Swarm Intelligence

Overview

Patricia J Riddle

Swarm Intelligence

- **Swarm intelligence (SI)** is artificial intelligence based on the collective behavior of decentralized, self-organized systems.

- **Swarm intelligence** is the discipline that deals with natural and artificial systems composed of many individuals that coordinate using decentralized control and self-organization.

Main Focus

- **collective behaviors** that result from the
- **local interactions** of the individuals with
  - each other and/or with
  - their environment.

Examples

colonies of ants and termites,

schools of fish,

flocks of birds,

bacterial growth,

herds of land animals.

Artificial Systems:

- some multi-robot systems
- certain computer programs that are written to tackle optimization and data analysis problems

Simple Local Rules

- agents follow very simple local rules
- no centralized control structure dictating how individual agents should behave
- local interactions between agents lead to the **emergence** of complex global behavior.

Emergence

- **emergence** - the way complex systems and patterns arise out of a many simple interactions

- A **complex system** is composed of interconnected parts that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts

Emergence Definition

- "the arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems.”
- Classic Example: Life

Taxonomy of Emergence

- Emergence may be generally divided into two perspectives,
  - "weak emergence" and
  - "strong emergence".

Weak Emergence

- new properties arising in systems as a result of the interactions at an elemental level

- when the high-level phenomenon arises from the low-level domain, but truths concerning that phenomenon are unexpected given the principles governing the low-level domain

- Emergence is merely part of the language, or model that is needed to describe a system's behaviour.

Weak Emergence Example

- John Conway's Game of Life

- Demo 1
- http://www.radicaleye.com/lifepage/patterns/contents.html

Strong Emergence

- qualities not directly traceable to the system's components rather to how those components interact
- when the high-level phenomenon arises from the low-level domain, but truths concerning that phenomenon are not deducible even in principle from truths in the low-level domain
- These new qualities are irreducible to the system's constituent parts
- The whole is greater than the sum of its parts

Strong Emergence Example

- Consciousness

- Just like AI, once you understand it it is no longer AI

- Scientist view “strong emergence” is when we don’t understand how it works

Intuitive Strong Emergence

- Unintended consequences and side effects are closely related to emergent properties.

- *"A component has a particular functionality but this is not recognizable as a subfunction of the global functionality. Instead a component implements a behaviour whose side effect contributes to the global functionality [...] Each behaviour has a side effect and the sum of the side effects gives the desired functionality"*.

- In other words, the global or macroscopic functionality of a system with "emergent functionality" is the sum of all "side effects", of all emergent properties and functionalities.

Properties of a Swarm Intelligence System

- The typical swarm intelligence system has the following properties:
  - it is composed of **many individuals**; the individuals are relatively homogeneous (i.e., they are either all identical or they belong to a few typologies);
  - the interactions among the individuals are based on **simple behavioral rules that exploit only local information** that the individuals exchange directly or via the environment (**stigmergy**);
  - the overall **behaviour of the system results from the interactions of individuals with each other and with their environment**, that is, the group behavior self-organizes.

Characterising Property

- is its ability to act in a coordinated way without the presence of a coordinator or of an external controller.
- Notwithstanding the lack of individuals in charge of the group, the swarm as a whole can show an intelligent behavior.
- This is the result of the interaction of spatially neighboring individuals that act on the basis of simple rules.
- Most often, the behavior of each individual of the swarm is described in probabilistic terms:
  - Each individual has a stochastic behavior that depends on his local perception of the neighborhood.

Stimergy

- **Stigmergy** is a mechanism of spontaneous, indirect coordination between agents or actions, where the trace left in the environment by an action stimulates the performance of a subsequent action, by the same or a different agent.

- Stigmergy is a form of self-organization.

Self-organization

- **Self-organization** is the spontaneous (often seemingly purposeful) formation of spatial, temporal, spatio-temporal structures or functions in systems composed of few or many components.

- In physics, chemistry and biology self-organization occurs in open systems driven away from thermal equilibrium.

- In the animate world, objects grow, acquire their form, and function without being created by humans.

Self-organization

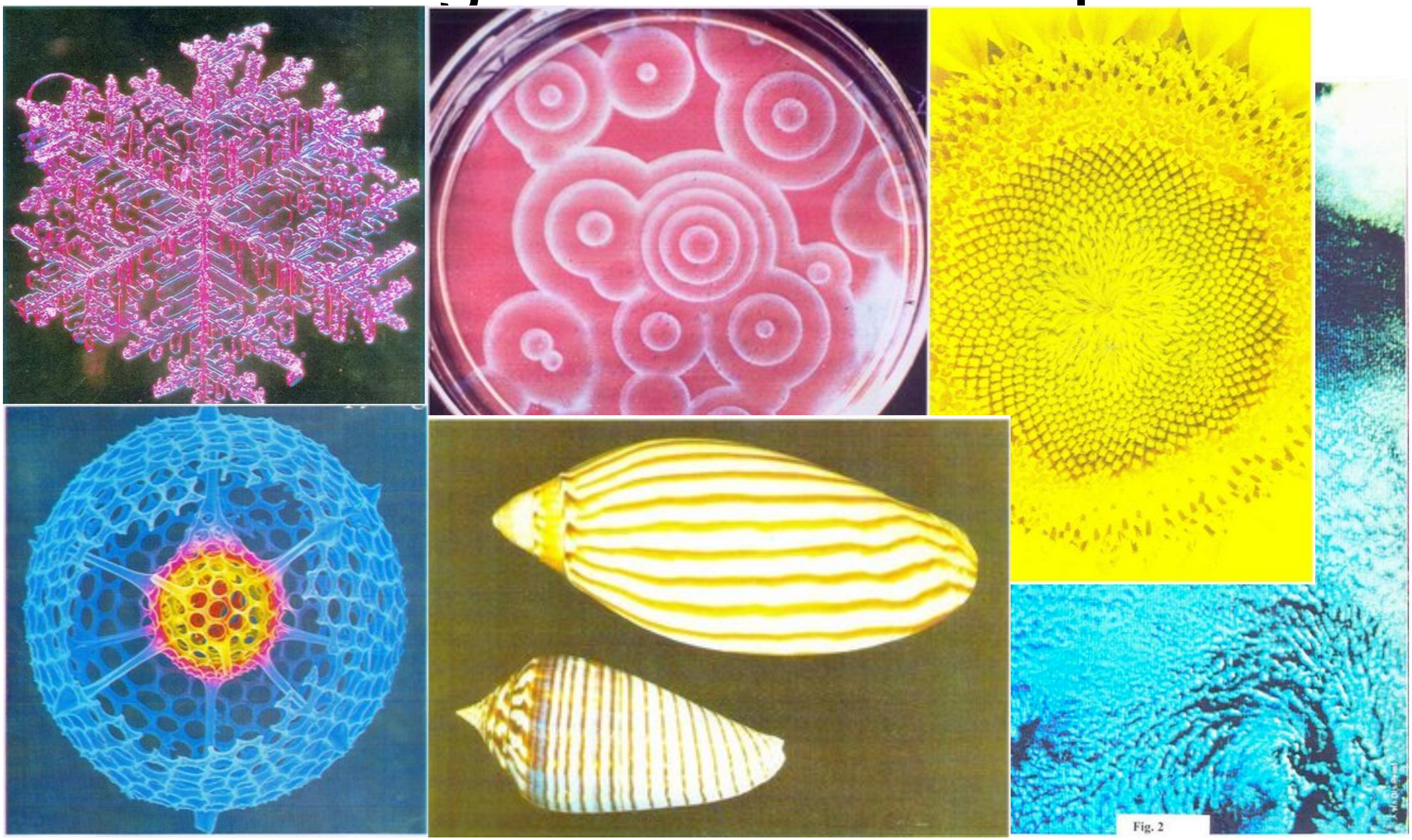
- The animal kingdom abounds of examples.
- It is increasingly recognized that even the human brain may be considered as a self-organizing system as well as quite a number of manifestations of human activity, such as in economy and sociology.
- But processes of self-organization can be found also in the inanimate world:
  - formation of cloud streets,
  - planetary systems,
  - galaxies etc.

Self-organization

- A fundamental question is: *Are there general principles for self-organization*?

- In the inanimate world a positive answer could be found for large classes of phenomena.
- In the animate world so far at least some insights could be gained.
  - In biology (and perhaps other fields) there is a controversy: are there general principles or do we need special rules and mechanisms in each individual case?

Self-organization Examples



Back to Stigmergy

- Stigmergy is a form of self-organization.
- It produces complex, apparently intelligent structures, without need for any planning, control, or even communication between the agents.
  - (but it really is communication isn't it???)
- As such it supports efficient collaboration between extremely simple agents, who lack any memory, intelligence or even awareness of each other.

Social Insects

- Stigmergy was first observed in social insects.
  – ants exchange information by laying down pheromones on their way back to the nest when they have found food.
  – they collectively develop a complex network of trails, connecting the nest in the most efficient way to the different food sources.

Termites

- Other eusocial creatures, such as termites, use pheromones to build their complex nests by following a simple decentralized rule set.
- Each insect scoops up a 'mudball' or similar material from its environment, invests the ball with pheromones, and deposits it on the ground.
- Termites are attracted to their nestmates' pheromones and are therefore more likely to drop their own mudballs near their neighbors'.
- Over time this leads to the construction of pillars, arches, tunnels and chambers.

Termite Rules

- walk randomly
- pick up wood unless already carrying
- put down carried wood if adjacent to wood.

- DEMO2
- http://www.cs.utk.edu/~mclennan/Classes/420/NetLogo/Termites.html

Stigmergy in Computers

- Stigmergy is not restricted to eusocial creatures, or even to physical systems.
- On the Internet there are many emergent phenomena that arise from users interacting only by modifying local parts of their shared virtual environment.
- Wikipedia is a perfect example of this.

Stigmergy on the Web

- The massive structure of information available in a wiki could be compared to a termite nest;
  - one initial user leaves a seed of an idea (a mudball)
  - which attracts other users
    - who then build upon and modify this initial concept
  - eventually constructing an elaborate structure of connected thoughts.

Stigmergy with Robots

- The term is also employed in experimental research in robotics, multi-agent systems and communication in computer networks.
- In these fields there exist two types of stigmergy: active and passive.

Active Stigmergy

- The first kind occurs when a robotic or otherwise intelligent "agent" alters its environment so as to affect the sensory input of another agent.
  - A typical example of active stigmergy is leaving behind artifacts for others to pick up or follow.

Passive Stigmergy

- The second occurs when an agent's action alters its environment such that the environmental changes made by a different agent are also modified.
  - If one agent turns off the main water valve to a building, the effect of another agent turning on the kitchen faucet is altered.
  - An example of passive stigmergy is when agent-A tries to remove all artifacts from a container, while agent-B tries to fill the container completely

Applications

- The U.S. military is investigating swarm techniques for controlling unmanned vehicles.
- ESA is thinking about an orbital swarm for self assembly and interferometry.
- NASA is investigating the use of swarm technology for planetary mapping.
- A 1992 paper by M. Anthony Lewis and George A. Bekey discusses the possibility of using swarm intelligence to control nanobots within the body for the purpose of killing cancer tumors.

Entertaining Applications

- Artists are using swarm technology as a means of creating complex interactive systems or simulating crowds.
  - Tim Burton's *Batman Returns* was the first movie to make use of swarm technology for rendering, realistically depicting the movements of a group of penguins using the Boids system.
  - The *Lord of the Rings* film trilogy made use of similar technology, known as Massive, during battle scenes.
- Swarm technology is particularly attractive because it is cheap, robust, and simple.

- **DEMO3**
- http://www.massivesoftware.com/assets/Video/film/cinesite_bedtime_web.mov

Examples of swarm intelligence

- Clustering Behavior of Ants
- Nest Building Behavior of Wasps and Termites
- Flocking and Schooling in Birds and Fish
- Ant Colony Optimization
- Particle Swarm Optimization
- Swarm-based Network Management
- Cooperative Behavior in Swarms of Robots
- Stochastic Diffusion Search

Clustering Behavior of Ants

- Ants build cemeteries by collecting dead bodies into a single place in the nest.

- They also organize the spatial disposition of larvae into clusters with the younger, smaller larvae in the cluster center and the older ones at its periphery.

- **DEMO4**
- http://distrinet.cs.kuleuven.be/software/agentwise/downloads/demos/index.php

The Behavior

- The basic models state that an unloaded ant has a probability to pick up a corpse or a larva that is inversely proportional to their locally perceived density,

- while the probability that a loaded ant has to drop the carried item is proportional to the local density of similar items.

- This clustering behavior has motivated a number of scientific studies.
  - Scientists have built simple probabilistic models of these behaviors and have tested them in simulation (Bonabeau et al. 1999).

Nest Building Behavior of Wasps and Termites

- Wasps build nests with a highly complex internal structure that is well beyond the cognitive capabilities of a single wasp.

- Termites build nests whose dimensions (they can reach many meters of diameter and height) are enormous when compared to a single individual, which can measure as little as a few millimeters.

- Scientists have been studying the coordination mechanisms that allow the construction of these structures and have proposed probabilistic models exploiting stygmergic communication to explain the insects' behavior.

Flocking and Schooling in Birds and Fish

- Flocking and schooling are examples of highly coordinated group behaviors exhibited by large groups of birds and fish.
- Scientists have shown that these elegant swarm-level behaviors can be understood as the result of a self-organized process where no leader is in charge and each individual bases its movement decisions solely on locally available information: the distance, perceived speed, and direction of movement of neighbours.
- These studies have inspired a number of computer simulations (of which Reynolds' Boids simulation program was the first one) that are now used in the computer graphics industry for the realistic reproduction of flocking in movies and computer games.
- In the taxonomy these are examples respectively of natural/scientific and artificial/engineering swarm intelligence systems.

Flocking, Schooling Demos

- http://www.red3d.com/cwr/boids/
- http://www.research.scea.com/pscrowd/
- http://www.red3d.com/cwr/steer/Unaligned.html

Ant Colony Optimization

- Ant colony optimization is a population-based metaheuristic that can be used to find approximate solutions to difficult optimization problems.
- It is inspired by the foraging behavior of ant colonies.
- A set of software agents called "artificial ants" search for good solutions to a given optimization problem transformed into the problem of finding the minimum cost path on a weighted graph.
- The artificial ants incrementally build solutions by moving on the graph.
- The solution construction process is stochastic and is biased by a pheromone model, that is, a set of parameters associated with graph components (either nodes or edges) the values of which are modified at runtime by the ants.

Particle Swarm Optimization

- Particle swarm optimization (Kennedy and Eberhart 1995; Kennedy, Eberhart and Shi, 2001) is a population based stochastic optimization technique for the solution of continuous optimization problems.

- It is inspired by social behaviors in flocks of birds and schools of fish.

- In particle swarm optimization (PSO), a set of software agents called particles search for good solutions to a given continuous optimization problem.

- Each particle is a solution of the considered problem and uses its own experience and the experience of neighbor particles to choose how to move in the search space.

Cooperative Behavior in Swarms of Robots

- There are a number of swarm behaviors observed in natural systems that have inspired innovative ways of solving problems by using swarms of robots.
- This is what is called **swarm robotics**.
  - In other words, swarm robotics is the application of swarm intelligence principles to the control of swarms of robots.

- **DEMO**
- **http://www.swarm-bots.org/dllink.php?id=738&type=movies**
- **http://www.swarm-bots.org/dllink.php?id=587&type=movies**
- http://leurre.ulb.ac.be/Pub_illustrs.html