Swarm Intelligence

CompSci 760

Patricia J Riddle

Swarm Intelligence

Swarm intelligence (SI) 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**

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**

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 0 –

http://www.bitstorm.org/gameoflife/

Strong Emergence

qualities not directly traceable to the system's components rather to **how 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.

Taxonomy of Swarm Intelligence

Swarm intelligence has a marked multidisciplinary character since systems with the above mentioned characteristics can be observed in a variety of domains.

Research in swarm intelligence can be classified according to different criteria.

Natural vs Artificial

divide swarm intelligence research into two areas according to the nature of the systems under analysis.

natural swarm intelligence research, where biological systems are studied;

artificial swarm intelligence, where human artifacts are studied.

Scientific vs. Engineering

goals that are pursued: a *scientific* and an *engineering* stream.

The goal of the **scientific** stream - model swarm intelligence systems and to single out and understand the mechanisms that allow a system as a whole to behave in a coordinated way as a result of local individual-individual and individual-environment interactions.

the goal of the **engineering** stream - exploit the understanding developed by the scientific stream in order to design systems that are able to solve problems of practical relevance.

Orthogonal Dicotomies

The two dichotomies are orthogonal

typical **scientific** investigation concerns **natural** systems and

typical **engineering** application concerns an **artificial** system,

a number of swarm intelligence studies have been performed with swarms of robots for validating mathematical models of biological systems. (**artificial/scientific**)

one could influence or modify the behavior of the individuals in a biological swarm so that a new swarm-level behavior emerges that is somehow functional to the solution of some task of practical interest. (**natural/engineering**)

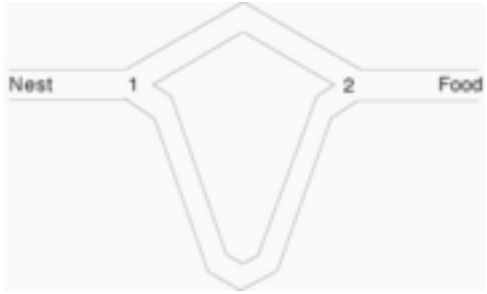
Natural/Scientific: Foraging Behavior of Ants

classic experiment done in 1990, Deneubourg and his group

- when given the choice between two paths of different length joining the nest to a food source, a colony of ants has a high probability to collectively choose the shorter one.

Deneubourg has shown this behavior can be explained via a simple probabilistic model

- each ant decides where to go by taking random decisions based on the intensity of pheromone perceived on the ground, the pheromone being deposited by the ants while moving from the nest to the food source and back



Artificial/Scientific: Clustering by a Swarm of Robots

Several ant species cluster corpses to form cemeteries.

Deneubourg et al. (1991) among the first to propose a distributed probabilistic model to explain this clustering behavior.

In their model, ants pick up and drop items with probabilities that depend on information on corpse density which is locally available to the ants.

Beckers et al. (1994) have programmed a group of robots to implement a similar clustering behavior demonstrating in this way one of the first swarm intelligence scientific oriented studies in which artificial agents were used

DEMO 1 - http://distrinet.cs.kuleuven.be/software/agentwise/downloads/demos/index.php

Natural/Engineering:

Exploitation of collective behaviors of animal societies

A possible development of swarm intelligence is the controlled exploitation of the collective behavior of animal societies.

- No example is available in this area of swarm intelligence although some promising research is currently in progress:

For example, in the **Leurre project**, small insect-like robots are used as lures to influence the behavior of a group of cockroaches.

The technology developed within this project could be applied to various domains including agriculture and cattle breeding

DEMO2 - http://leurre.ulb.ac.be/Pub_illustrs.html

Artificial/Engineering:
Swarm-based Data Analysis

Engineers have used the models of the clustering behavior of ants as an inspiration for designing data mining algorithms.

A seminal work by Lumer and Faieta in 1994.

They defined an artificial environment in which artificial ants pick up and drop data items with probabilities that are governed by the similarities of other data items already present in their neighborhood.

The same algorithm has also been used for solving combinatorial optimization problems reformulated as clustering problems (Bonabeau et al. 1999).

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**.

Characterizing 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.

Stigmergy

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

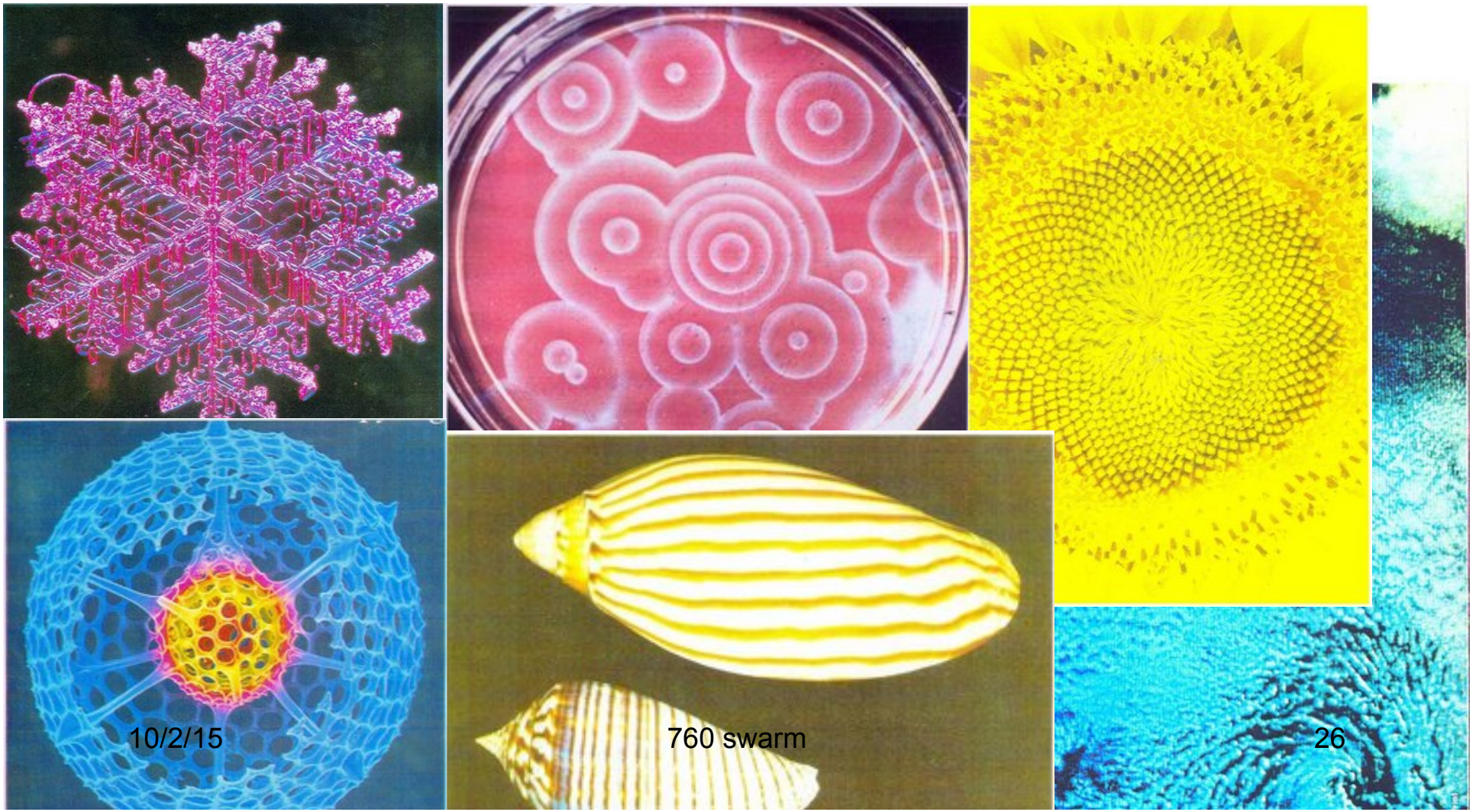
The **animal** kingdom abounds of examples.

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 examples



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?

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 mud unless already carrying

put down carried mud if adjacent to mud.

DEMO3

http://www.permutationcity.co.uk/alife/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.

When an 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.

DEMO 4 - http://www.massivesoftware.com/gallery.html

http://www.youtube.com/watch?v=gzGu0D7qks0&feature=related

Swarms & Phliosophy

The inherent intelligence of swarms has inspired many social and political philosophers, in that the **collective movements of an aggregate often derive from independent decision making** on the part of a single individual.

A common example is how the **unaided decision of a person in a crowd to start clapping will often encourage others to follow** suit, culminating in widespread applause.

Such knowledge, an individualist advocate might argue, should **encourage individual decision making** (however mundane) as an effective tool in bringing about widespread social change.

Telecommunication Applications

The use of Swarm Intelligence in Telecommunication Networks has also been researched, in the form of **Ant Based Routing**.

This was pioneered separately by Dorigo et al and Hewlett Packard in the mid-1990s, with a number of variations since.

Basically this uses a **probabilistic routing table rewarding/ reinforcing the route successfully traversed by each "ant"** (a small control packet) which flood the network.

As the system behaves stochastically and is therefore lacking repeatability, there are large hurdles to commercial deployment.

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.

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).

In the taxonomy this is an example of natural/scientific swarm intelligence system.

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 model has been validated against experimental data obtained with real ants.

DEMO5- same as demo 1

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

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 stigmergic communication to explain the insects' behavior.

- Some of these models have been implemented in computer programs and used to produce simulated structures that recall the morphology of the real nests (Bonabeau et al. 1999).

In the taxonomy this is an example of natural/scientific swarm intelligence system.

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.

DEMO6 & DEMO7 & DEMO8

Flocking, Schooling, Steering Demos

Demos 6-8

http://www.red3d.com/cwr/boids/

http://www.research.scea.com/pscrowd/2d_crowd_goals_obs_360p.mp4

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.

In ant colony optimization (ACO), 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.

As with swarm intelligence systems in general, swarm robotics systems can have either a scientific or an engineering flavour.

Clustering in a swarm of robots was mentioned before as an example of artificial/scientific system.

An example of artificial/engineering swarm intelligence system is the collective transport of an item too heavy for a single robot, a behavior also often observed in ant colonies.

DEMO 9-10 –

http://www.swarm-bots.org/dllink.php?id=578&type=movies

http://www.swarm-bots.org/dllink.php?id=587&type=movies