Distributed Intelligent Systems

SSIE (spec. Geomatics), SIN (spec. Computer Engineering), SSC, SGC (spec. Transportation), and SSV (minor Biocomputing)

EPFL, WS 2009-2010

http://disal.epfl.ch/teaching/distributed_intelligent_systems/
Distributed Intelligent Systems – W1

Part I: Course Organization, Team, and Content
Team beyond this Course
Distributed Intelligent Systems and Algorithms Lab:
http://disal.epfl.ch

• **Instructor:** Alcherio Martinoli
• **Guest lecturers:** TBA – typically some of the TAs
• **Teaching assistants** (office hours on the web):
  – Sven Gowal (head TA, PhD student)
  – Amanda Prorok (PhD student)
  – Alexander Bahr (postdoctoral fellow)
  – perhaps a student TA
• **Support staff:**
  – Grégory Mermoud (PhD student)
  – Thomas Lochmatter (PhD student)
  – Yvan Bourquin (R&D engineer)
  – Florian Vaussard (visiting R&D engineer)
Access to e-material and exercise room

• For non SSIE student we need to request for you explicit rights for the computer room: please register by Fri to IS-academia
• Web site moodle for the course: need to register also there (using the pass communicated); this will not be public access since a lot of copyrighted material
Rationale for This Course
Rationale (1)

- Well-balanced course: theory, algorithms, experimental labs and projects
- Understand quantitatively natural collective phenomena (focus on biological societies) and how to combine bio-inspired principles with engineering knowledge
- Understand how to model, design, control, evaluate, and optimize distributed intelligent systems
- Learning to present and review a research work and digging out literature
Rationale (2)

• For **SIN/SSC** students: not only computing and communication aspect but full system including sensing and acting; learning about new applications areas

• For **SSIE/SGC** students: follow up of the BS course “An introduction to embedded and real-time systems”; become a power user (i.e. able to bring problem-domain knowledge into the instrument by programming) of potentially revolutionary distributed field instruments

• For **all**: participating to a pioneering experience worldwide
What is this Course about

• Distributed natural and artificial systems
• Coordination algorithms
• Distributed sensing and action
• Models, simulation tools, and machine-learning targeted to distributed intelligent systems
• Multi-robot systems, wireless sensor networks, intelligent transportation systems
Course Prerequisites

- C/C++ and Matlab knowledge
- Fundamentals of programming
- Fundamentals of probability calculus
- Fundamentals of analysis (differential equations, continuous and discrete time)
- Fundamentals of linear algebra

For SSIE/SGC students: BS introductive course on embedded, real-time systems
Organization of the Course
Credits and Workload

• 6 ECTS
• 1 ECTS = 30 h workload → 180 h workload
• Rough breakdown
  – 90 h lecture (including reading and exam prep)
  – 45 h hwk+lab (including preparation + reporting)
  – 45 h course project (including reading, implementation, defending, reviewing, and reporting)
Grade

- Final oral exam, winter session; 20 minutes
- 50% performance during semester, 50% performance during the exam (compromise US/Europe style)
  - During semester: 25% performance of lab+hwk (average 3 series); 25% performance project (report + presentation)
  - During exam: 3 topics (and 3 initial questions), starting question on course project, 2 other questions on lecture/exercises topics
Lecture

- 10:15 – 1 p.m.
- Who has another course at 1:15?
- Possible solution: single break and finishing 12:45 at latest, perhaps earlier if possible
Lecture Notes & Reading

• Policy: master, research-oriented course → no manuscript! → slides + papers + web

• Roughly 50-60 pages/week to read; list subject to change during the semester, as a function of the lecture

• Preliminary lecture slides in pdf format available for download on the course web site possibly before each lecture (wed – perhaps very - late evening, definitive ones after lecture (couple of days max)

• List of additional reading for each topic provided in the lecture notes/sample books brought to class
Suggestions for a Successful Course Material Processing

From last years experience:

• For high-gear courses such as this one with a lot of raw material to process and digest is worth taking advantage of the lecture for having an idea about what’s important and what not
Labs and Hwk

- Lab session 8:15-10:00 am on Wed, GR B0 01
- SIG course in GR B0 01 from 10:15 am; if less than 13 students GR C0 02 free; flexibility with the lecture start possible
- Mini-tutorial (< 10 min) by the main lab designer at the beginning of the lab
- 9 lab + hwk sets total, ONLY 3 graded
- Download/upload via moodle server (see student area on the course web site).
- dis-ta@groupes.epfl.ch for ANY issue!
Ungraded Labs and Hwk

• Possible debriefing on ungraded labs during lecture time (general message) or office hours
• 2h lab per week + 2 h hwk for ungraded including assignment reading (6x4 = 24h total)
Graded Labs and Hwk (1)

• Labs and hwk individually reviewed, distributed in a timely fashion (target 1 week after submission, commented pdf)

• No official solution of lab+hwk distributed; TAs available during office hours for discussion

• 2h lab + 5 h hwk for graded ones, including assignment reading and write-up; hwk of graded includes also questions on previous 2 ungraded labs (7x3 = 21h total)
Graded Labs and Hwk (2)

- **Tue noon deadline, 6.5 days time to get write-ups done; no late submission accepted unless motivated by provable health problems**
- **Specific planifiable issues in attending a lab session/submitting a write-up should be mentioned in advance to the TAs**
- **Network/moodle server problems → TAs immediately notified**
Suggestions for a Successful Exercise Series

From last years experience:

• Read the assignment in advance, in this way you will be more efficient when the TAs are around for helping you on the toughest questions …

• Have an idea of the point distribution: this roughly correspond to the breakdown in time you should have; if your time is tight invest where it is worth!

• You do not have to achieve always 100/100: bonuses, exam, project are also great opportunities to round up ….
Course Project (1)

- Course project list distributed on Oct 7 (W4)
- 45 h effort, from Oct 21 (W6, definitive assignment) until Dec 16 (W14, defenses)
- Team of 2 students (recommended) or 1
- Will distribute hw/sw at home
- Short intermediate report (compulsory but not graded, 1 page) and debriefing with responsible TA/staff member in W9
- Mini-report to be submitted (max # of pages pre-established)
Course Project (2)

- Final presentation in front of the class
- Each of the project will have another team of students as reviewers
- For two-student teams:
  - Each of the team members has to present
  - Questions during the exam on the whole project
Suggestions for a Successful Course Project

From last years experience:

• We might organize a small social event in week 4 or 5: take advantage for asking question to TAs/staff about projects and for choosing a project partner

• Contact ASAP the responsible supervisor when the projects will have been assigned for getting started

• Plan your effort (milestone, time, etc.), coordinate your team

• Arrive at the intermediate report milestone with a clear plan, reading, tool handling, project understanding behind you
Collaboration Policy

• Lecture and exam preparation: encouraged
• Project: encouraged (team up)
• Lab and hwk: discussion encouraged but problem solved and submitted individually! We will be very strict in penalizing too similar write-ups copies because 25% of the grade is acquired with lab&hwk (n copies = # of points/n)!
A Final Note
5th iteration at EPFL

• Inversion of lecture and exercise weight: 3 h lecture, 2 h labs -> syllabus and labs significantly re-designed

• Same credits, same reading and but less graded exercises -> hopefully more control on exercise workload; however, remains a high-gear course!

• 2 to 5 sections (+ SSIE and SGC, SSV as minor); sometimes SEL, SMT, or SME students
Course Syllabus and Summary
Goal

• Course overview
• Short description of each topic so that course projects can be better chosen
• 5 main blocks
• A few slides per block
Block I – Swarm Intelligence

- Key Principles of Swarm Intelligence
- Trail laying/following mechanisms
- Ant Colony Optimization as an example of a successful multi-agent metaheuristic
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
Biological Mechanisms and Models

Choice occurs randomly

\( L = 14 \text{ cm} \)

(Deneubourg et al., 1990)
The Traveling Salesman Problem

Graph \((N,E)\)

\(N\) : set of cities (nodes)

\(E\) : set of connecting roads (links)

\(d_{ij}\) : distance between city \(i\) and \(j\)

**Problem:** Find the shortest path which allow the salesman to visit once and only once each city in the graph

**Difficulty:** NP-hard problem; time for computing the shortest route grows in a nonpolynomial way with the number of cities in the network -> metaheuristics provide near-optimal solutions!
Block II – Individual Nodes

- Introduction to mobile robotics
- Robotic tools (simulation and real HW)
- Basic control architectures
- Machine-learning for control shaping (single-robot examples)
e-puck Real Robot

- For course project and labs
- Multi-robot operation ok
- No manipulation, no highly accurate odometry
- Total 100 robots

- DsPIC30F6014 platform up to 30Mips
- 2 motors
- 8 IR sensors
- 3 microphones
- Color camera
- 3 axis accelerometer
- Bluetooth serial transmission
- A light ring around the robot
- Bus connectors to allow board stack
- Area to add a floor sensor board
- Robot size is Ø 7cm x 5cm
• Webots realistic robotic simulator
• Discrete sensor and actuators
• Noise and nonlinear characteristics faithfully reproduced
• Single and multi-robot simulator
• Different levels of simulation (different accuracy/faithfulness trade-offs)
Perception-to-Action Loop

- **Reactive** (e.g., nonlinear transform, single loop)
- **Reactive + memory** (e.g., filter, state variable, multi-loops)
- **Deliberative** (e.g., planning, multi-loops)

- **sensors**
- **actuators**

**Perception** → **Computation** → **Action**

Environment
Note:
Controller architecture can be of any type but worth using GA/PSO if the number of parameters to be tuned is important.
Block III – Distributed Systems

• Machine-learning for multi-unit systems
• Multi-level modeling
• Collective movements (flocking, formation, traffic)
• Division of labor and task allocation
Co-Learning Collaborative Behavior

Three orthogonal axes to consider (extremities or balanced solutions are possible):

- **Individual** and group fitness
- **Private** (non-sharing of parameters) and **public** (parameter sharing) policies
- Homogeneous vs. heterogeneous systems

Example with binary encoding of candidate solutions
Multi-Level Modeling Methodology

\[ \frac{dN_n(t)}{dt} = \sum_{n'} W(n' \mid n, t) N'_n(t) - \sum_{n'} W(n' \mid n, t) N_n(t) \]

- **Macroscopic**: rate equations, mean field approach, whole swarm
- **Microscopic – Agent-based**: multi-agent models, only relevant robot feature captured, 1 agent = 1 robot
- **Microscopic – Module-based**: intra-robot (e.g., S&A, transceiver) and environment (e.g., physics) details reproduced faithfully

**Target system** (physical reality): info on controller, S&A, communication, morphology and environmental features
Ex. of Collective Movements
Reynolds’ Rules for Flocking

1. **Separation**: avoid collisions with nearby flockmates

2. **Alignment**: attempt to match velocity (speed and direction) with nearby flockmates

3. **Cohesion**: attempt to stay close to nearby flockmates
Implementation of Flocking Rules in Artificial Embedded Agents

Real robots

Realistic simulator (Webots)
278 e-pucks at EPFL (BC atrium)
Graph-Based Distributed Control
Distributed Intelligent Transportation Systems

- Multi-vehicle dynamic car simulator (Webots)
- Noise-resistant automatic design methods
- Driving assistance systems
- Possible applications: intelligent transportation systems
- [Zhang, 2001 – 2006, Caltech; Gowal 2008 –, EPFL]
- Sponsors:
The control of task allocation explained with a fixed-threshold model

The lower the threshold, the lower can be the stimulus for achieving a given response; respectively, the lower the threshold, the higher will be the response of an individual for a given stimulus.
Market-Based Coordination

Robots simulate a market economy:

- Tasks, resources are commodities of measurable worth.
- When robot performs task:
  - gets paid for service it provided (+ $)
  - pays for resources it consumed (- $)
- Robots trade tasks and resources to maximize profit

Idea! pursuit of individual profit leads to efficient team solutions.

- Robust, fast, handle complex tasks
- Can take advantage of centralized planning
Block IV – Distributed Sensing

• Sensor networks
• Robotic sensor networks
• Application examples:
  – Collective search
  – Collective coverage
MICAz

- Atmel ATmega128L
  - 8 bit microprocessor, ~8MHz
  - 128kB program memory, 4kB SRAM
  - 512kB external flash (data logger)
- Chipcon CC2420
  - 802.15.4 (Zigbee)
- 2 AA batteries
  - about 5 days active (15-20 mA)
  - about 20 years sleeping (15-20 µA)
- TinyOS
Wireless Sensor Networks

Features:
- Very low sampling frequency < 1Hz
- Very low power consumption: 25mW
- Solar panel
- Radio communication

Sensors:
- Air Temperature and Humidity
- Infrared Surface Temperature
- Anemometer
- Solar Radiation
- Pluviometer
- Soil moisture
- Soil pressure

http://sensorscope.epfl.ch

At DISAL: [Bahr, Vaussard, Jordan, 2009 -]
E-Puck Communication Module

- ZigBee ready platform
- TinyOS on MSP430 microcontroller
- ~10cm to ~100m transmission range via software and hardware signal attenuation
- I²C communication with E-Puck
- Programmable through E-Puck Bluetooth serial transmission
- Resetable via I²C commands
Mixed Mobile and Static Nodes

- 100 e-pucks, 60 mica-Z; audition
- Power-aware resource allocation
- Distributed attention algorithms
- Self-deployment, self-reconfiguration, self-gathering, interpolation
Distributed Boundary Coverage

- Case study: turbine inspection
- Goal: complete sensor coverage of the turbine/compressor blades
- Technical challenges limit possible designs of robotic sensors
- Test-bed: 40 Alice II
- Could pave the way for similar applications in coverage/inspection of engineered or natural, regular structures with heavily constraints on robotic equipment
- [Correll, 2003-2007]
Distributed Odor Source Localization

- Bio-inspired and information theoretical algorithms
- Distributed control and sensing
- Integration of anemometry, olfaction, and inter-robot localization capabilities
- Wind tunnel and simulation experiments
- Possible applications: environmental pollution, search and rescue operations, humanitarian demining
- [Lochmatter, 2005 -]
Block V – Distributed Manipulation and Building

- Aggregation and segregation
- Distributed building
- Self-assembling
Corpse Aggregation in the Ant 
*Messor Sancta*

Reduction of the spread of infection? Chretien (1996)
Aggregation/segregation using Robots

Becker et al, 1994

Holland & Melhuish, 1998
Aggregation and Collective Decision in Mixed-Societies

• Given an delimited area containing two similar or dissimilar (i.e. one bright and one dark) shelters infiltrate using mechatronic lures the insect society and participate to the collective decision, voting for a natural or artificial solution

• Applications:
  – Low-stress animal management
  – Alternative pest control

• Robot endowed with:
  – 1D Vision
  – Chemical camouflage
  – IR-based navigation and com modules

[Halloy et al, *Science* 2007]
Self-Assembling in Micro-/Nano-systems

Alice mobile robot

- Size: 2 centimeters
- Typical swarm size: a few dozen units
- Sensing, computation, communication
- Controllable (but noisy) self-locomoted units

SU-8 microfabrcicated parts

- Size: 50 to 500 μm
- Typical swarm size: $10^3$ to $10^6$ units
- No sensing, no computation, no communication, but local interactions
- No self-locomotion, stochastic motion

[Mermoud, 2006 -]
Conclusion
Take Home Messages

1. Course is rich and intensive; consider your overall semester load before enrolling

2. Balanced theoretical contents and hands-on experience; first two lab sessions give an idea of the workload (but no real/simulated embedded systems)

3. Course projects are aligned with course content and current research (TAs/staff ideas …); have a look to past course project on the web

4. Check previous editions, discuss with TAs if appropriate, to decide whether to definitively enroll in the course
Distributed Intelligent Systems – W1
Part II: An Introduction to Swarm Intelligence and Foraging Strategies in Ant Societies
Outline

• Swarm Intelligence
  – A possible paradigm and motivation
  – Key principles

• 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).
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
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
Embedded 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

Beyond bio-inspiration: combine natural principles with engineering knowledge and technologies
Some Definitions of Swarm Intelligence

• 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)
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
• “La coordination des taches, la regulation des constructions ne dependent pas directement des ouvriers, mais des constructions elles-memes. 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, piqure; ergon, travail, oeuvre = oeuvre 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).”]
It defines a class of mechanisms exploited by social insects to coordinate and control their activity via indirect interactions.

Stigmergy mechanisms can be classified in two different categories:

- **quantitative (or continuous) stigmergy**
- **qualitative (or discrete) stigmergy**

[Theraulaz & Bonabeau., *Alife J.* 1999]
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

Les différentes stratégies de récolte chez les fourmis

1. Récolte individuelle

Distribution spatiale de l’activité de récolte et carte des routes empruntées par les ouvrières chez la fourmi Neopenra apicalis
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

3. Recrutement de groupe

Recrutement de groupe chez la fourmi Camponotus socius
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

- Picking up food
- Laying a chemical trail
- Following the trail
- Deposition of food
- Stimulating nest mates

Food source  Foraging area  Nest
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
The Role of Randomness in the Organization of Foraging

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)

- **Successful recruitments (%):** Tetramorium impurum 18, Tapinoma erraticum 74
- **Length of trail followed (%):** Tetramorium impurum 17, Tapinoma erraticum 68

*Tapinoma* follow trails much more reliably than *Tetramorium* → depends on the environment the species have evolved (food scattering, etc.)
Probability of Trail Losing is Constant over Time

- 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)

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.
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

Nest

© J.-L. Deneubourg
Experimental Results
Microscopic Model
(Deneubourg 1990)

\[ P_A = \frac{(k + A_i)^n}{(k + A_i)^n + (k + B_i)^n} = 1 - P_B \]

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

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

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

\( A_i + B_i = i \)

\( \delta = \) 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

Total number of ants having traversed the bridge

Parameters that fit experimental data:

- $n = 2$
- $k = 20$

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

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

Food source

Nest

© J.-L. Deneubourg
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).

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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**
  - Nid
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 pheromone-based recruitment mechanisms; probably since nest-sources path not so misaligned 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
An Example with Three Different Food Sources

- Different richness
- Different distances from nest
- Obstacle-free environment
Ant Networks
Ant Super-Colonies

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)

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

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

[Aron, 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 Traveling 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 embedded 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 1

Books

Additional Literature – Week 1

Papers
• Peter Miller “Swarm Theory”, *National Geographic*, July 2007, pp. 126-147.