Swarm Intelligence - W2: An Introduction to Swarm Intelligence and Foraging Strategies in Ant Societies
Outline

• Introduction to Swarm Intelligence
  – Key principles
  – Community, trends, events

• Foraging Strategies
  – Recruitment-based mechanisms
  – Inaccuracies of chemical communication

• Bridges experiments in the lab
  – Experimental results
  – Microscopic models

• Open space and multi-source experiments
  – Experimental results
  – Microscopic models

• Ant networks
An Introduction to Swarm Intelligence – Motivation, Definitions, and Key Principles
Some natural collective phenomena implying a close interconnection among individuals
Some astonishing capabilities of ants

- Leaf cutter, fungus growing ants
Collective Phenomena

- **Limited local information**
  Each individual in the group has access only to limited local information and has no global knowledge of the structure which it is engaged in constructing together with the other members of the group.

- **A set of simple individual rules**
  Each individual obeys a collection of a few simple behavioural rules. This rule set permits the group collectively to coordinate its activities and to build a global structure or configuration.

- **The global structures which emerge accomplish some function**
  These structures often allow the group to solve problems. They are flexible (adapting easily to a novel environment), and they are robust, (if one or several individuals fail in their behaviour or make a simple mistake, the structures spontaneously re-form).
A few Explanations and Facts about Insect Societies ...
Facts about the Ecological Success of Social Insects

• $10^{18}$ living insects (rough estimate)
• ~2% of all insects are social
• Social insects are:
  – All ants
  – All termites
  – Some bees
  – Some wasps
• 50% of all social insects are ants
• Avg weight of one ant between 1 and 5 mg
• Tot weight ants ~ Tot weight humans
• Ants have colonized Earth for 100 million years, *Homo sapiens sapiens* for 100 thousands years
Social Life is the Main Reason for the Success of Ants

• Ant colony size: from as few as 30 to millions of workers

• Work division:
  – Reproduction → queen
  – Defense → soldiers
  – Food collection → specialized workers
  – Brood care → specialized workers
  – Nest brooming → specialized workers
  – Nest building & maintenance → specialized workers
Ex.: Behavioral Castes

Allocation of the daily activities in a colony of desert harvester ants (Portal, AZ)

From D. Gordon, “Ants at Work”, 1999
Insect Societies

Collective complexity out of individual simplicity

• The behavioural repertoire of the insects is limited

• Their cognitive systems are not sufficiently powerful to allow a single individual with access to all the necessary information about the state of the colony to guarantee the appropriate division of labour and the advantageous progress of the colony

• The colony as a whole is the seat of a stable and self-regulated organisation of individual behaviour which adapts itself very easily to the unpredictable characteristics of the environment within which it evolved
From Natural to Artificial Systems and more ...
Collective/Swarm Intelligence?

Some questions arise ... 

• How do animal societies manage to perform difficult tasks, in dynamic and varied environments, without any external guidance or control, and without central coordination?

• How can a large number of entities with only partial information about their environment solve problems?

• How can collective cognitive capacities emerge from individuals with limited cognitive capacities?
Insect Societies

A natural model of distributed problem solving

• Collective systems capable of accomplishing difficult tasks, in dynamic and varied environments, without any external guidance or control and with no central coordination

• Achieving a collective performance which could not normally be achieved by any individual acting alone

• Constituting a natural model particularly suited to distributed problem solving

• Many studies have taken inspiration from the mode of operation of social insects to solve various problems in the artificial domain
From Natural to Artificial Systems

- **Modeling** to understand microscopic to macroscopic transformation
- **Modeling** as interface to artificial systems

Individual behaviors and local interactions

Ideas for artificial systems

Global structures and collective decisions
Collective Artificial Systems

• Sometimes at the computational level only (e.g., multi-agent algorithms), sometimes real-time, embedded systems (e.g., multi-robot systems)
• Engineering and technological component
• Analysis and synthesis
• Possibility to mix them with natural systems in a shared real world (symbiotic systems)
A common Methodological Framework?

Symbiotic societies

Traffic systems

Traffic systems

Social insects

Networks of S&A

Vertebrates

Pedestrians

Multi-robot systems
Definitions of Swarm Intelligence and Historical Perspective
Historical Definition Milestones

• Beni and Wang (1989):
  – Used the term in the context of cellular automata (based on cellular robots concept of Fukuda)
  – Decentralized control, lack of synchronicity, simple and (quasi) identical members, self-organization

• Bonabeau, Dorigo and Theraulaz (1999)
  – Any attempt to design algorithms or distributed solving devices inspired by the collective behavior of social insect colonies and other animal societies

• Beni (2004)
  – Intelligent swarm = a group of non-intelligent robots (“machines”) capable of universal computation
  – Usual difficulties in defining the “intelligence” concept (non predictable order from disorder, creativity)
What do we mean by Intelligence in this Course?

- **Intelligence**: Ability to act in the environment so that a viability condition is always satisfied and the individual identity (in a broad sense) is maintained (Theraulaz, 1995).

- A team is provided with collective intelligence if it is able to satisfy its viability and this is required in order to achieve the viability of the individual (Theraulaz, 1995).

- Can be applied to the Swarm Intelligence definition as well, emphasis on the large-scale numbers.
Current Tendencies

• IEEE SIS-05
  – self-organization, distributedness, parallelism, local communication mechanisms, individual simplicity as invariants
  – More interdisciplinarity, more engineering, biology not the only reservoir for ideas

• ANTS-06, IEEE SIS-06, IEEE SIS-07 followed the tendency

• Swarm Intelligence Journal (2007 -); EIC: Prof. Marco Dorigo; AM among the AEs; publisher: Springer Verlag
Key Mechanisms behind Natural Swarm Intelligence
Two Key Mechanisms
in Natural Swarm-Intelligent Systems

1. Self-Organization

2. Stigmergy
Self-Organization

• Set of dynamical mechanisms whereby **structure appears at the global level** as the result of **interactions among lower-level components**

• The rules specifying the interactions among the system's constituent units are executed on the basis of **purely local information**, without reference to the global pattern, which is an **emergent property of the system** rather than a property imposed upon the system by an external ordering influence
Characteristics of Natural Self-Organized Systems

- **Creation of spatio-temporal structures**
  - E.g., foraging trails, nest architectures, clusters of objects, ...

- **Multistability**
  (i.e., possible co-existence of several stable states)
  - E.g., ants exploit only one of two identical food sources, build a cluster in one of the many possible locations, ...

- **Existence of bifurcations when some parameters change**
  - E.g., termites move from a non-coordinated to a coordinated phase only if their density is higher than a threshold value
Basic Ingredients of Natural Self-Organized Systems

- **Multiple interactions**
- **Randomness**
- **Positive feedback**
  - E.g., recruitment, reinforcement
- **Negative feedback**
  - E.g., limited number of available foragers, pheromone evaporation
Stigmergy

Grassé P. P., 1959

• “La coordination des taches, la regulation 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 du STIGMERGIE (stigma, pique; ergon, travail, œuvre = œuvre stimulante).”

• [“The coordination of tasks and the regulation of constructions does not depend directly on the workers, but on the constructions themselves. The worker does not direct his work, but is guided by it. It is to this special form of stimulation that we give the name STIGMERGY (stigma, sting; ergon, work, product of labor = stimulating product of labor).”]
Definition

It defines a class of mechanisms exploited by social insects to coordinate and control their activity via indirect interactions.

Stigmergic mechanisms can be classified in two different categories:
- quantitative (or continuous) stigmergy
- qualitative (or discrete) stigmergy

[Theraulaz & Bonabeau., *Alife J.* 1999]
Key Mechanisms behind Artificial Swarm Intelligence
Computational Swarm-Intelligent Systems

- In a virtual world, most of the mechanisms shown by natural SI can be easily reproduced
- Some of the mechanisms are intentionally modified and further are added in order to improve the performance of a given algorithm
Real-Time Swarm-Intelligent Systems

- **Beyond bio-inspiration:** combine natural principles with engineering knowledge and technologies
- **Unit coordination**
  - fully distributed control (+ env. template)
  - individual autonomy
  - self-organization (extend definition)
- **Communication**
  - explicit/implicit local communication
  - indirect communication through signs in the environment (stigmergy)
- **Scalability**
- **Robustness vs. efficiency trade-off**
  - redundancy
  - balance exploitation/exploration
  - individual simplicity
- **System cost effectiveness**
  - individual simplicity
  - mass production
Self-Organization

- [Wikipedia] Self-organization refers to a process in which the internal organization of a system, normally an open system, increases automatically without being guided or managed by an outside source; self-organizing systems typically (though not always) display emergent properties.

- [Scholarpedia, H. Haken] 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. The process of self-organization can be found in many other fields also, such as economy, sociology, medicine, technology.
Basic Ingredients of Artificial Self-Organized Systems

- **Multiple interactions**
- **Randomness**
- **Positive feedback**
  Spatiotemporal continuity of feedback not required; digital information can be exploited; limited spatio-temporal internal organization (according to specific metrics different from natural ones)
- **Negative feedback**
  All sort of active and passive feedback can be used, based on digital or analog information; targeted to counterbalance the positive feedback introduced in the system
Foraging Strategies in Ants
Different Ants, Different Strategies
Not All Foraging Strategies are Collective and based on Stigmergy …

- Example: *Cataglyphis desert ant*
- Excellent study by Prof. R. Wehner (University of Zuerich, Emeritus)
- Individual foraging strategy
- Underlying mechanisms
  - Internal compass (polarization of sun light)
  - Dead-reckoning (path integration on neural chains for leg control)
  - Local search (around 1-2 m from the nest)
- Extremely accurate navigation: averaged error of a few tens of cm over 500 m path!
More individual Foraging Strategies

Individual navigation + learning capabilities for memorizing the foraging zone
Tandem Recruitment Strategies

- Mediated by thropallaxis, antennal contact
- Based on food chemical signatures on the ant body

Les différentes stratégies de récolte chez les fourmis

2. Recrutement en tandem

Recrutement en tandem chez la fourmi asiatique
Camponotus sericeus
Les différentes stratégies de récolte chez les fourmis

3. Recrutement de groupe

Recrutement de groupe chez la fourmi Camponotus socius

Leader
Mass Recruitment Strategies

Les différentes stratégies de récolte chez les fourmis

4. Recrutement de masse

Recrutement de masse chez la fourmi Solenopsis geminata
Mass Recruitment
Behavior of Individual Ants

Sequence of actions performed by an ant communicating the discovery of a food source

- Food source
- Foraging area
- Nest

1. **Picking up food**
2. **Laying a chemical trail**
3. **Stimulating nest mates**
4. **Following the trail**
5. **Deposition of food**
Formation of Recruitment Trails in Ants
Number of Ants at the Food Source vs. Time

Le recrutement de masse

1. Caractéristiques du recrutement

Croissance logistique (Pierre François Verhulst, 1845)

du nombre de fourmis présentes à la source de nourriture

Growing phase (positive feedback)

Saturation phase (negative feedback)
Stochastic Individual Behavior Combined with the Amplification of Information can lead to Collective Decisions
How does individual behavior with a strong stochastic component lead to statistically predictable behavior at the level of the colony and collective decisions?
Experimental Studies

• Most of the quantitative studies have been carried out in the lab because:
  – Controlled environmental conditions
  – Repeated runs for statistics

• Studies in the field might be influenced by:
  – Multiple food sources
  – Predators and competitors
  – Environmental changes (temperature, climate, etc.)
Exploration: The Inaccuracy of Chemical Communication
Termite Following a Pheromone Trace

Prof. J.-L. Deneubourg (ULB, Bruxelles)
Ants can Reacquire a Trail by Local Search

Rôle du hasard et du bruit dans l'organisation de la récolte
1. Orientation des fourmis le long d'une piste

Osmotropotaxie (Hangartner, 1967)
Probability of Trail Losing depends on the Ant Species

Example: Accuracy of recruitment of the first recruit (Verhaeghe et al., 1980)

<table>
<thead>
<tr>
<th></th>
<th>Tetramorium impurum</th>
<th>Tapinoma erraticum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Successful recruits (%)</td>
<td>18</td>
<td>74</td>
</tr>
<tr>
<td>Length of trail followed (%)</td>
<td>17</td>
<td>68</td>
</tr>
</tbody>
</table>

*Tapinoma* follow trails much more reliably than *Tetramorium* → depends on the environment the species have evolved (food scattering, etc.)
The longer the traveled path and the smaller is the number of ants on the trail appears to be independent of phenomena such as learning or sensory adaptive response (at least under such short time scale).

Probability of Trail Losing is Constant over Time

Log # of ants on the trail as a function of the traveled path for a constant pheromone concentration.
Probability of Trail Losing depends on Chemical Concentration

The higher is the pheromone concentration and the more reliably can be followed a trail

Mean path length as a function of the pheromone concentration

$4 \times 10^{-14} \text{g/cm} \leq c \leq 12 \times 10^{-12} \text{g/cm}$
Biological Significance of the Exploitation-Exploration Balance

Does the accuracy of the chemical communication channel used by ants increase or decrease their efficiency?

• Noise can have a certain flexible value for the organization of the society.

• The fact that a significant proportion of recruits get lost en route can be of benefit when food is scattered throughout the environment or when several sources are present simultaneously.

• If too many ants get lost for a given food scattering the efficiency of recruitment also decreases.

Sacrifice a little bit efficiency in order to be robust at facing environmental unpredictability.
Bridge Experiments: Selecting the Shortest Path
The Suspended, Symmetric Bridge Experiment

Food source

Two branches (A and B) of the same length connect nest and food source.

© J.-L. Deneubourg
Experimental Results

% of ant passages on the two branches vs. Time (minutes)
Microscopic Model (Deneubourg 1990)

\[
\begin{align*}
P_A &= \frac{(k + A_i)^n}{(k + A_i)^n + (k + B_i)^n} = 1 - P_B
\end{align*}
\]

Probabilistic choice of an agent at the bridge’s bifurcation points

\(P_A\) and \(P_B\): probability for the ant \(i+1\) to pick up the branch A or B respectively

\(A_i\): number of ants having chosen branch A

\(B_i\): number of ants having chosen branch B

\(n\) (model parameter): degree of nonlinearity

\(k\) (model parameter): degree of attraction of a unmarked branch

\[
\begin{align*}
A_{i+1} &= \begin{cases} 
A_i + 1 & \text{if } \delta \leq P_A \\
A_i & \text{if } \delta > P_A
\end{cases} \\
B_{i+1} &= \begin{cases} 
B_i + 1 & \text{if } \delta > P_A \\
B_i & \text{if } \delta \leq P_A
\end{cases}
\end{align*}
\]

\(A_i + B_i = i\)

\(\delta = \text{uniform random variable on } [0,1]\)
Parameters of the Choice Function

- The higher is $n$ and the faster is the selection of one of the branches (sharper curve); $n$ high corresponds to high exploitation.
- The greater $k$, the higher the attractivity of a unmarked branch and therefore the higher is the probability of agents of making random choices (i.e. not based on pheromones concentration deposited by other ants); $k$ high corresponds to high exploration.
Model vs. Experiments

Parameters that fit experimental data:
- \( n = 2 \)
- \( k = 20 \)

Note: microscopic model -> Montecarlo simulations
The Suspended, Asymmetric Bridge Experiment

Food source

- Two branches (A and B) differing in their length (length ratio $r$) connect nest and food source
- Test for the optimization capabilities of ants

© J.-L. Deneubourg

Nest
All Bridge Experiments

4 different experimental scenarios

1. $r = 1$, $l = 14\text{ cm}$
2. $r = 1.4$, $L = 20\text{ cm}$
3. $r = 2$, $L = 28\text{ cm}$
4. $r = 2$, $L = 28\text{ cm}$

Shortest branch added later
Selection of the Shortest Branch

Repeated experiments with different ant colonies of the same ant species (*Linepithema Humile*) – finite experimental time window
What happens if the shorter branch is presented after 30 minutes?

- Argentine Ants (*Linepithema Humile*) get stuck on the longer branch (mainly pheromone-based navigation), see previous slide.

- *Lasius Niger* ants find the shorter branch because they integrate other navigation modalities (compass, dead-reckoning) with pheromone navigation -> U-Turns (different from random walk)!

- *Pharaoh ants* recognize the right way to go from geometry of trails (trails geometry provide polarity information!), again dead-reckoning/compass capabilities!
Asymmetric Bridge – Microscopic Modeling

- The previous model does not work any more: distance/traveling time has to be considered in order to incorporate the geometry of the bridge.
- Multi-agent simulation incorporating pheromone deposition, avoidance rules, ... point simulator (take into account trajectories but no body) by Prof. M. Dorigo (ULB Bruxelles).

© Marco Dorigo
Foraging in Free Space
Selecting the Richest Source

Three different experimental scenarios:

- **Experiment N°1**
  - Source 1: 1M

- **Experiment N°2**
  - Source 1: 1M
  - Source 2: 0.1M

- **Experiment N°3**
Selecting the Richest Source

Results obtained with *Lasius Niger* ants:

The ants might get stuck within their trail system and therefore the colony exploits primarily the first food source that has been discovered even if this might lead to neglecting a richer source which just appeared at a later time. *Lasius niger*: exclusively uses mass recruitment mechanisms; probably since nest-sources not so different u-turn strategy does not help in this scenario!
Selecting the Richest Source – Scenario 3

Results obtained with *Tetramorium caespitum, Myrmica sabuletti*

- These two ant species exploit mixed recruitment strategies: mass (trail laying/following) and group (no stigmergy) and do not get stuck in their trail network
Mitchel Resnick, MIT, Media Lab
An Example with Three Different Food Sources

- Different richness
- Different distances from nest
- Obstacle-free environment
Ant Networks
The organization of inter-nest traffic in ants

- For most social insects, the fundamental ecological unit is the colony.

- In a number of ant species, groups of workers, larvae, and reproductives can leave the nest and set up a new nest while maintaining close connections with the parent nest.

- The collection of nests, or sub-colonies, forms what is called a super-colony.
Super-colony of *Formica Lugubris* (Switzerland)
Prof. D. Cherix (Uni Lausanne)
The Organisation of Inter-Nest Traffic in Ants

Results for a triangular network (3 nest super-colony) with *Linepithema humile* (Argentine ants)

\[a, b, c = \% \text{ of traffic on branch} \]
\[a, b, \text{ or } c\]
\[n = \text{absolute number of passages}\]

[Aron, Deneubourg, Goss, Pasteels, 1991]
The Organisation of Inter-Nest Traffic in Ants

Results for a quadrangular network (4 nest super-colony) with *Linepithema humile* (Argentine ants)

\[ a, b, c, d = \% \text{ of traffic on branch } a, b, \text{ or } c \]

\[ n = \text{ absolute number of passages} \]

[Arn, Deneubourg, Goss, Pasteels, 1991]
Ants are Able to Optimize!

• All the nests are connected either directly or indirectly

• Ants are able to find the **minimal spanning tree** connecting all the nests (probable ecological reasons: cost building and maintaining redundant spanning tree higher + extend predator exposure)

• This is similar to the Travel Salesman Problem (TSP)

• Can artificial ants solve the TSP? More next week!
Conclusion
Take Home Messages

1. Differences between artificial and natural SI
2. Differences between computational and real-time SI
3. Key mechanisms for natural SI: self-organization and stigmergy
4. Self-organization ingredients: positive feedback, negative feedback, randomness, multiple interactions
5. SI-based systems exploit careful balance between exploration and exploitation
6. Microscopic models help understanding SI-based systems
7. Ants exploit trail laying/following mechanisms and other strategies for foraging
8. Ants are able to generate efficient inter-nest networks
Additional Literature – Week 2

Books

Papers