Collective and Swarm Intelligence

Master in Intelligent Systems, 2011–2012

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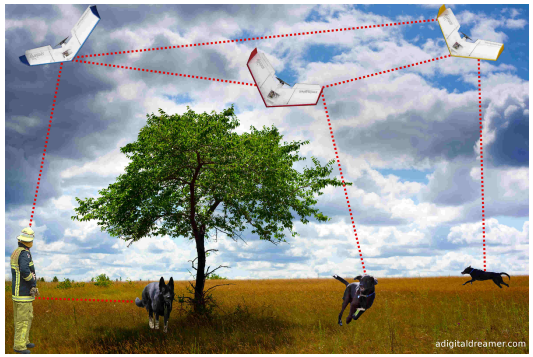
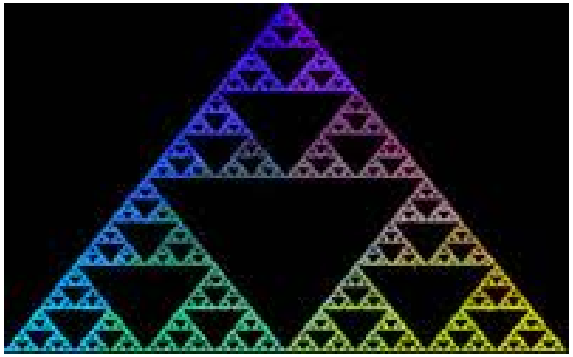
Road map

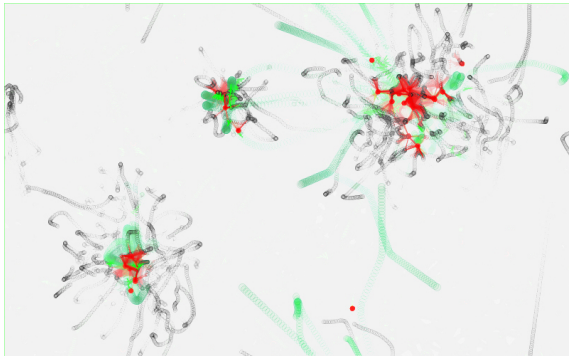
1. Collective and Swarm Intelligence (SI): Nature's inspiration, general principles, self-organization
2. Main characteristics of SI design
3. Focus: Swarm Robotics
4. Focus: Particle Swarm Optimization (PSO)

Swarm Intelligence (SI) in a nutshell

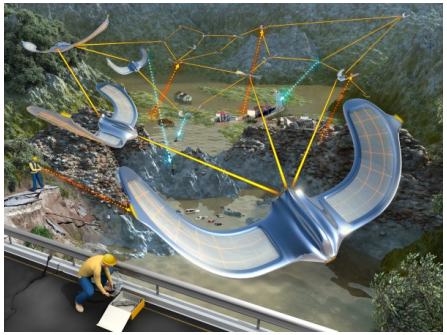
Swarm Intelligence: a relatively novel research field that deals with collective behaviors that result from the local interactions of individual *components* with each other and with their environment

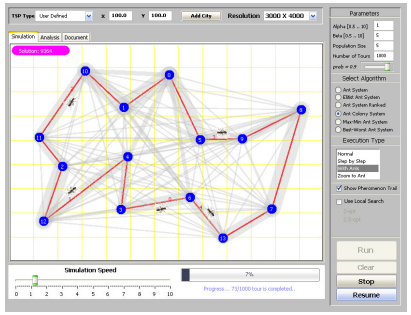






1. Modeling: Study of collective behaviors in *nature*, such as nest building, foraging, and item sorting in *insect societies*, and swarming, flocking, herding, and schooling behaviors in *vertebrates*





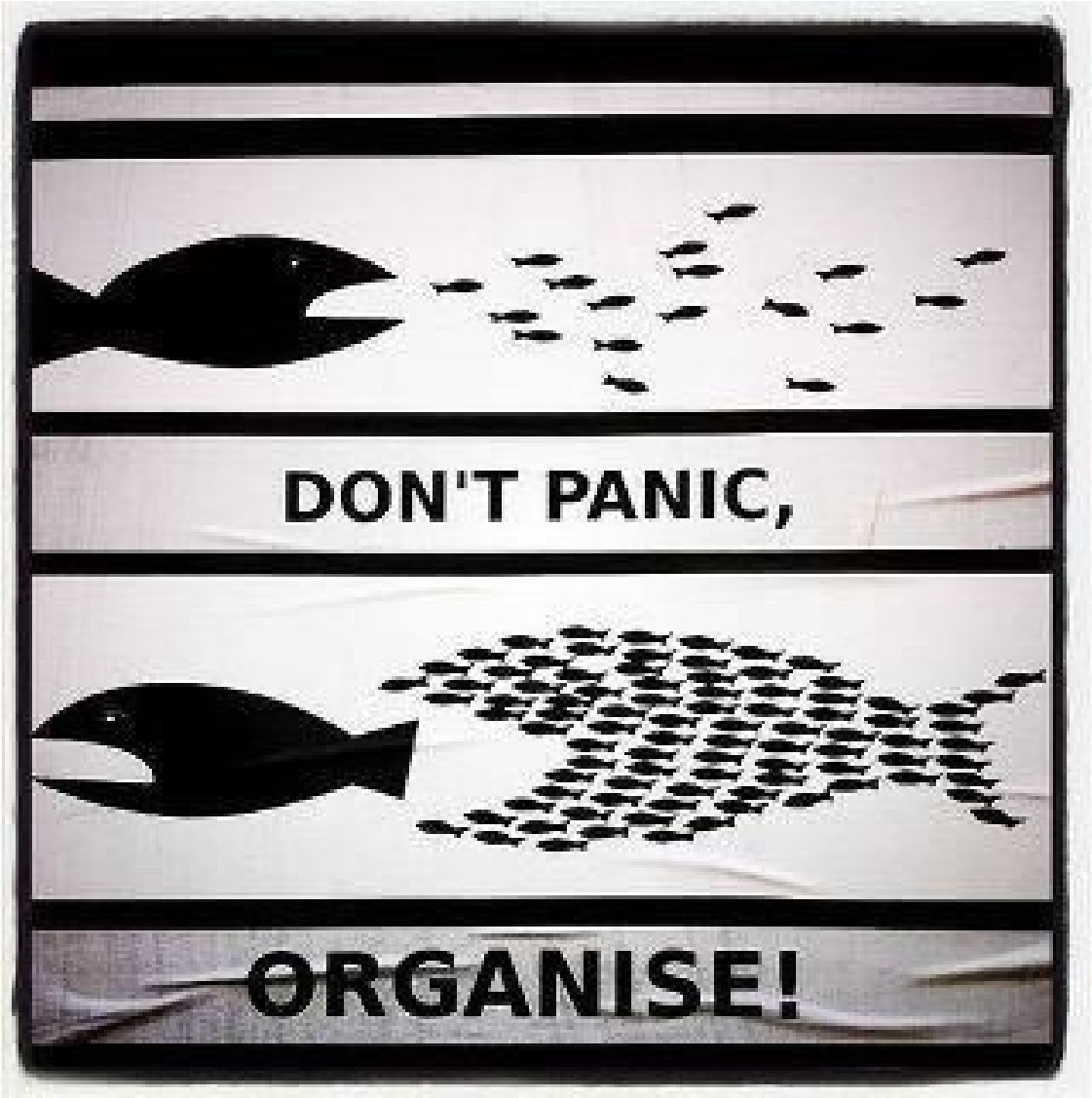
2. Engineering: Bottom-up design of distributed systems that display forms of useful and/or interesting behavior at the global level as a result of the actions of a number of units interacting with one another and with their environment at the local level. This design can get useful inspiration from Nature's systems!
   - Applications: *complex optimization problems, routing in networks, swarm robotics, . . .*

Acting as a swarm, not as an individual!

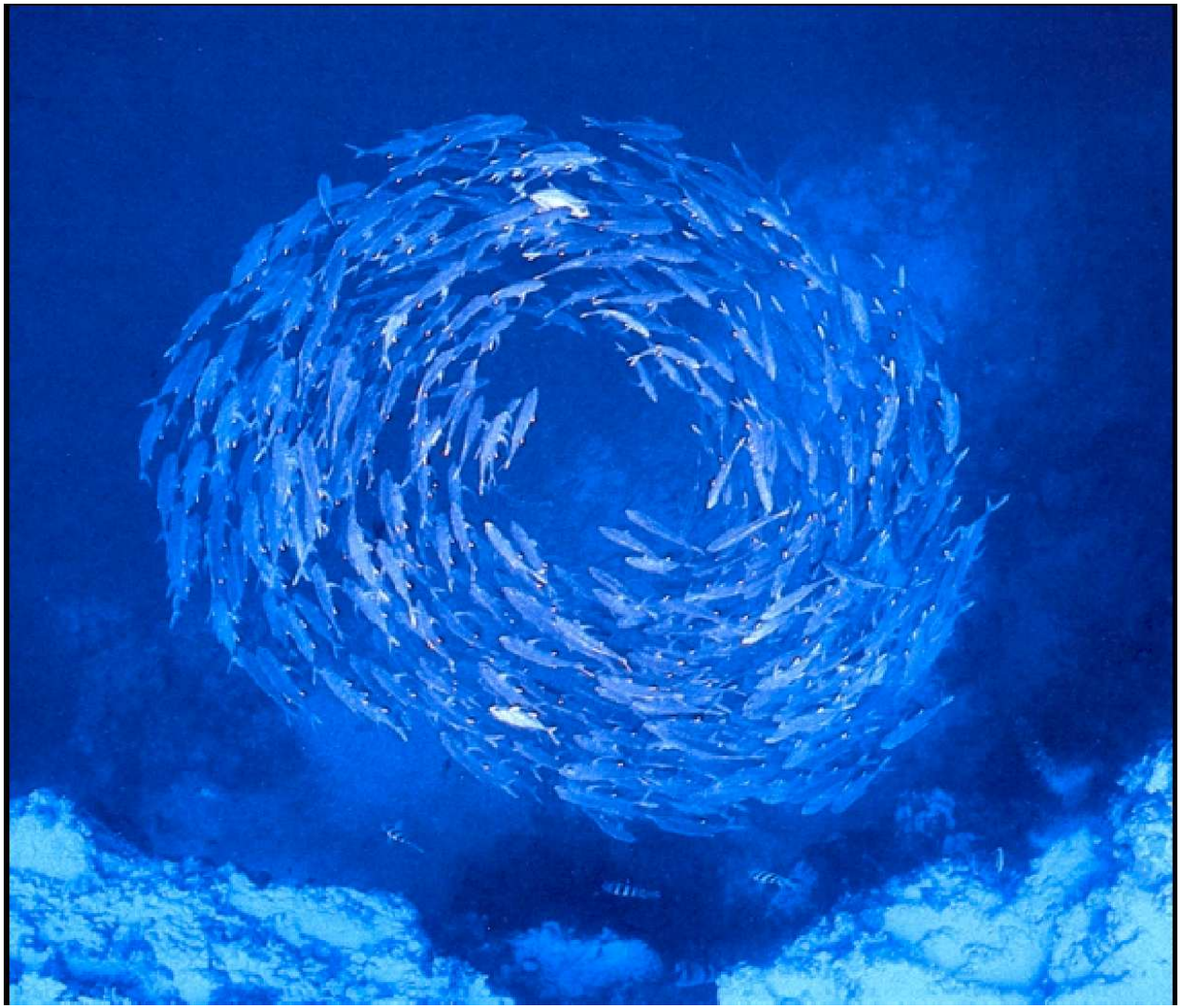
- Social behavior pays back!
- Many is better than one (right?)
- Implicit and/or explicit cooperation is an (evolutionary) advantage
- Acting as a unit is the key, here it is some compelling evidence!

https://www.youtube.com/watch?v=TWew0EqM7e4

Swarm intelligence *Manifesto*

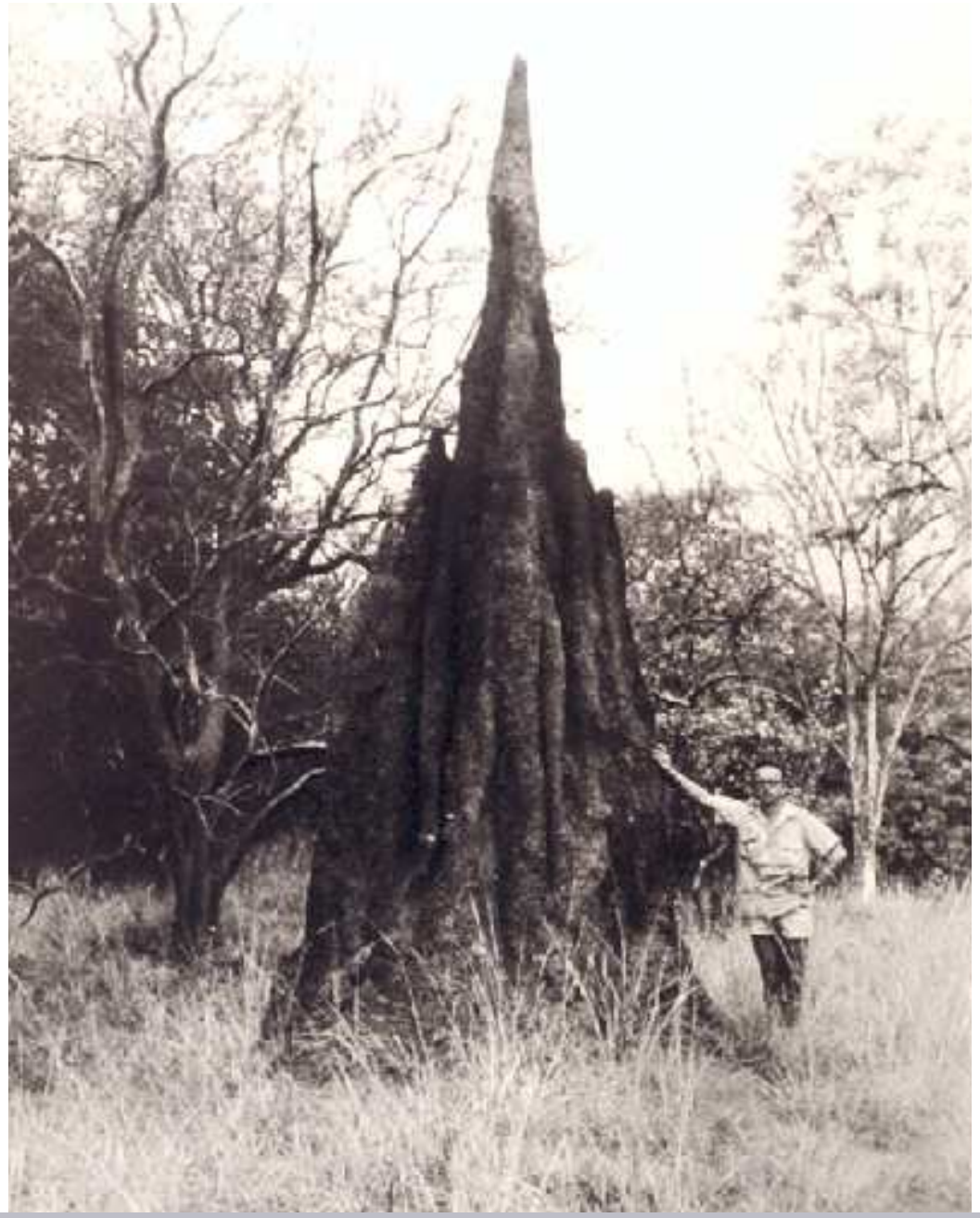


Fish schooling



Birds flocking in V-formation

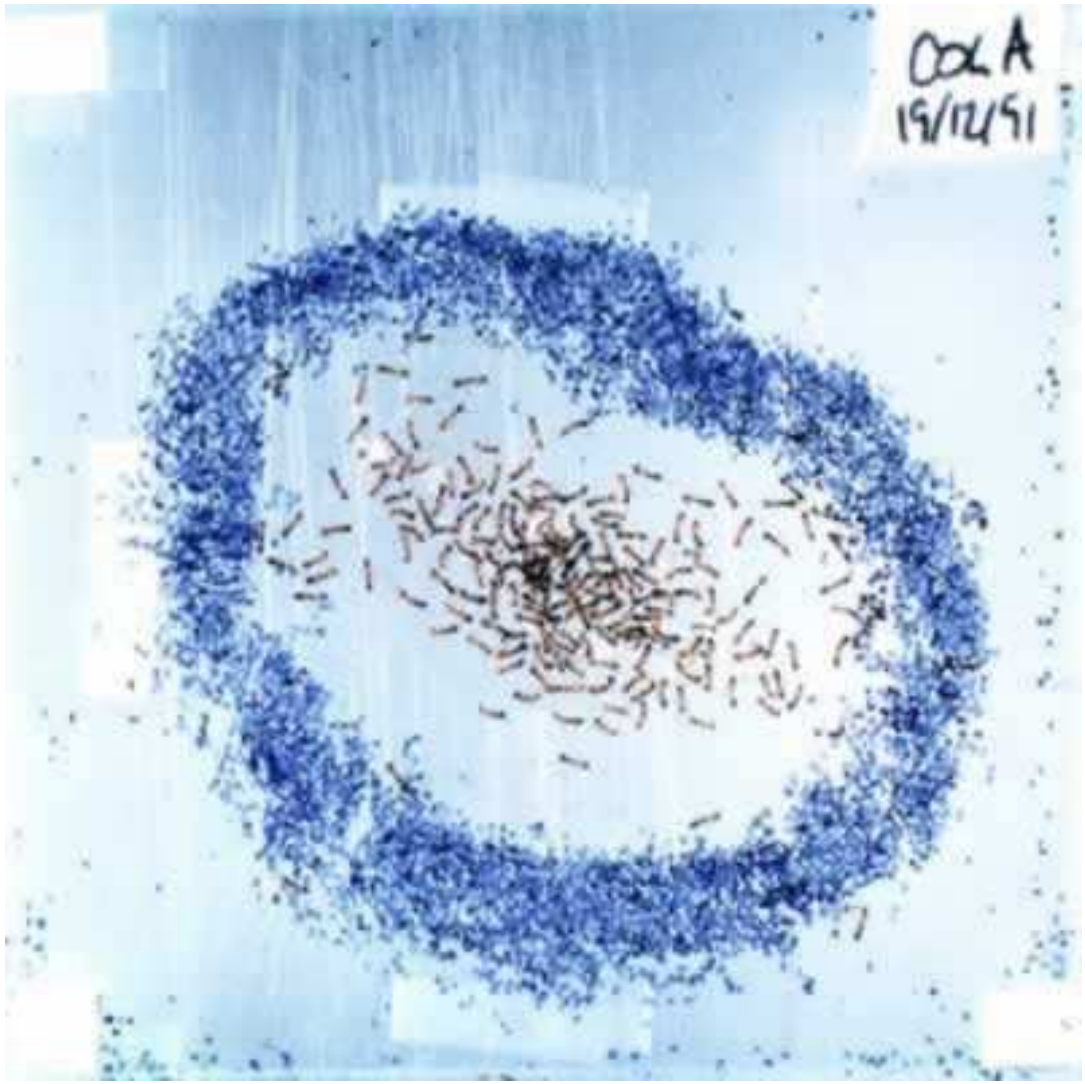
Termites' nest



Honeybee comb

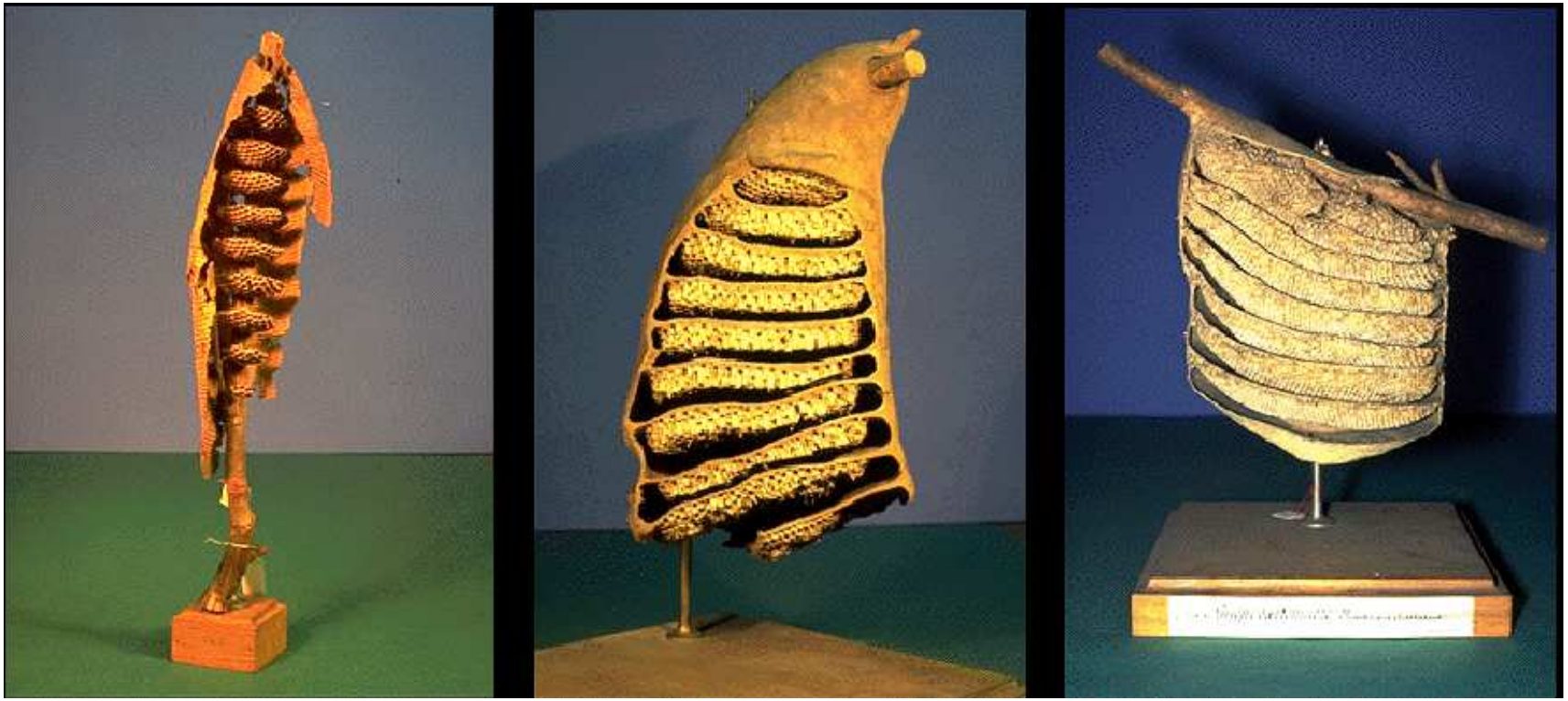
Cooperation in ant colonies

Ant chain



Ant wall

Wasps' nest



Ants, bees, and fishes and at work

- Ants: leaf-cutting, breeding, chaining
- Ants: Food catering
- Ants: Learning the shortest path between food and nest
- Ants: an agricultural and transportation system
- Bees: waggle dance to recruit workers
- Sardines: schooling and escaping predators

Locusts, birds, and fireflies at work

- Locusts: swarming and eating everything
- Birds: Roosting
- Fireflies: synchronized flashing

What do all these behaviors have in common?

- Distributed society of autonomous individuals/agents
- Control is fully distributed among the agents
- Communications among the individuals are localized
- Interaction rules and information processing seem to be simple: minimalist agent capabilities and interaction protocols
- System-level behaviors appear to transcend the behavioral repertoire of the single agent
- Deliberative and/or self-organizing cooperation is at work
- Local information propagates in a multi-step fashion
- The overall response of the system features:
  - Robustness
  - Adaptivity
  - Scalability

Swarm Intelligence design applies these same principles to obtain these same objectives as in Nature's complex adaptive systems

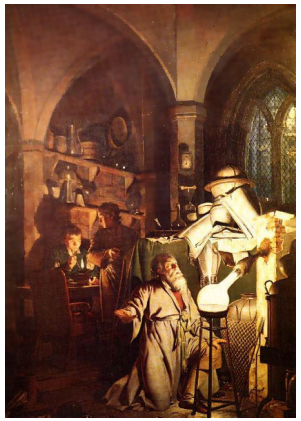
Bottom-up vs. Top-down design

- Ontogenetic and phylogenetic evolution has (necessarily) followed a bottom-up approach (grassroots) to design systems:
  - Instantiation of the basic units (atoms, cells, organs, organisms, individuals, . . .) composing the system and let them (self-)organize to generate more complex/organized system-level behaviors and/or structures
  - Population + Interaction protocols are “more important” than the single modules
- On the other hand, from an engineering point of view we can also choose a top-down approach:
  - Acquisition of comprehensive knowledge about the problem/system to deal with, analysis, decomposition, definition of a possibly optimal strategy

Challenges of SI design

- Given a task/problem to deal with, a number of design choices:
  1. Characteristics/skills of the agents
  2. Size of the population (related to the choice 1.)
  3. Neighborhood definition
  4. Interaction protocols and information to exchange
  5. Where the information is updated (agent, channel, environment)
  6. Use or not of randomness (or, heuristic decisions)
  7. Synchronous or asynchronous activities and interactions
  8. ...
- Lots of parameters
- Predictability and efficiency are important issues
- Is a top-down approach better?

The philosopher's stone of computing?



1. Create a large number of autonomous, minimalist units
2. Spread them in the environment and *forget* about them
3. Let them sensing and interacting locally
4. Let them exchange information and act cooperatively
5. They will (self-)adapt, (self-)learn, (self-)evolve, (self-)repair, (self-)organize . . .
6. They will create a fully autonomic system
7. They will do the job for us, adapting to changes in the environment, in the structure of the system, in the tasks . . .

This is the ultimate goal of swarm intelligence design!

Taxonomy based on Neighborhood, Communication, & Mobility

- Point-to-point: antennation, trophallaxis (food or liquid exchange), mandibular contact, direct visual contact, chemical contact, hardwired direct connections (neurons, cells), unicast radio contact
- Limited-range Broadcast: the signal propagates to some limited extent throughout the environment and/or is made available for a rather short time (e.g., use of lateral line in fishes to detect water waves), generic visual detection, radio broadcast
- Indirect: two individuals interact indirectly when one of them modifies the environment and the other responds asynchronously to the modified environment at a later time. This is called stigmergy [Grassé, 1959] (e.g., pheromone laying/following, post-it, web)
- Physical mobility: individuals autonomously move across the states of an embedding environment, such as connection topology changes over time (based on neighborhood and communication capability), different areas of the environment are accessed in parallel, density and connectivity of the system network depend on time and space
- Static positioning, state evolution: connection topology and environment embedding do not change over time. It is the information that moves in multi-hop fashion. The internal state of an individual changes over time, and, as a consequence, also it surrounding environment

SI algorithmic frameworks (and relatives)

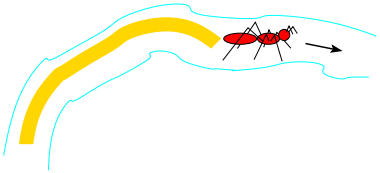
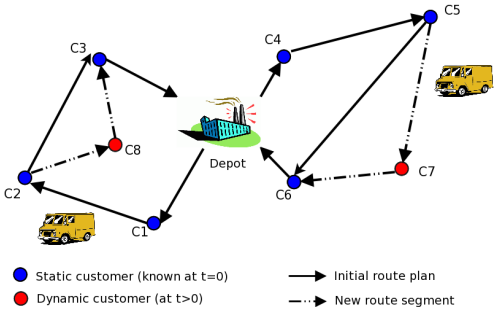
- Stigmergy, Mobility → Ant Algorithms and in particular to Ant Colony Optimization (ACO) [Dorigo & Di Caro, 1999], which is based on the shortest path finding abilities of ant colonies
- Stigmergy → Cultural Algorithms [Reynolds, 1994], are population-based algorithms derived from processes of cultural evolution and exchange in societies
- Broadcast-like, Mobility → Particle Swarm Optimization [Kennedy & Eberhart, 2001], related to schooling and flocking behaviors
- Point-to-point → Hopfield neural networks [Hopfield, 1982], derived from brain's structure and behavior
- Point-to-point and neighbor broadcast → Cellular Automata [Wolfram, 1984], Gossip algorithms [Demers et al., 1987]
- Different combinations of communication and mobility → Swarm robotics, Adaptive Routing and Information Gossip in telecommunication networks
- Genetic algorithms, Artificial immune systems, . . .

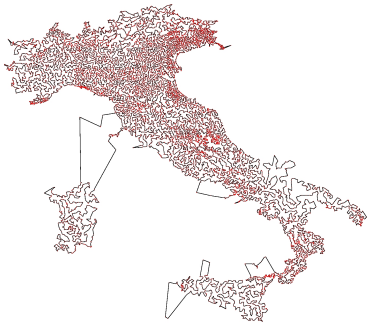
IDSIA research on the application of SI design principles

- Swarm robotics: study of cooperation, interaction and self-organization in systems composed of many (relatively) simple robots

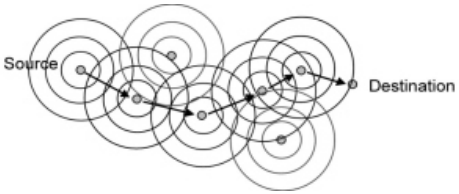


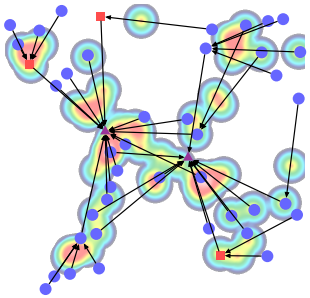
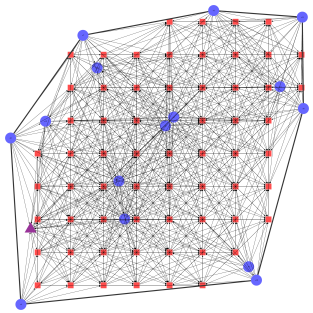
- Combinatorial optimization: reverse-engineering of the *pheromone-based shortest path finding behavior* of *ant colonies* to solve complex optimization problems such as the *Traveling Salesman Problem (TSP)* or the *Vehicle Routing Problem (VRP)* (both in academic and industrial contexts)



- Network routing: application of the same behaviors from ant colonies to solve problems of data routing (i.e., *minimum length/delay paths*) in dynamic telecommunication networks



Self-assembly in homogeneous swarms

- Swarm-bots project, EU-funded (2002-2005): self-assembly and cooperation in homogeneous robotic swarms

http://www.youtube.com/watch?v=CJOubyiITsE

Self-organization and cooperation in heterogeneous swarms

- Swarmanoid project, EU-funded (2006-2010): communication, self-organization, and cooperation in heterogeneous swarms

http://www.youtube.com/watch?v=M2nn1X9Xlps

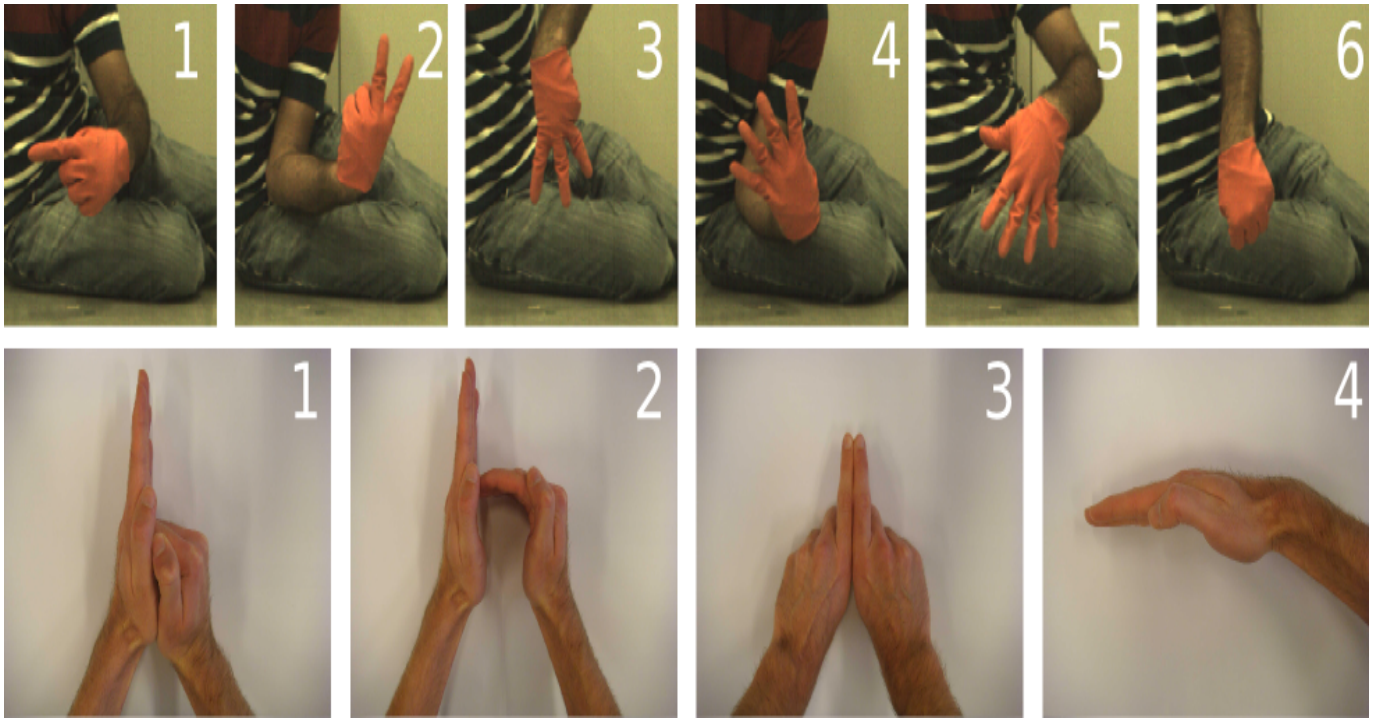
Self-organized path finding

http://www.youtube.com/watch?v=Ghphiawt058

http://www.youtube.com/watch?v=hYhid0dcAtI

Human-swarm interaction and cooperation

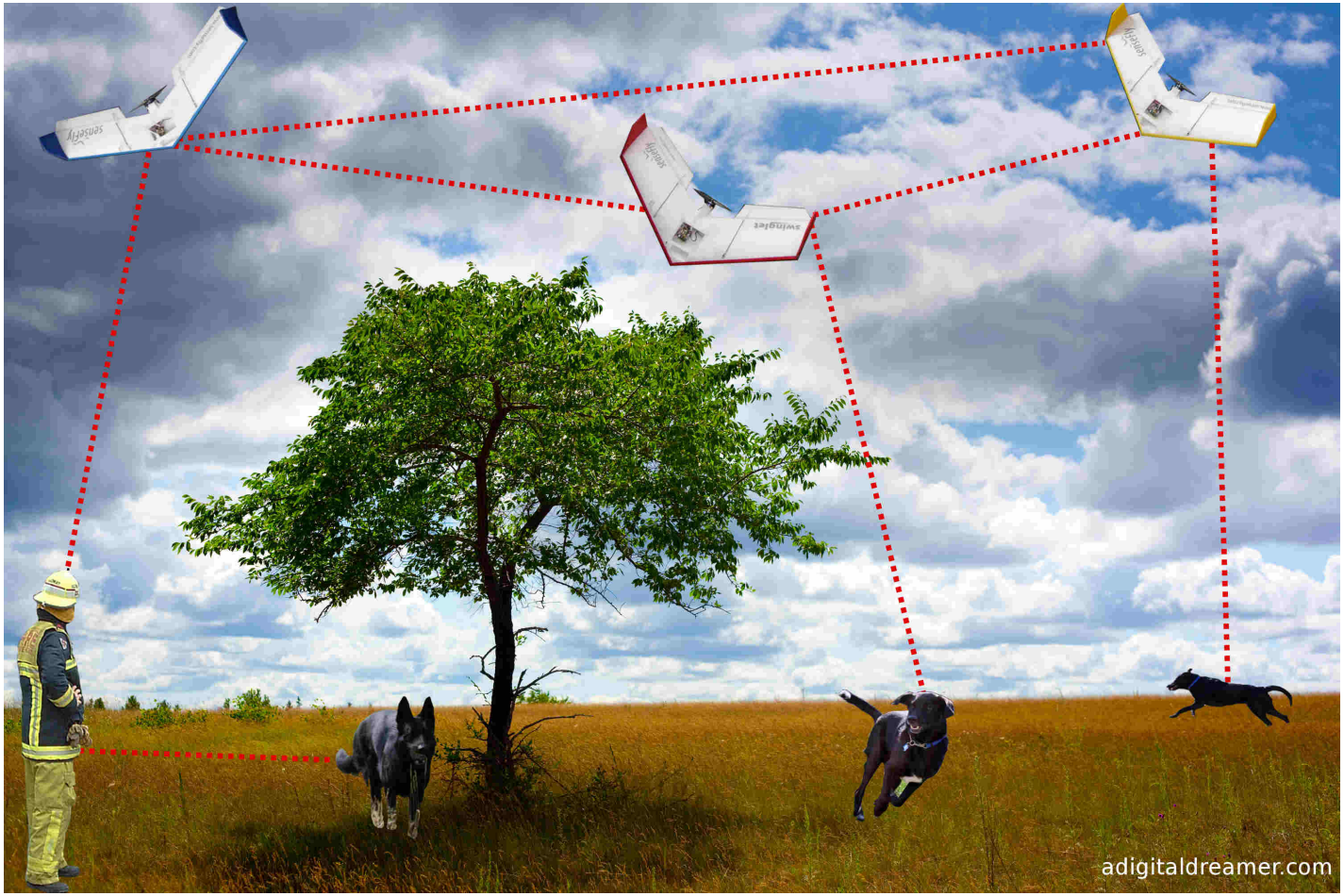
- NCCR Robotics project, Swiss-funded (2011-2014): symbiotic peer-to-peer interaction and cooperation between humans and robotic swarms



http://www.youtube.com/watch?v=kHpXEcYanvY

Mixed swarms of humans, animals, and robots

- SWARMIX project, Swiss-funded (2011-2014): cooperation and interaction in mixed swarms of humans, dogs, and robots for *search and rescue missions*



https://www.youtube.com/watch?v=C-ix2iBMoyY

Swarm-bots, swarmanoids, self-reconfiguration, crowds, . . .

- The Swarmanoid system

  http://www.youtube.com/watch?v=M2nn1X9Xlps

- Swarming can be very scary for humans!

  http://www.youtube.com/watch?v=CJOubyiITsE

- Morphogenesis: reshaping swarm structure

  http://www.youtube.com/watch?v=-G66iL__VdA

- Another example of self-reconfiguring swarms, with human interaction

  http://www.youtube.com/watch?v=se318w2LXD0

- The Smavnet project: flying like birds

  http://www.youtube.com/watch?v=pfYs5C8D4uk

- Human crowd simulations

  http://www.youtube.com/watch?v=Hc6kng5A8lQ

- Human-swarm interaction at IDSIA

  https://www.youtube.com/watch?v=Q9OOGf7YCOc