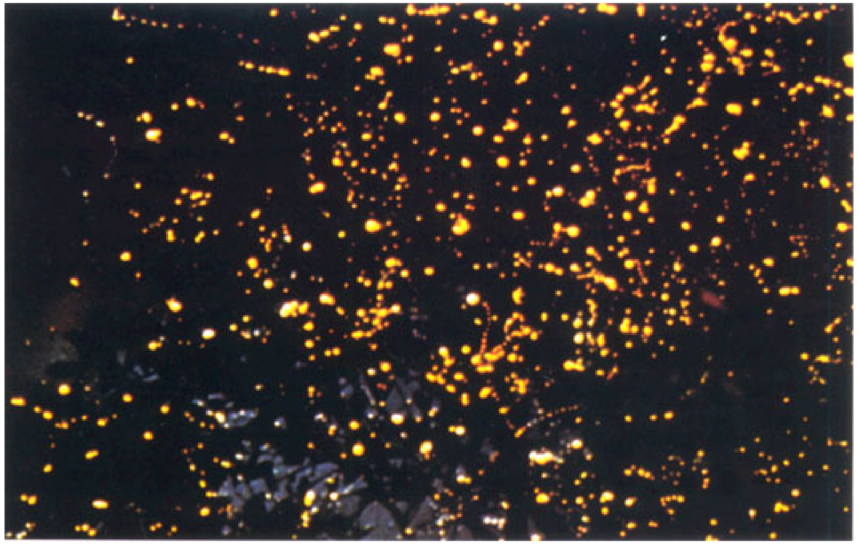
- A system composed by preys and predators evolves in a periodical fashion, self-regulating
- Modelled by the Lotka-Volterra equations





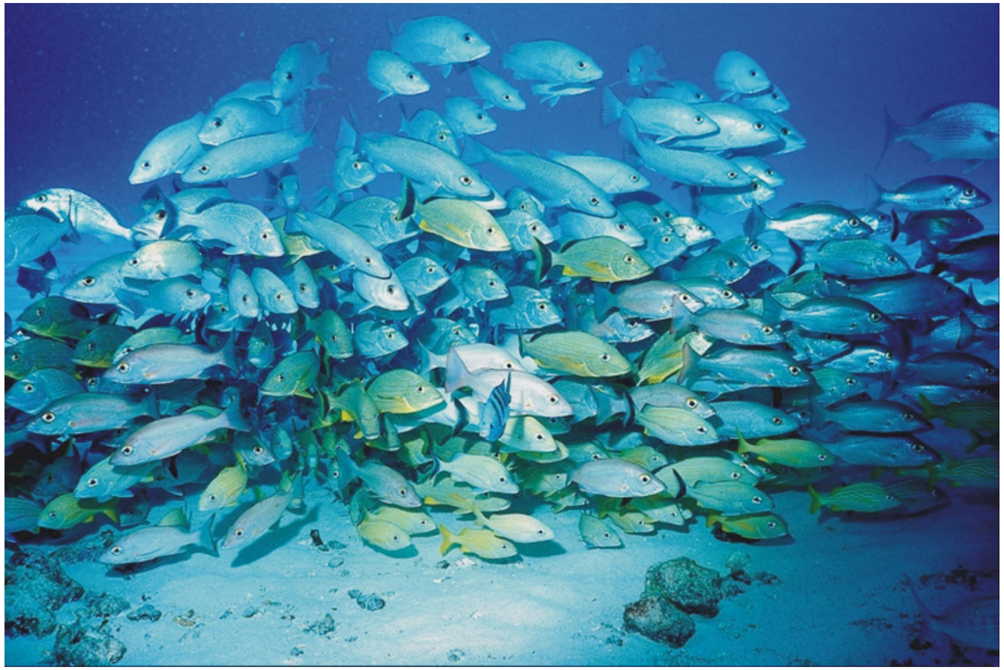
Entomology: Synchronous Flashing

- In certain species of fireflies, male insects flashes synchronously
- The behaviour can be reproduced by simple local rules
  - Count periodically
  - If see a flash, flash yourself and restart counting



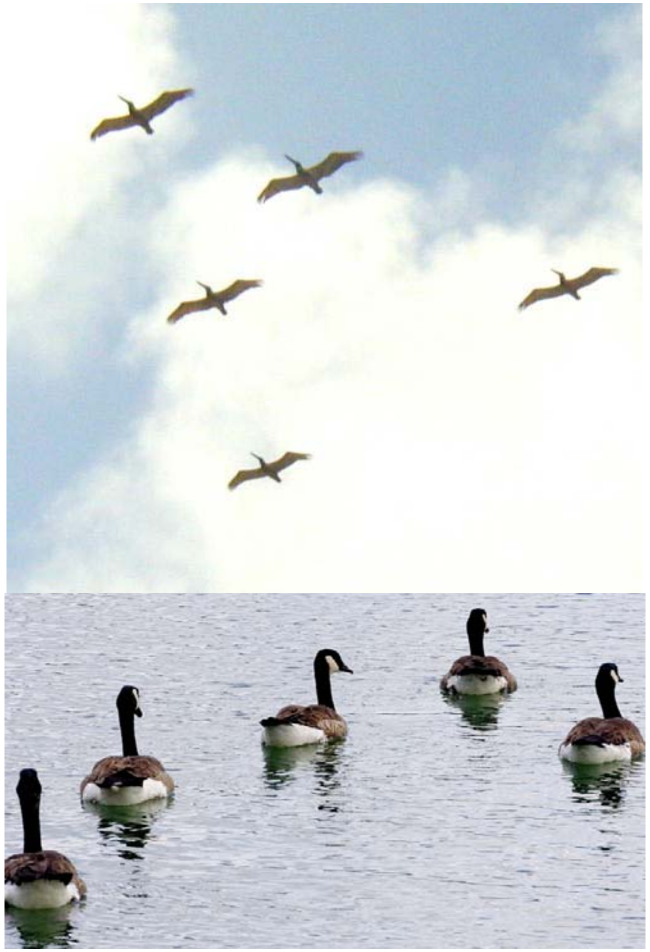
Zoology: School of Fishes

- Fishes moves in schools
- The coordinated movements can be reproduced using local rules based on speed, distance and orientation



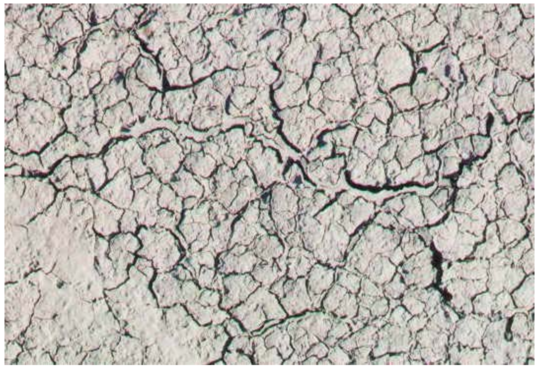
Zoology: Flocks of Birds

- Birds usually fly and swim in flocks, especially when migrating
- The coordinated movements can be reproduced using local rules based on speed, distance and orientation

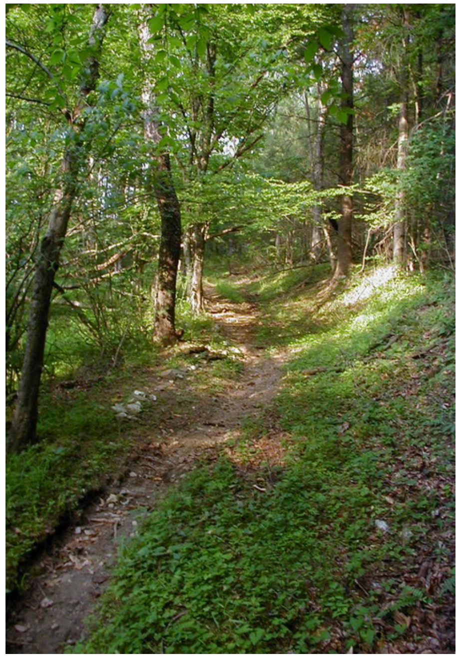


Other Examples

Camazine, S.; Deneubourg, J.; Franks, N.R.; Sneyd, J.; Theraulaz, G. & Bonabeau, E. Anderson, P.W.; Epstein, J.M.; Foley, D.K.; Levin, S.A. & Nowak, M.A. (ed.) **Self-Organization in Biological Systems** Princeton University Press, 2001



Wikipedia



Self-Organization

Stigmergy & Pheromone Based Coordination

Definition of Stigmergy

- The word *stigmergie* was coined by the French entomologist P.P. Grassé in 1959
- Stigmergy refers to the indirect coordination process observed in termites societies while building their nests

From Greek stigma+ergon

Stigma = Sign

Ergon = Work

Original Definition

"La coordination des tâches et la régulation des constructions ne dépendent pas directement des ouvriers, mais des constructions elles-mêmes. L'ouvrier ne dirige pas son travail, il est guidé par lui. C'est à cette stimulation d'un type particulier que nous donnons le nom de ***stigmergie****."*

"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**."

Grassé, P.P. (1959). La reconstruction du nid et les coordinations inter-individuelles chez Bellicositermes natalensis et Cubitermes sp. La théorie de la stigmergie: Essai d'interprétation du comportement des termites constructeurs. In Insect Sociaux., 6: 41-83, 1959.

Stigmergy: Mechanisms

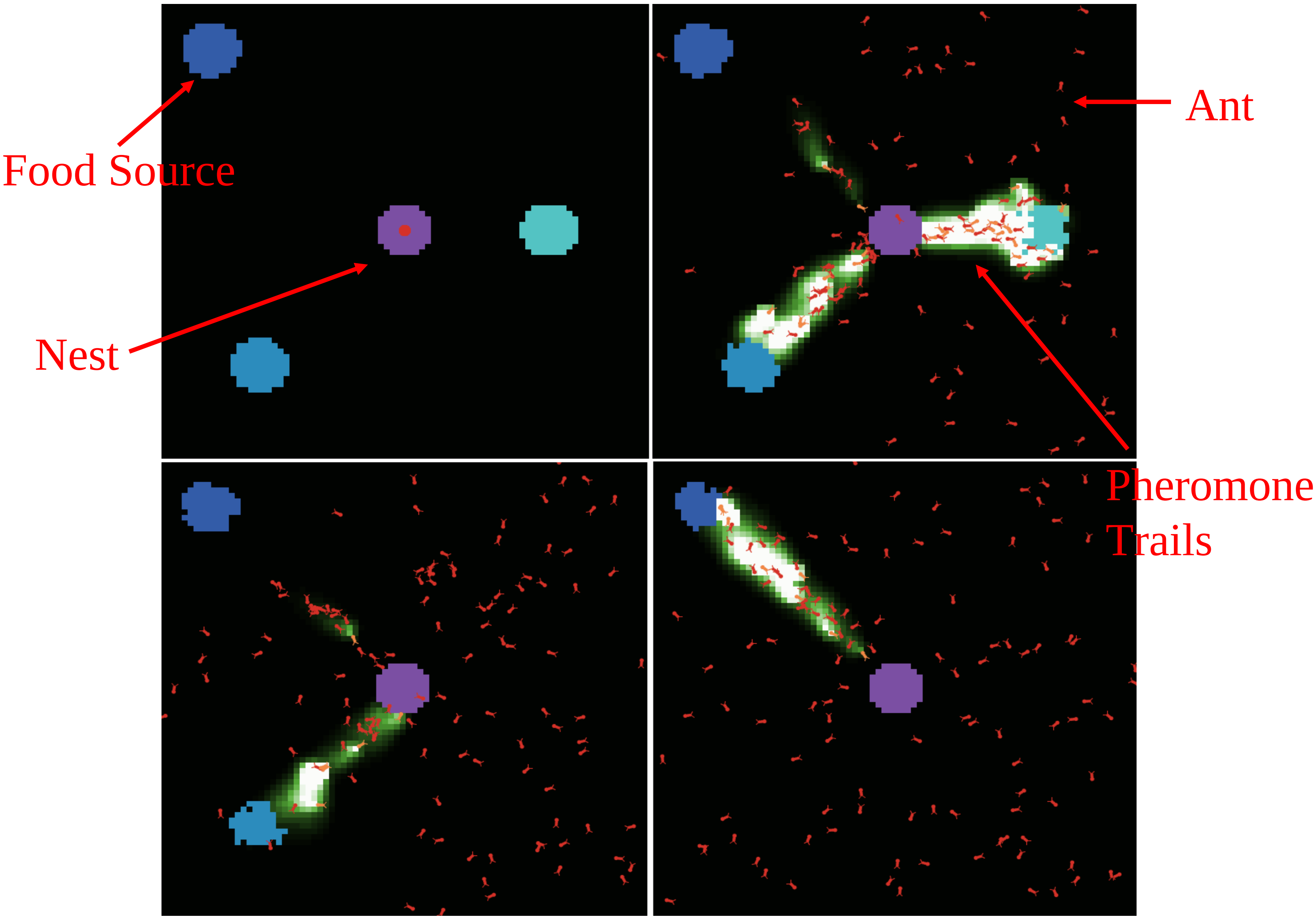
- In stigmergic coordination the agents do not interact each other directly
- The coordination process is mediated by the environment
- Agents manipulate shared artifacts in the environment enabling coordinated activities

Stigmergy: Pheromone

- A special kind of artifact is the pheromone, a chemical substance that is deposited by agents
- The environment then diffuses, evaporates and aggregates pheromone
- Agents are able to perceive the pheromone which is interpreted as a sign of “interesting” activity

Stigmergy: Ants Trails

- Ants wander randomly looking for food
- If they found food they pick it up and go back to the nest laying pheromone along the way
- If an ant sense the pheromone is not carrying food follow the pheromone trail



Simulated with NetLogo

Stigmergy: From Local to Global

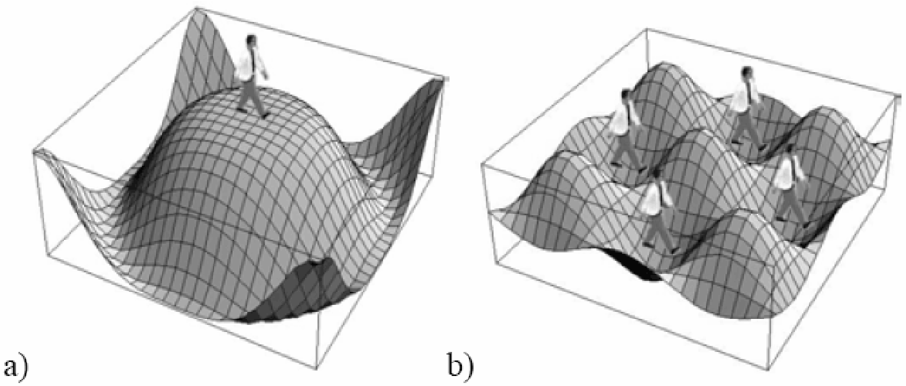
- The food foraging task (global) is achieved by applying a set of rules at the ant level (local)
- The emergent phenomena is the trail that converges to the shortest path

> *" 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."*

Mitchel Resnick. Turtles, Termites, and Traffic Jams: Explorations in Massively Parallel Microworlds. MIT Press, Cambridge, MA, USA, 1994.

Field Based Coordination

- Generalize the approach of pheromone based coordination to fields
- A field is a scalar function of time and space
- Fields are generated by entities in the systems
- Environmental fields can be manipulated in order to guide the entities to a specific location
- This approach avoids driving the entities individually



a) b)

Self-Organization

Related Paradigms and Scenarios

From an Engineering Viewpoint..

- Self-Organization offers
  1. a collection of robust algorithms to accomplish distributed tasks, tested for a lot of years :)
  2. interesting architectures for developing more autonomous, scalable and reliable artificial systems
  3. a compelling framework to handle complexity exploiting emergent behaviours

Flocking Application

Self-* Properties

- *Self-protecting* – protect itself against harmful perturbations in the environment
- *Self-healing* – recover from errors and failures without external agent's intervention
- *Self-configuring* – automatically organize its parts adapting to environment changes

Self-* Properties

- *Self-optimizing* – automatically adapt its parameters to environment changes
- *Self-assembling* – when made by physical parts, should be able to assemble itself
- *Self-localizing* – when topology is a major concern, parts must be able to identify their location within the system

MASs & SOSs

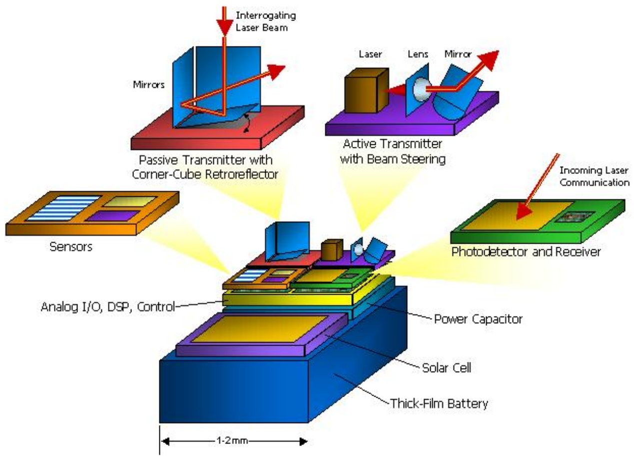
- Self-organizing systems do not require new paradigms, but naturally fit into the MAS one
  - autonomous distributed entities
  - active environment
  - interaction & coordination
- Self-organization offers
  - a framework to analyze global system dynamics
  - robust coordination strategies

Internet, Web Services & Grid Scenarios

- Massively parallel and large scale: mobility is weak… until now…
- How to coordinate services and distribute computation?
- We increasingly *depend* on these infrastructures: systems must be reliable, robust, accessible, secure…

Sensor Networks and Pervasive Computing Scenarios

- Different devices but same scenario
- Large scale systems made by mobile devices locally unreliably interconnected but able to communicate
- Computational power ranges are limited due to strong energy constraints
- Pervasive computing: PDAs, laptops, cel phones, personal ad hoc networks
- Sensor networks: computing devices equipped with sensors, SmartDust ~1 mm^3

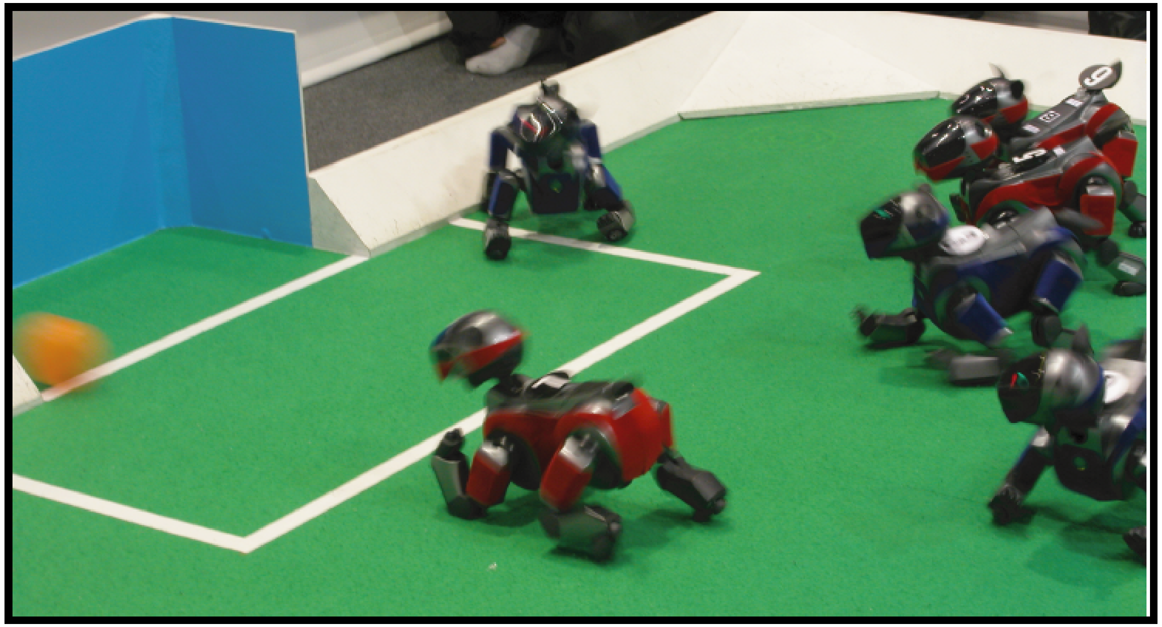


Swarm Robotics

- A field of robotics that apply principles of coordination gathered from insect societies
- The vision is about small-sized robots cooperating to achieve a common task
- Have read the Micheal Crichton’s novel Prey?

Team Robotics: RoboCup Scenario

- Robocup is an international event that promotes AI and MAS techniques applied to teams of robots playing soccer



Robotics and Lego Mindstorm

- We have at our disposal several kits of Lego Mindostorm in Cesena!
- Anyone can participate to the activities of the CELIG – CEsena Lego Interest Group!

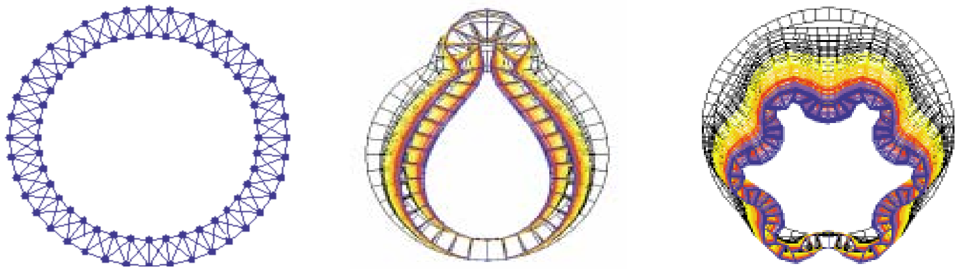
Swarm Intelligence Field

- Insects Swarms exhibit global "intelligent" behaviour that cannot be attributed to any individual entity
- Probably the most active field involving self-organization
- A collection of heuristic algorithms designed taking inspiration from collective behaviour of social insects
- As in Operations Research problems are solved offline
- Problems solved in that way include Travelling Salesman Problem, Shortest Path Problem…

Amorphous Computing Vision

- An amorphous computing medium is a system of irregularly placed, asynchronous, locally interacting identical computing elements.
- Self-assembly and smart-materials in general able to adapt their shape and configuration to the environment.

Abelson, H.; Allen, D.; Coore, D.; Hanson, C.; Homsy, G.; Thomas F. Knight, J.; Nagpal, R.; Rauch, E.; Sussman, G.J. & Weiss, R. Amorphous computing Communications of the ACM, ACM Press, **2000**, 43, 74-82



Spray Computers Vision

- Spray Cans containing smart paint made of small electronic devices with limited capabilities (e.g. SmartDust)
- When sprayed, these components self-organize in order to fulfil the required function
- Think about the “invisible” wall painted both sides with smart paint: light is absorbed by one side and re-emitted from the other side

Franco Zambonelli, Marie-Pierre Gleizes, Marco Mamei, Robert Tolksdorf. *Spray Computers: Explorations in Self-Organization.* Journal of Pervasive and Mobile Computing, Vol.1, No. 1, pp. 1-20. Elsevier.

Autonomic Computing Vision

- Autonomic computing are computing systems that can manage themselves given high-level objectives from administrators.
- Autonomic in the sense of the autonomic nervous system: should exhibit all the self-* properties
- A vision by IBM: it is neither a new paradigm nor a new technology
- It is a strategic refocus of their business: weakly related to research

Kephart, J.O. & Chess, D.M. The vision of autonomic computing *Computer*, **2003**, *36*, 41-50

Self-Organization

Methodologies and Tools

Methodologies

- We can rely on MAS methodologies such as GAIA, SODA and ADELFE...
- But most of the issues of self-organizing systems are not addressed
- How to design entities behaviour in order to produce the desired global dynamics?
- How can we guarantee the emergence of specific properties?

W.I.P. Research

- We are exploring a *design* methodology
  1. Prototyping – provide a basic model expressed in formal languages
  2. Dynamics Analysis – simulate the system specifications
  3. Modelling – refine the specifications of the best prototype
  4. Coarse Tuning – devise a set of system parameters
  5. Verification – verify the global properties of the system via model-checking

Simulation

- Simulation is one of the most useful tool to qualitatively investigate self-organization mechanisms
- Devise a basic set of rules and execute simulations to observe the desired behaviours
- Most models specify the system behaviour in terms of Transition Rules
- When simulating a system it is to notice that small changes in the parameters lead to completely different results
- This will be probably shown in the seminar about *Complex Systems*!

Simulation Tools

- Some useful tools are
  - Repast
  - NetLogo
  - Swarm
  - Cellular Automata in general
  - ..also Matlab
- Other tools are based on formal languages like
  - Petri Nets
  - **Pi-Calculus** and Process Algebra in general
  - **MAUDE**

Model-Checking

- It is about verifying that one or more property will hold, i.e. *model-checking*
- A property is expressed by a logic formula:
  a few formalisms account for time or probability issues, but none about stochasticity
- *“Will the ants find a path to the food source within 5 minutes with a probability >80%?”*

Self-Organization

Conclusions

State of the Art

- Self-Organizing Systems Engineering is not a well-established field, hence everything still work in progress :)
- ..this implies neither a mature methodology nor widespread tools are available..
- Most of the investigation is about mimicking nature, i.e. simulating and modelling

Role of Self-Organization

- Self-Organization is not a science per se, but crosscuts several sciences
- It is a view focused on basic elements
  - autonomy
  - topology
  - concurrency
  - coordination
  - redundancy

Challenges

- How to deduce the individual behaviour of agents to achieve the desired global property?
- How to provide guarantees about the emergence of global patterns?
- Which are the principles underlying all self-organizing systems?