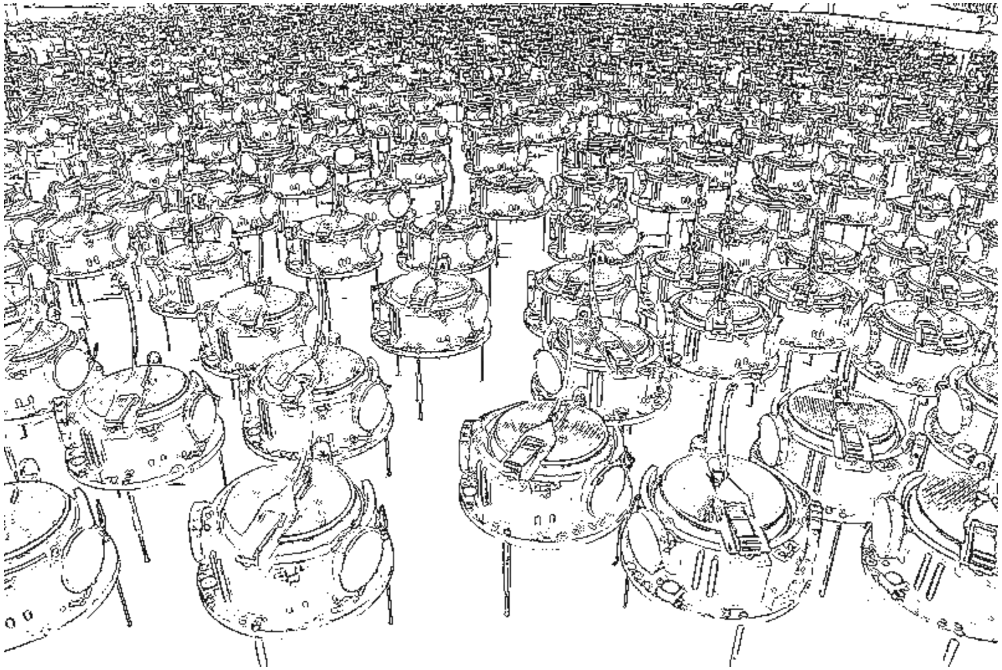
Intelligent Multi Agent Systems



Swarm Intelligence and Swarm Robotics

Gerhard Neumann

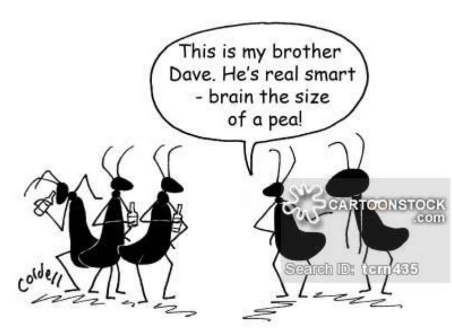
Motivation

So far, we have looked at mathematical models that allow a few agents to interact. However:

- Optimal solutions are intractable
- Limited to a couple of agents
- Mostly toy examples can be solved

Yet, in nature we observe a multitude of multi-agent systems that show very complex behavior

- Does an ant have a build-in Dec-POMDP solver? Most likely not.....
- Maybe we do not need to model everything in order to generate complex behavior?



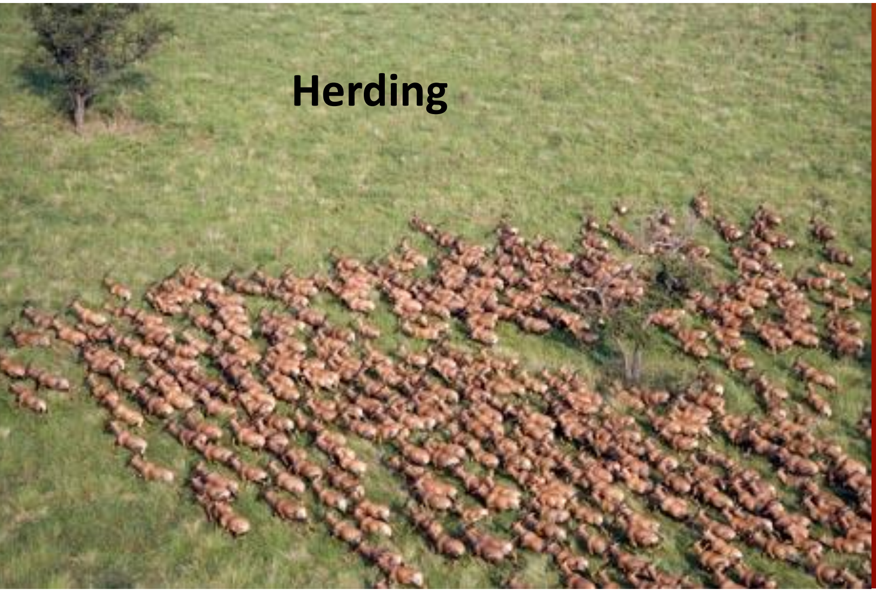
Emergent Collective Behavior

Yet, in nature we observe a multitude of multi-agent systems that show very complex behavior

- Coordinated and purposeful navigation of several individuals
- Each individual uses only local information about the presence of other individuals and of the environment.
- There is no predefined group leader.

Emergent Collective Behavior

In some cases there is a leader and more restrictive rules on relative motion, but individuals still use local information to decide how to move.



Swarm Intelligence

"The emergent collective intelligence of groups of simple agents."
(Bonabeau et al, 1999)

Main principles:

1) The swarm can solve complex problems that a single individual with simple abilities (computational or physical) could not solve.

2) The swarm is composed of several individuals, some of which may be lost or make mistake, but its performance is not affected.

3) Individuals in a swarm have local sensory information, perform simple actions, have little/no memory; they do not know the global state of the swarm or its goal.

Bees

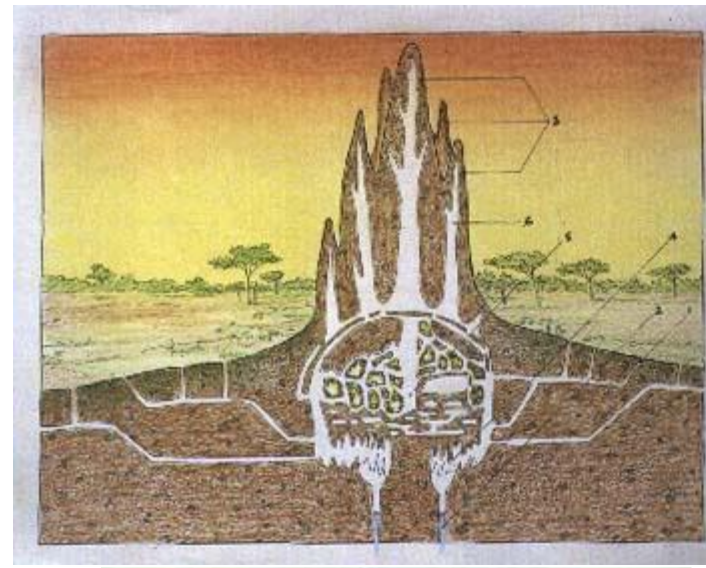
- Colony cooperation
- Regulate hive temperature
- Efficiency via Specialization: division of labour in the colony
- Communication : Food sources are exploited according to quality and distance from the hive

Wasps

- Division of labour: Pulp foragers, water foragers & builders
- Complex nests
  - Horizontal columns
  - Protective covering
  - Central entrance hole

Termites

- Cone-shaped outer walls and ventilation ducts
- Brood chambers in central hive
- Spiral cooling vents
- Support pillars



Ants

- Organizing highways to and from their foraging sites by leaving pheromone trails
- Form chains from their own bodies to create a bridge to pull and hold leafs together with silk
- Division of labour between major and minor ants
- Cemetry formation

Swarm Intelligence

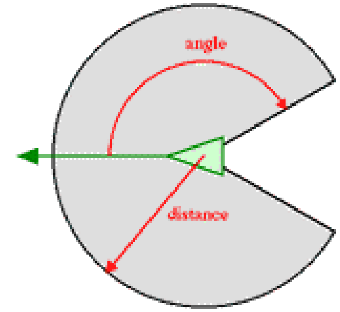
Interesting behaviour

- group foraging of social insects
- cooperative transportation
- division of labour
- nest-building of social insects
- collective sorting and clustering
- Navigation and predator evasion

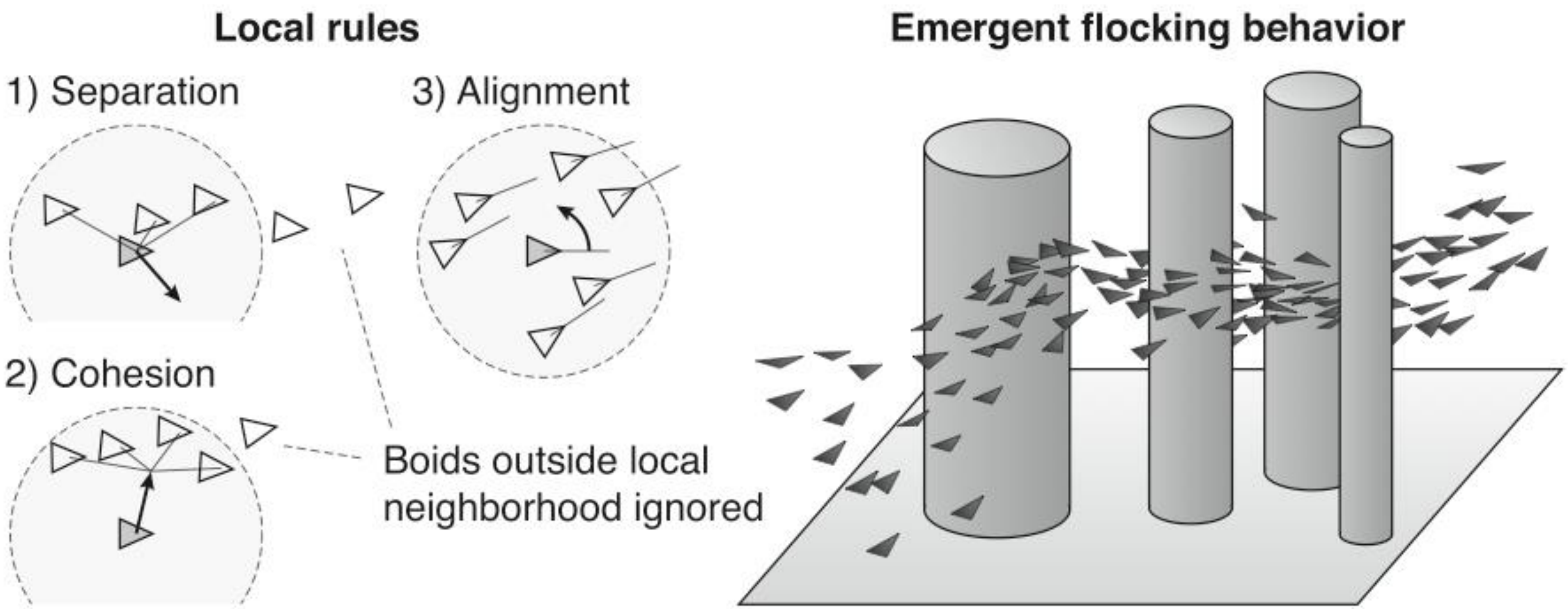
Outine

- Algorithms from Swarm Intelligence
  - Flocking
  - Particle Swarm Optimization
  - Ant Colony Optimization
- Swarm Robotics
  - Coordinated Exploration
  - Transportation
  - Physcial Cooperation

Reynolds Flocking (1987)



Sensing: Boid perceives angle and distance of neighboring boids



1. Separation: Boid maintains a given distance from other boids
2. Cohesion: Boid moves towards center of mass of neighboring boids
3. Alignment: Boid aligns its angle along those of neighboring boids

Examples of Character Animation

Emergent coordinated behavior. The approach is applicable to any type of animated characters in groups where behavior coordination is used.

The Lion King, 1994 (Walt Disney)

Particle Swarm Optimization

Particle Swarm Optimization is an optimization algorithm inspired upon birds flocking to find the best food area.

A caricature scenario:

- Find the area with the highest concentration of food (insects).
- Each bird can shout to their neighbors how many insects are at its location.
- Birds also remember their own best experienced location.

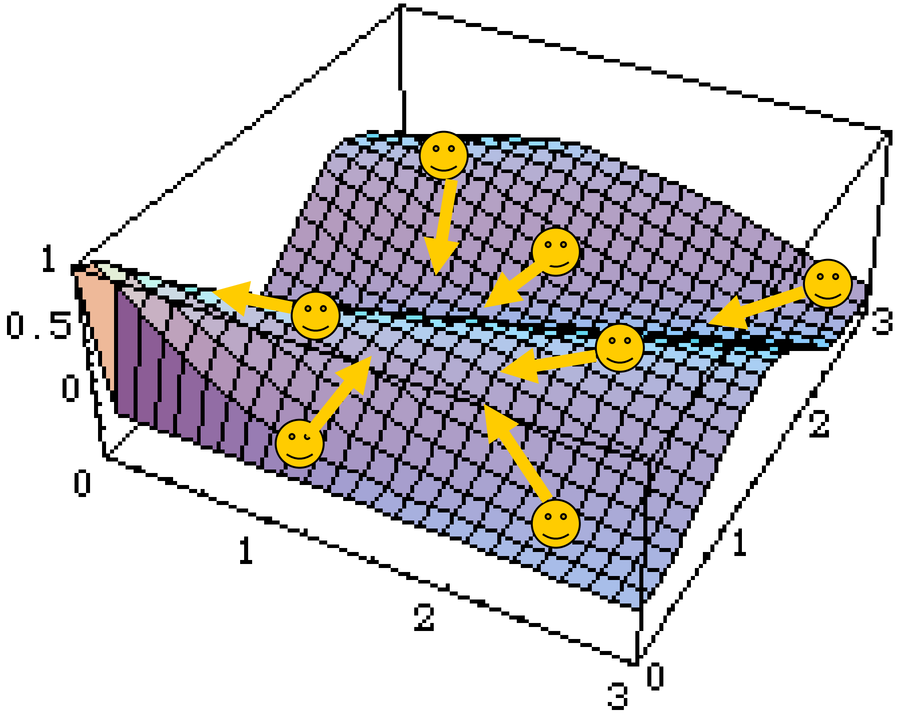
The flock is most likely to succeed when birds combine **three strategies**:

1) **Brave**: keep flying in the same direction
2) **Conservative**: fly back towards its own best previous position
3) **Swarm**: move towards its best neighbor

From Birds to Particles

The bird location describes the search space of the optimization problem.

- birds are the local solutions for that problem.
- They are called *particles* because they are very simple.



A particle **p** is described by:

- **s:** its position; e.g.: x, y
- **v:** its velocity; e.g. angle and distance of next step
- **f:** its performance; e.g.: value of the function at its location

Particle's perception

- A particle perceives performances and positions of neighboring particles.
- It can also tell which is the best particle among its neighbors

  $\boldsymbol{p}_g \ldots$ position of best neighbor

- A particle remembers the position where it obtained the best performance so far

  $\boldsymbol{p}_i^* \ldots$ position of best performance for particle i

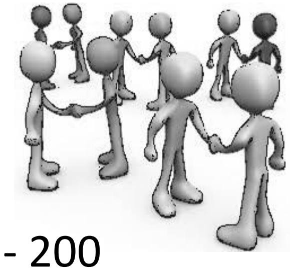
Update for particle i:

$$\text{Velocity: } \boldsymbol{v}_i = \boldsymbol{v}_i + c_1 \text{diag}(\boldsymbol{r}_1)(\boldsymbol{p}_i^* - \boldsymbol{x}_i) + c_2 \text{diag}(\boldsymbol{r}_2)(\boldsymbol{p}_g - \boldsymbol{x}_i)$$

$$\text{Position: } \boldsymbol{x}_i = \boldsymbol{x}_i + \boldsymbol{v}_i$$

- r1 and r2 are random vectors between 0 and 1
- Randomizes search

Initialization

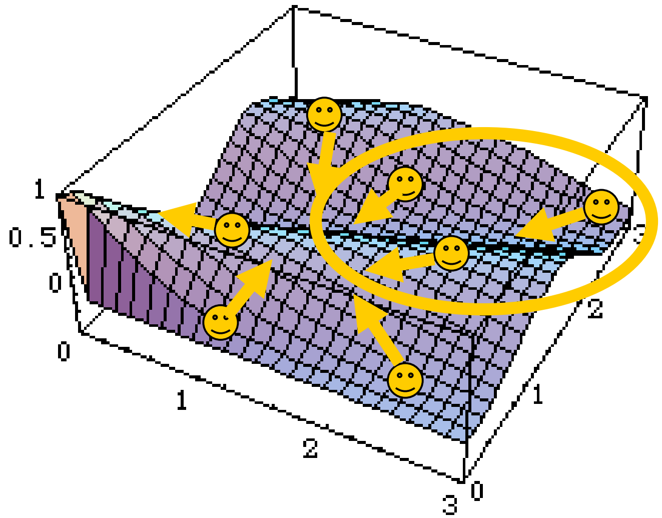


Swarm size: Typically 20 particles for problems with dimensionality 2 - 200

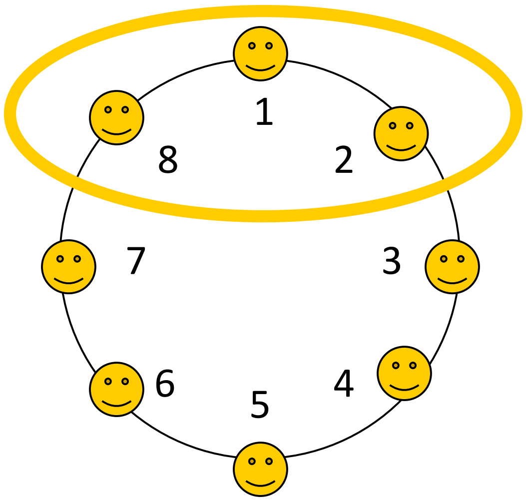
Initial position of each particle: Random

Neighborhood topology: Global, geographical or social (list based)

Geographical neighborhood



Social neighborhood



Neighborhood size: Typically 3 to 5

Set **max velocity** to v_{max}; if **v**(t+1) is larger, clip it to v_{max}

Iterate until best solution is found or no further improvement

Ants

Why are ants interesting?

- ants solve complex tasks by simple local means
- ant productivity is better than the sum of their single activities
- ants are 'grand masters' in search and exploitation

Which mechanisms are important

- cooperation and division of labour
- adaptive task allocation
- work stimulation by cultivation
- pheromones

Self-Organization

What are there principal mechanisms of natural organization?

„Self-organization is a set of dynamical mechanisms whereby structures appear at the global level of a system from interactions of its lower-level components.”

(Bonabeau et al, in Swarm Intelligence, 1999)

4 basic principles:

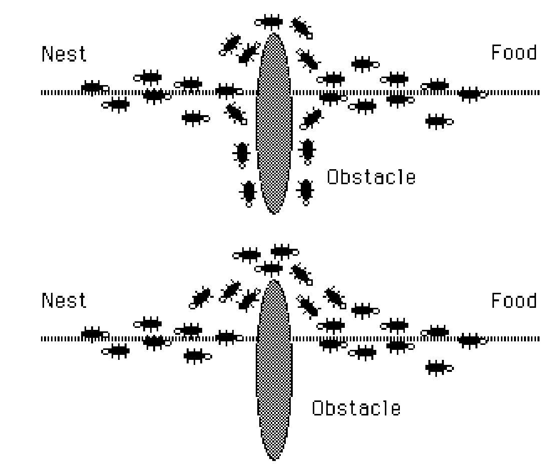
- positive feedback (amplification)
- negative feedback (for counter-balance and stabilization)
- amplification of fluctuations (randomness, errors, random walks)
- multiple interactions

Stigmergy

Stigmergy: *stigma* (sting) + *ergon* (work)

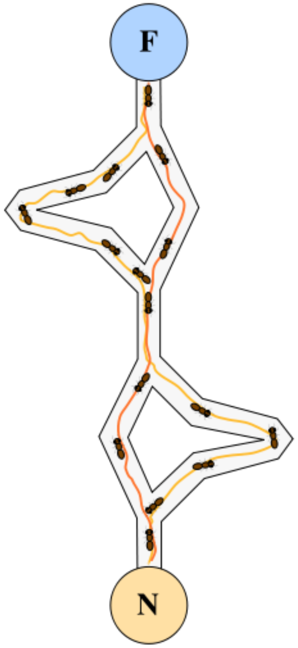
= 'stimulation by work'

- indirect agent interaction via modification of the environment
- environmental modification serves as external memory
- work can be continued by any individual
- the same, simple, behavioural rules can create different designs according to the environmental state



Finding the Shortest Path

1) As they move, ants deposit pheromone
2) Pheromone decays in time
3) Ants follow path with highest pheromone concentration
4) Without pheromone, equal probability of choosing short or long path

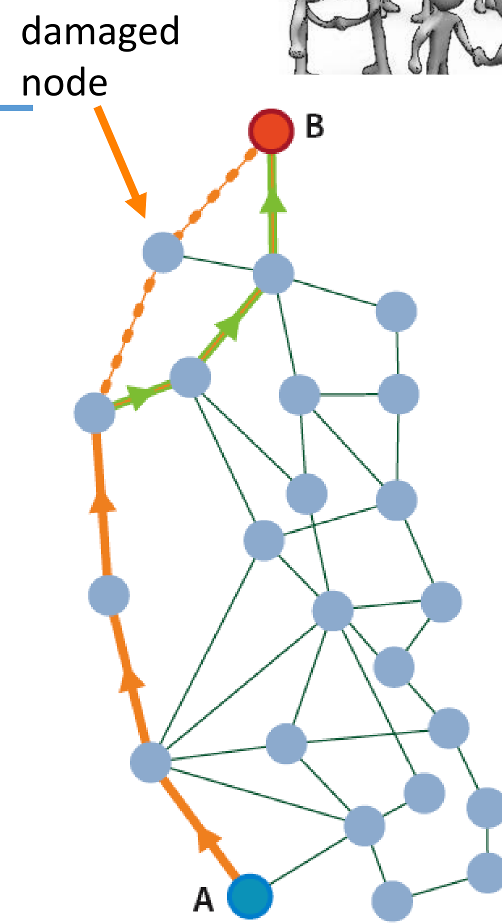


Shorter path allows higher number of passages and therefore pheromone level will be higher on shorter path.

Ants will increasingly tend to choose shorter path.

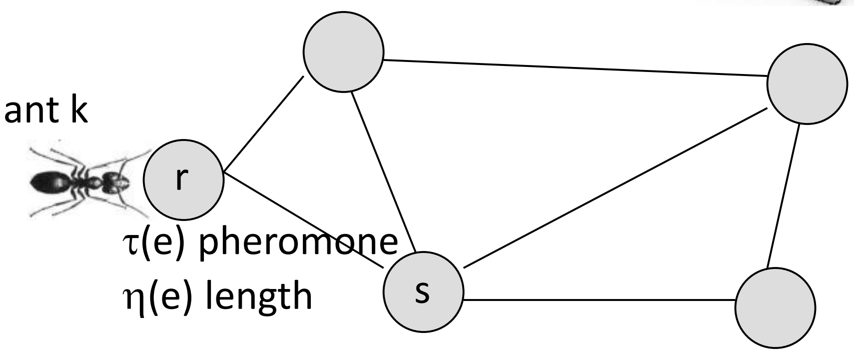
Goss et al. 1989, Deneubourg et al. 1990

Ant Colony Optimization



- Ant Colony Optimization is an algorithm developed by Dorigo et al. in 1994 inspired upon stigmergic communication to find the shortest path in a network.
- Typical examples are telephone, internet, and any problem that can be described as Travel Salesman Problem. Used/adopted by British Telecom, MCI Worldcom, Barilla, etc.
- Advantage of algorithm is that, as ants do, it allows dynamic rerouting through shortest path if one node is broken. Most other algorithms instead assume that the network is static.

Ant Colony Optimization



- Each ant generates a complete tour of nodes using probabilistic transition rule encouraging choice of edge with high pheromone and short distance
- Pheromone level on each edge is updated by considering evaporation and deposit by each ant
- Pheromone levels only of edges traveled by best ant are increased in inverse proportion to length of path.
- Result is that edges that belong to short tours receive greater amount of pheromone

Transition Rule

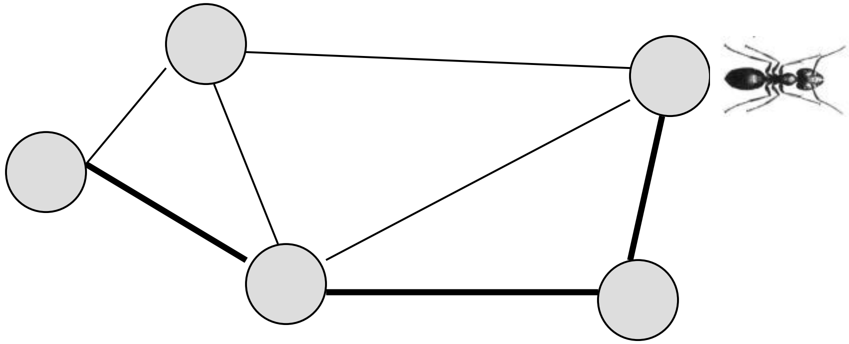
With probability q, take edge with maximum pheromone level

With probability (1-q), explore other edges

$$p(e,r) = \frac{\tau(e)\eta(e)^\beta}{\sum_{e' \in E(r)} \tau(e')\eta(e')^\beta}$$

- Ant *k* sitting at node r takes edge *e* with probability proportional to amount of pheromone τ and length η of edge relative to all other edges connected to *r* that remain to be visited.
- Choice of exponent β determines importance of edge length with respect to pheromone.

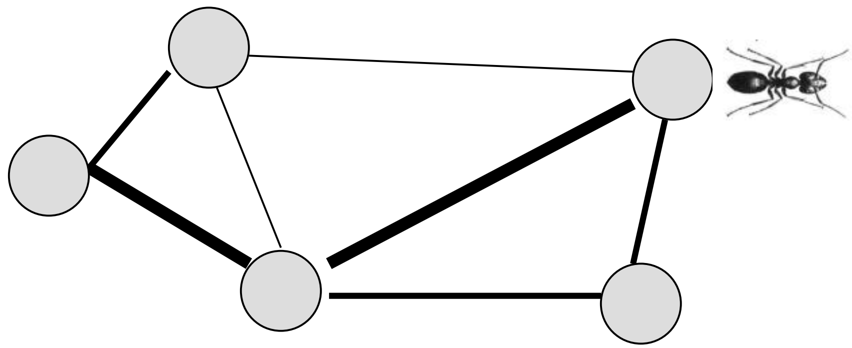
Pheromone Level Update: Local



$$\tau(e) \leftarrow (1-\rho)\tau(e) + \rho\tau_0$$

The pheromone level of each edge visited by an ant is decreased by a fraction (1- rho) of its current level and increased by a fraction rho of the initial level *tau0.*

Pheromone Level Update: Global



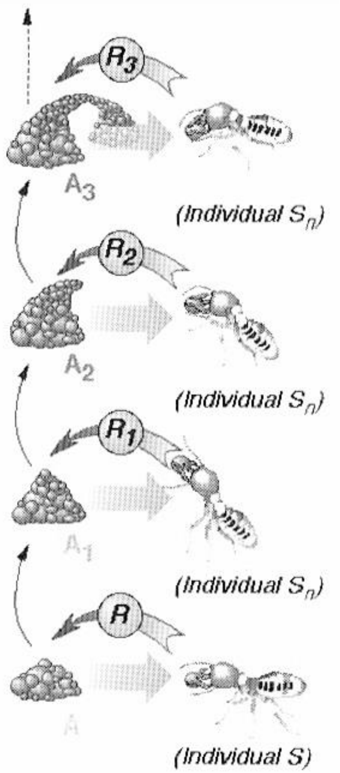
$$\tau(e) \leftarrow (1-\rho)\tau(e) + \rho L^{-1}$$

When all ants have completed their tours:

- Compute length L of the shortest tour
- pheromone levels of the edges of this shortest path are updated in inverse proportion to the path length.

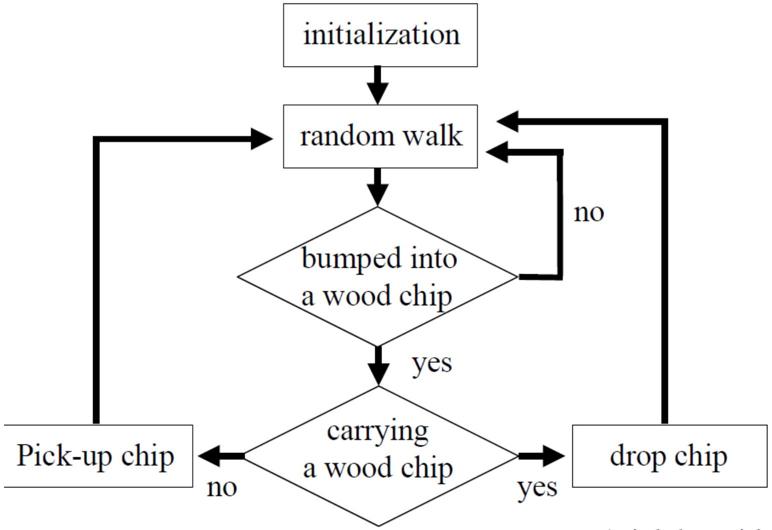
Other stigmantic behaviours

Stigmergy in termite nest building

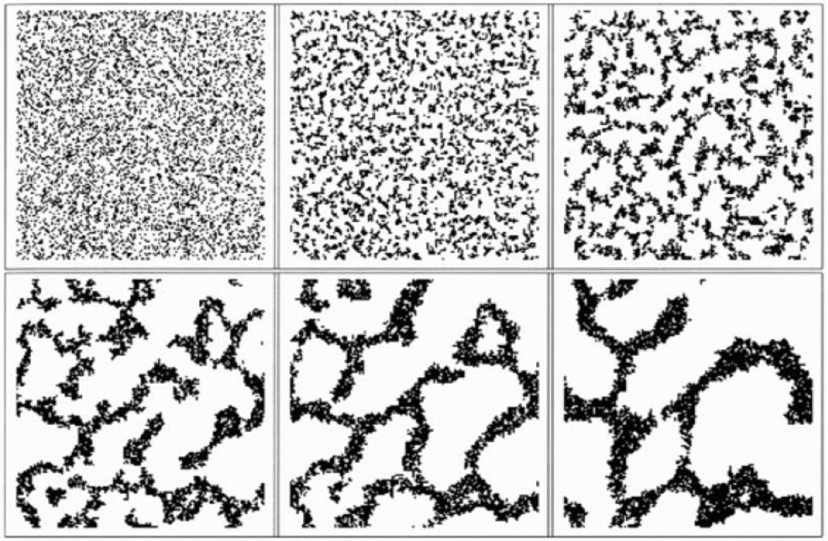


Other stigmantic behaviours

Clustering in Termites:



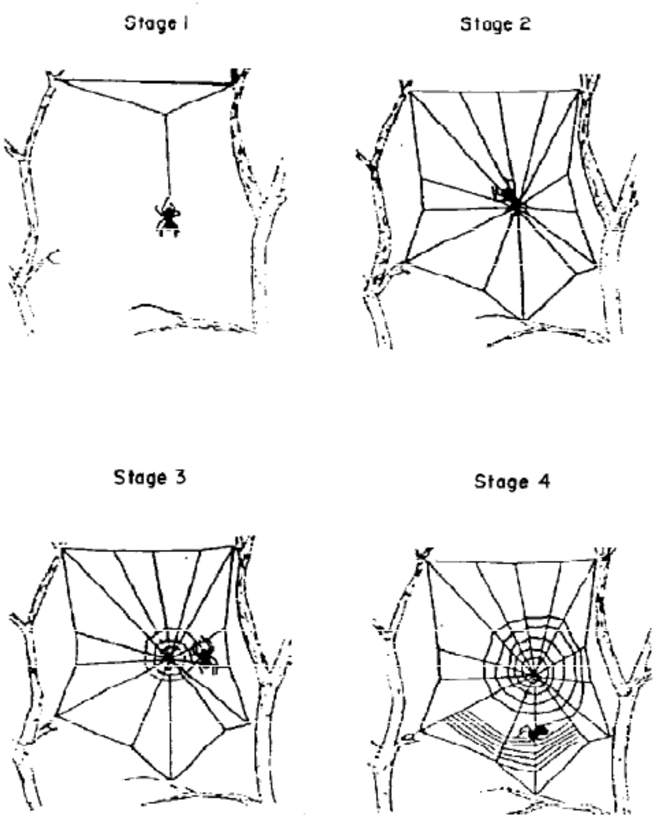
(Mitchel Resnick, 1994)



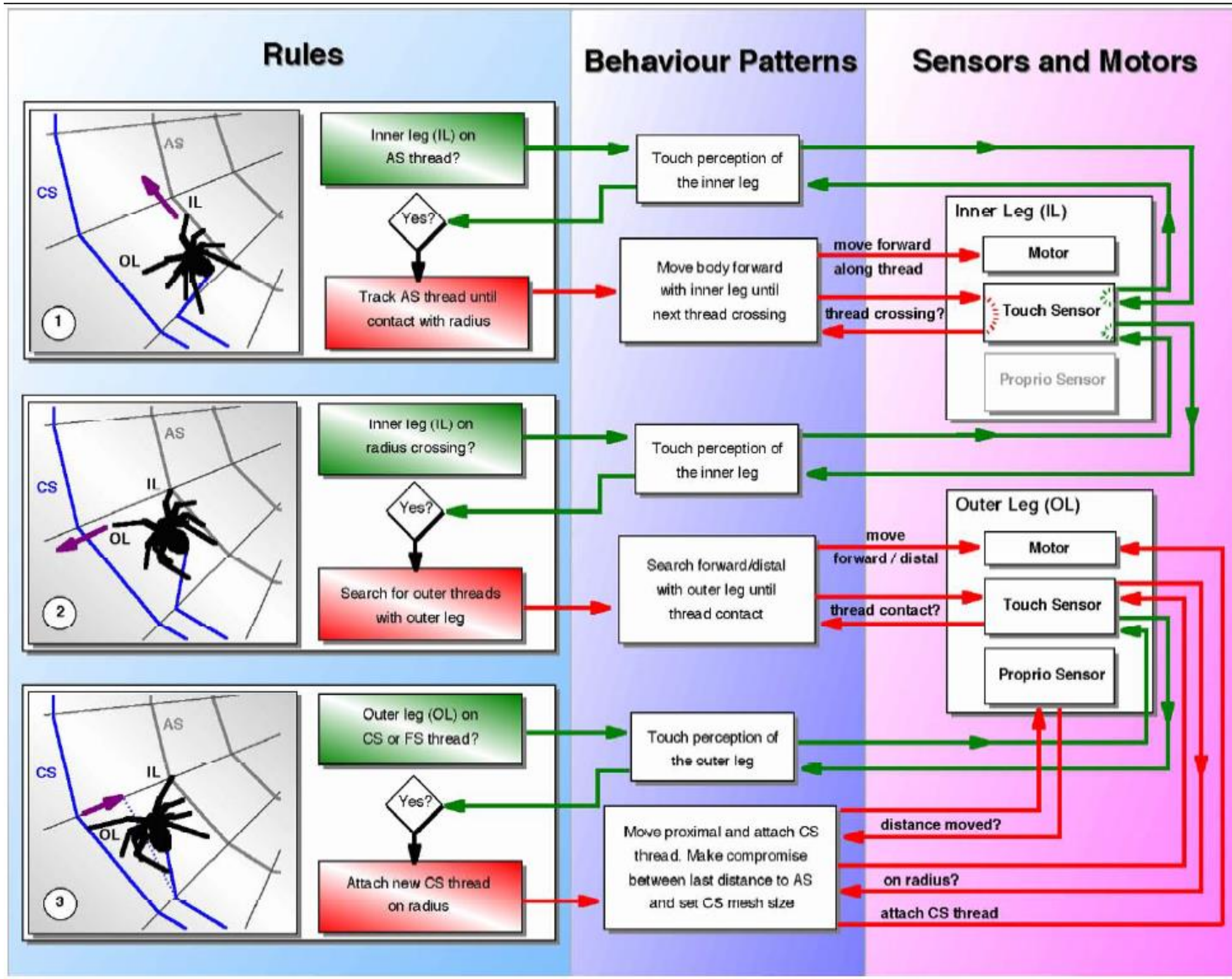
(Mitchel Resnick, 1994)

Other stigmantic behaviours

Stigmergy in spider webs

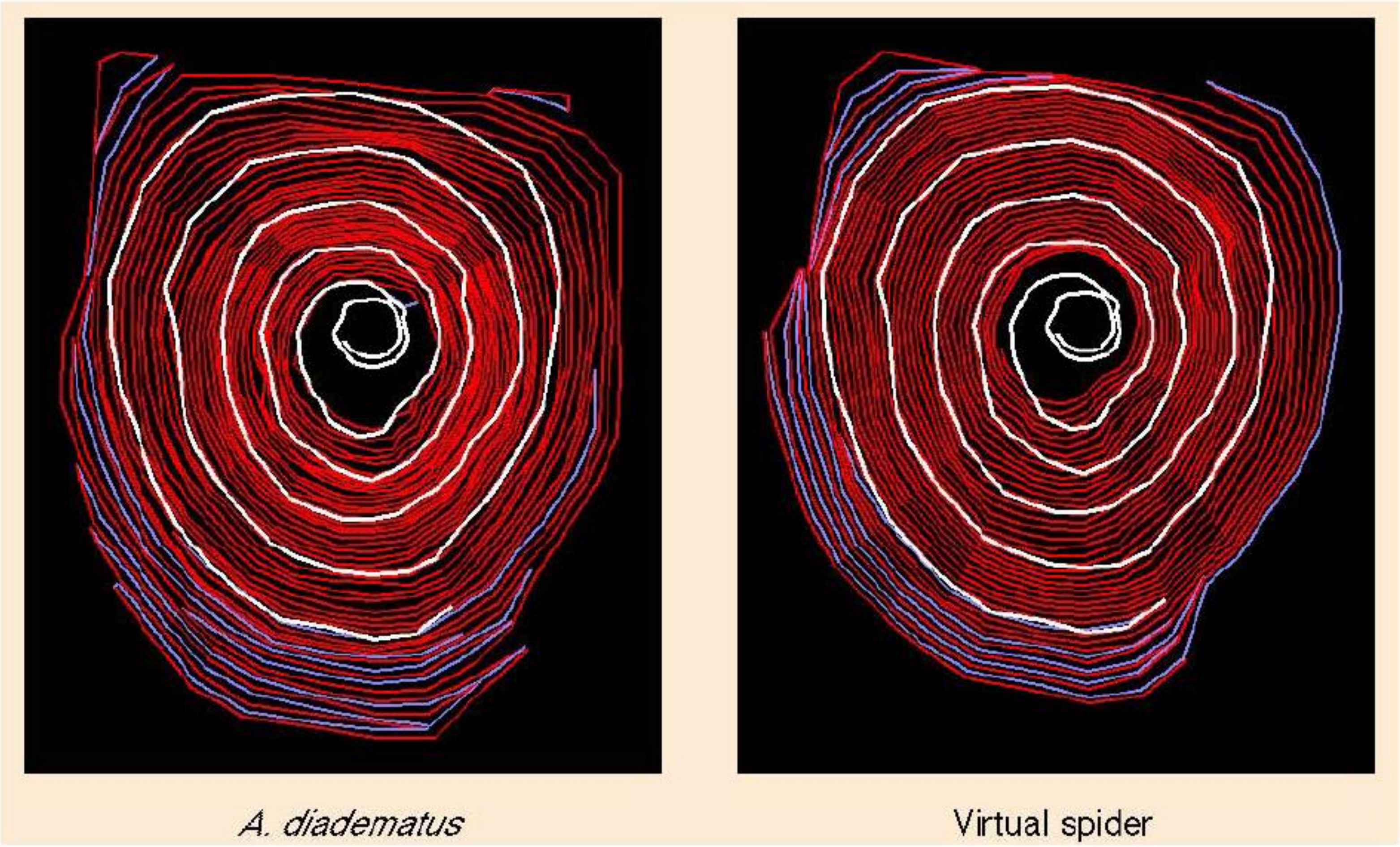


Other stigmantic behaviours



Other stigmantic behaviours

Spiral analysis - Real spider vs simulation



Outine

- Algorithms from Swarm Intelligence
  - Flocking
  - Particle Swarm Optimization
  - Ant Colony Optimization
- Swarm Robotics
  - Coordinated Exploration
  - Transportation
  - Physcial Cooperation

Key Properties

- Composed of many individuals
- The individuals are relatively homogeneous.
- The individuals are relatively incapable.
- The interactions among the individuals are based on simple behavioral rules that exploit only local information.
- The overall behavior results from a self-organized process.

Swarm Robotics

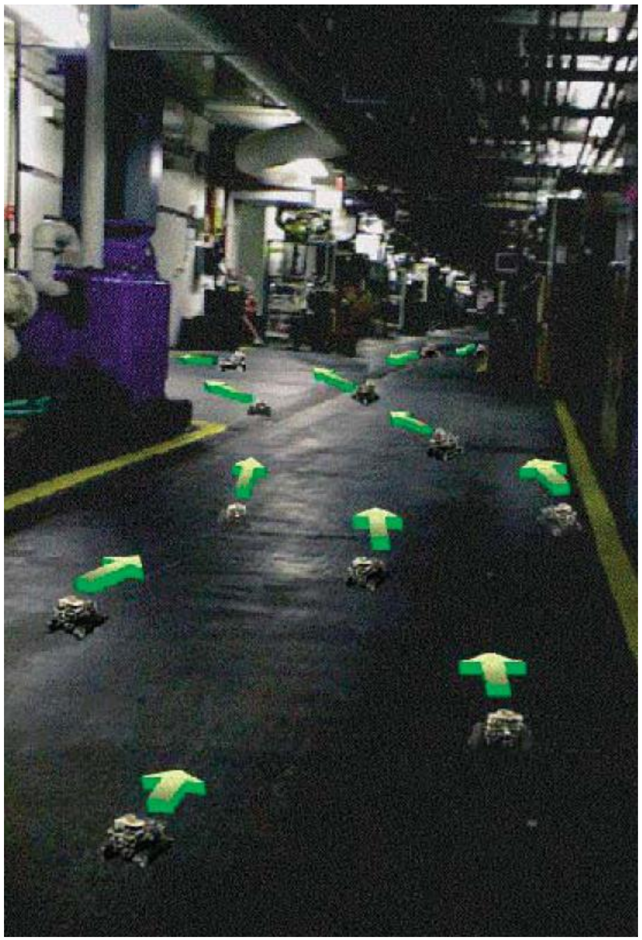
Technological Motivations

- Robustness
- Scalability
- Versatility / flexibility
- Super linearity
- Low cost?

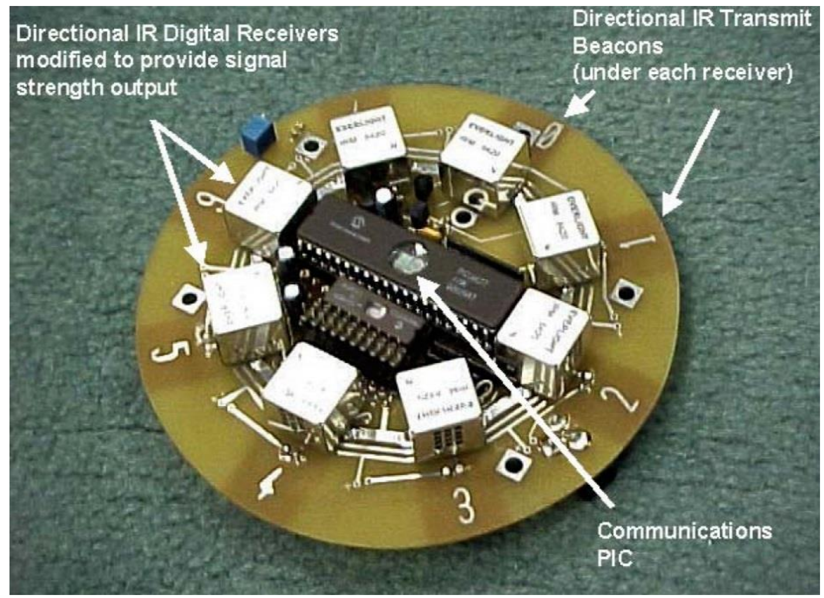
Coordinated Exploration

1. Pheromone robotics
2. Chaining

Example 1: Pheromone Robotics



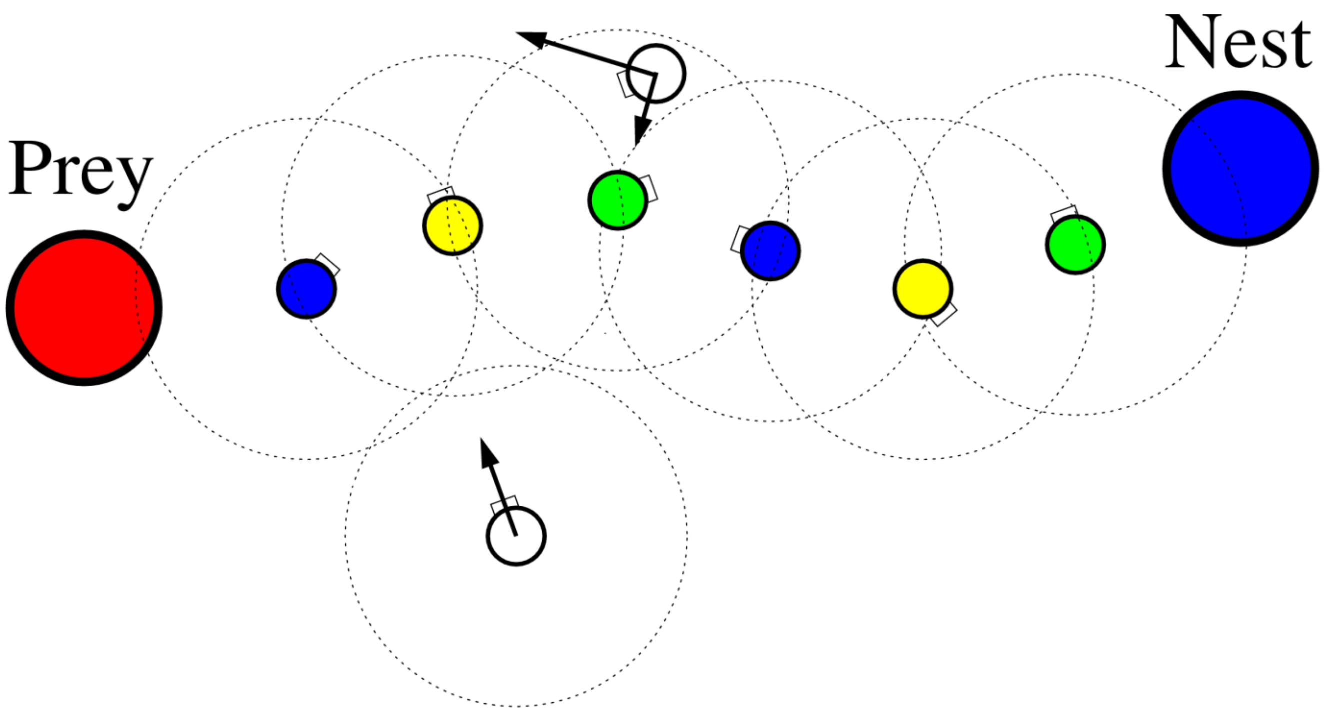
Payton et al., 2005



- robot dispersion
- gradient (via hop counts)
- shortest path
- pheromone diffussion / evaporation

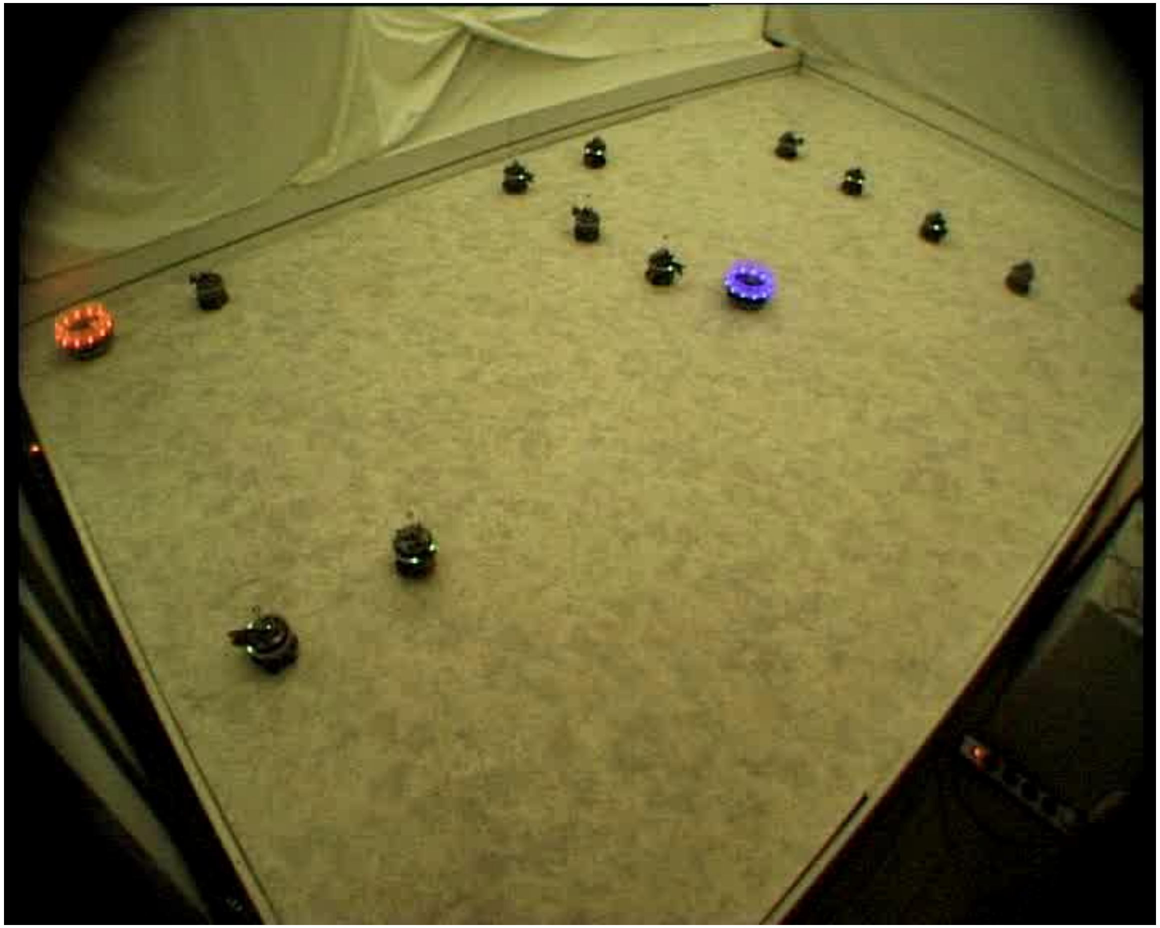
Example 2: Chaining

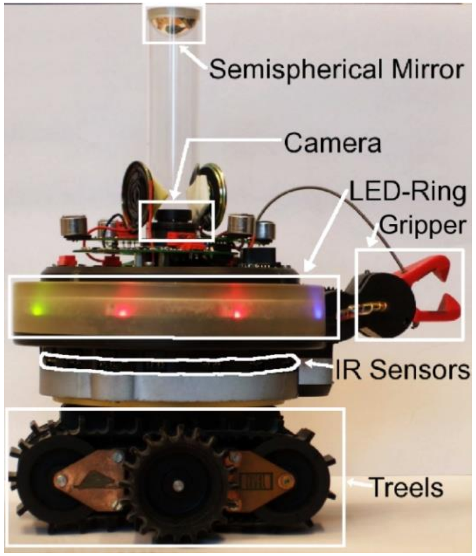
- Limited sensing range
- Signaling of colors (directional chains)



Nouyan et al., 2009

Example 2: Chaining (Cont.)





Chains in prey retrieval (division of labor)
Nouyan et al., 2009

Transportation and Clustering

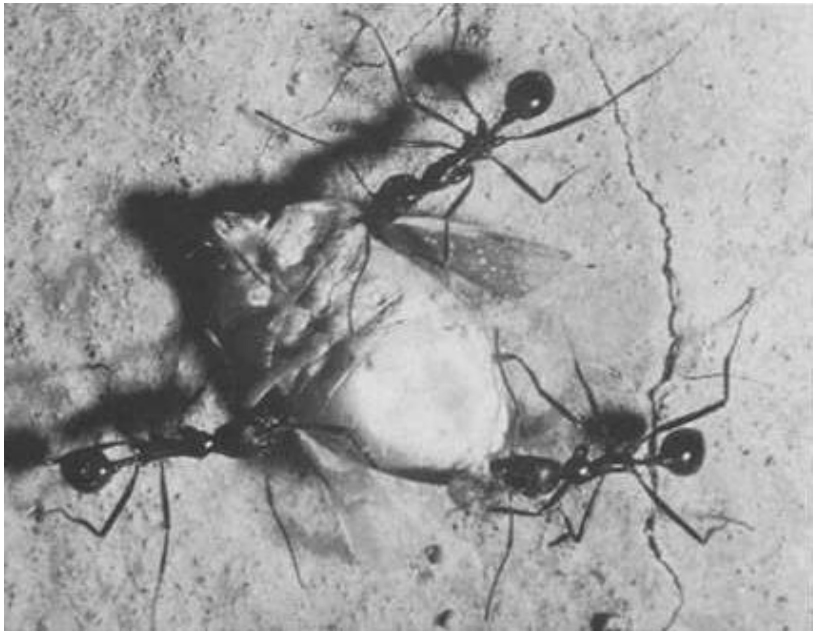
1. Coordinated box pushing
2. Blind bulldozing
3. Clustering
4. Cooperative Manipulation

Example 1: Coordinated Box Pushing

- Task requires cooperation
- No explicit communication
- Behavior-based approach
- Ant-inspired stagnation recovery mechanism

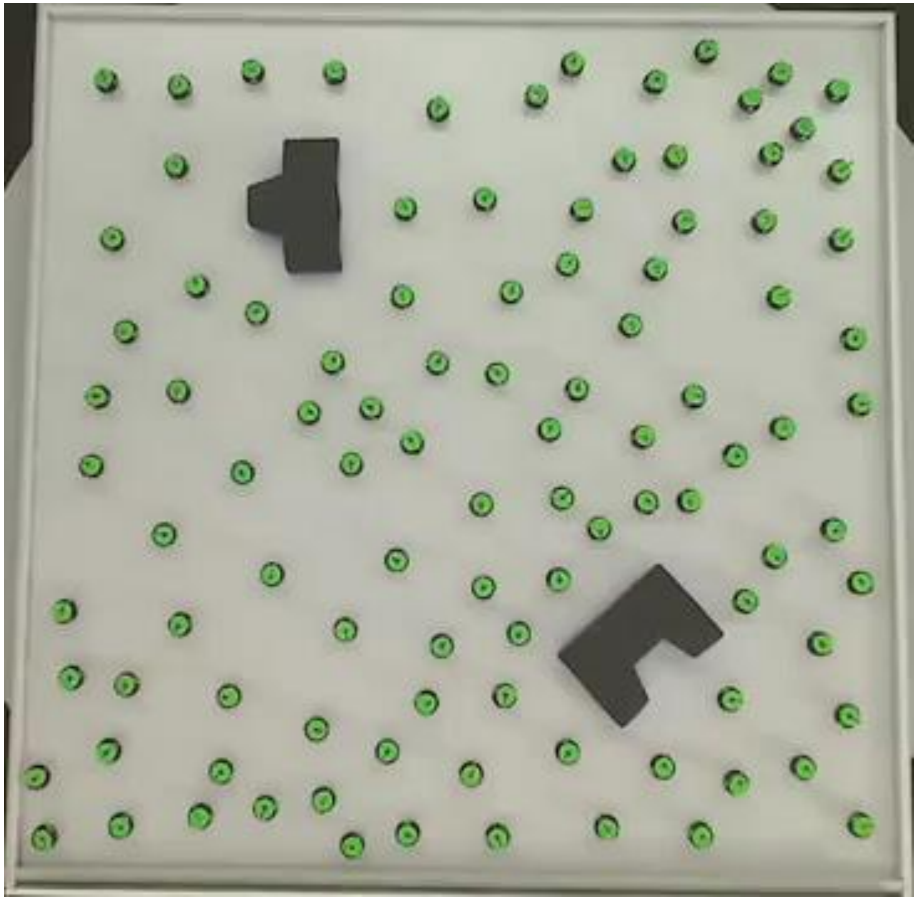
Kube and Zhang, 1993;
Kube and Bonabeau, 2000

Hoelldobler et al., 1978

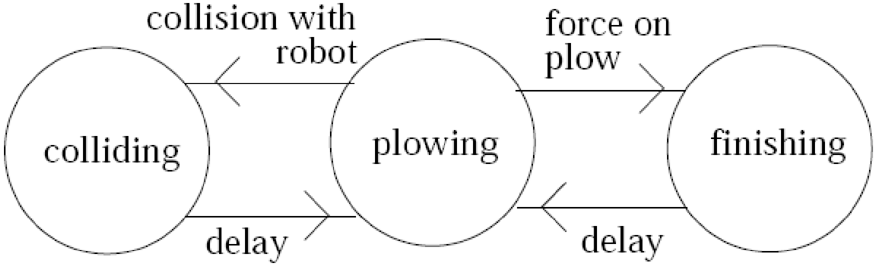


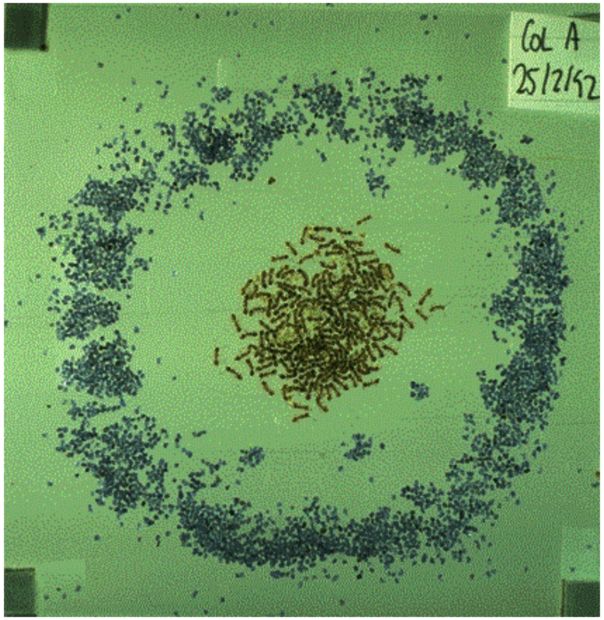
Example 1: Box-Pushing with Centralized Control

- Kilbots are controlled by torch-light
- Can sense direction of the light

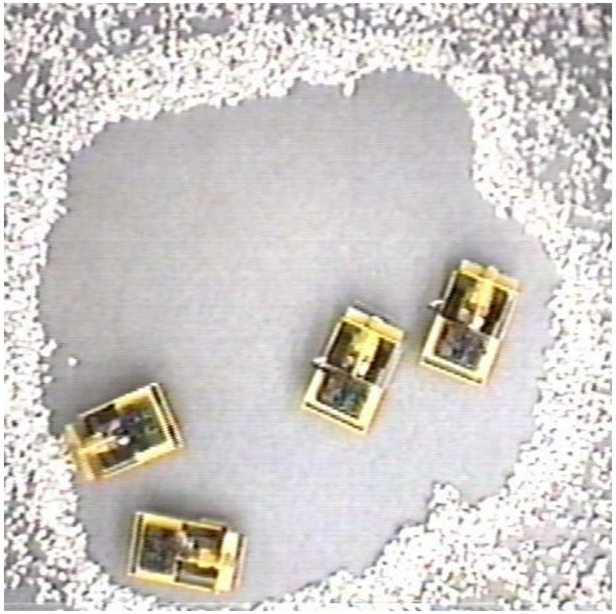


Example 2: Blind Bulldozing



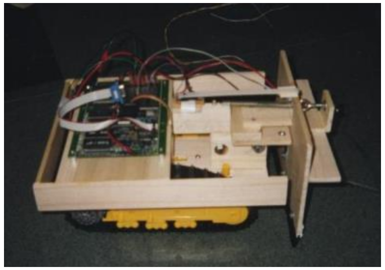


Nest construction by ants
Franks et al., 1992



Nest construction by robots
Parker et al., 2003

Force sensitive plow



Example 3: Clustering

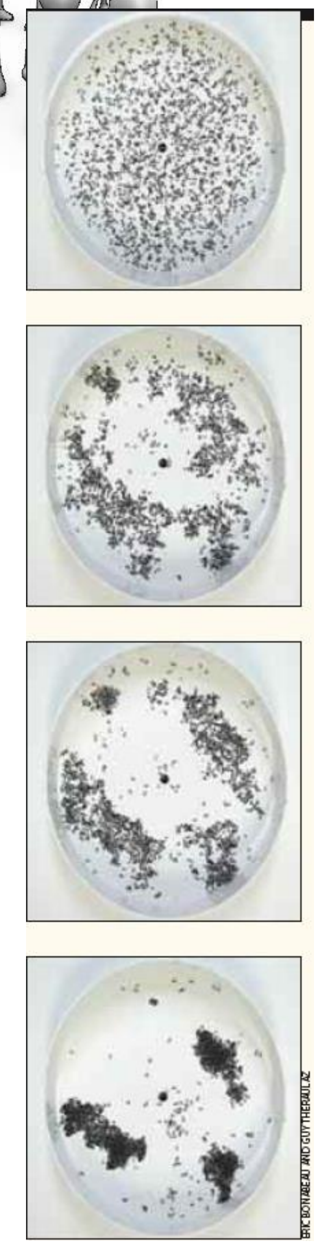
Clustering and sorting behavior can be observed in several ant species. Important mechanisms:

- stigmergic communication
- positive & negative feedback

Example rule (N = #objects experienced in a short time window):

1. Probability to pick up an object: inversely proportional to N
2. Probability to deposit an object: directly proportional to N

Cemetery clusters in *Messor sancta,* 26 hours in total, 1500 corpses



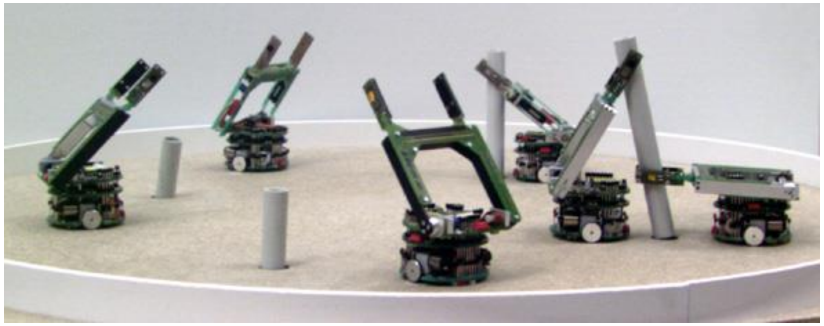
Example 4: Cooperative Manipulation

Desert ants cooperate to pull out of the ground long sticks (too long for a single ant). This behavior can be reproduced with a group of robots.

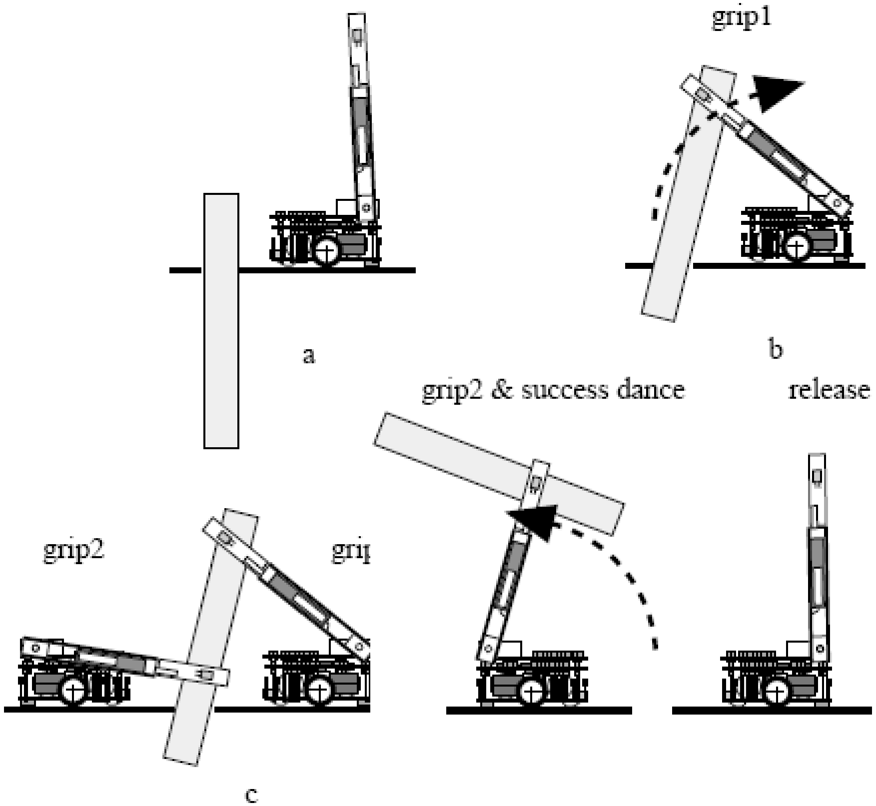
How long to wait for a teammate?

Super-linear performance:

sticks retrieved **per robot**
is optimal for ca. 6-robot groups.

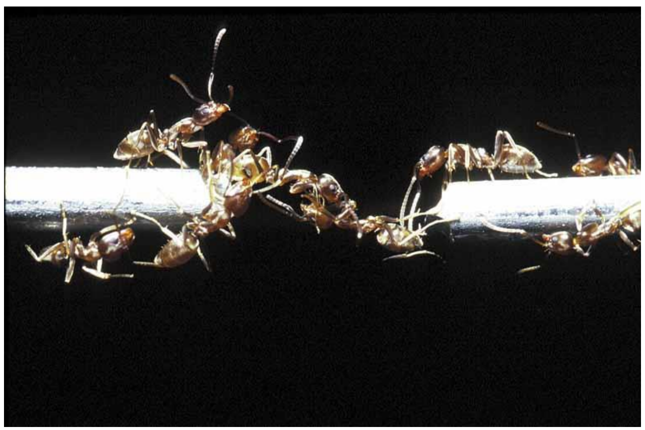


Ijspeert et al., 2001



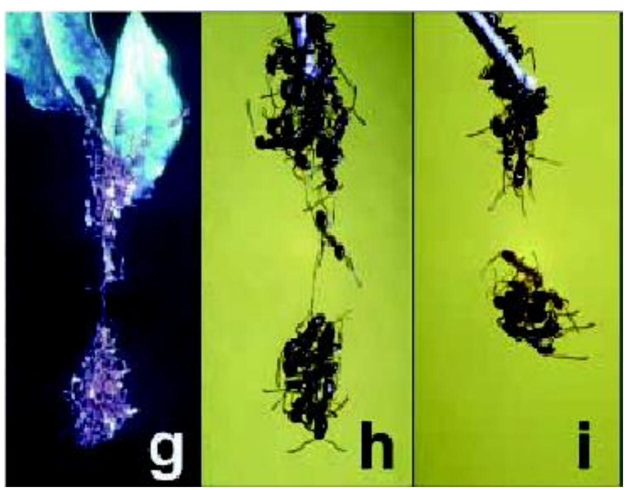
Physical Cooperation of Mobile Individuals

Passing a gap



Nest building

Grouped Fall



Plugging potholes in the trail

Mobile Reconfigurable Robots

Mobile units assemble into connected entities
that are larger and stronger than any individual unit.

Mondada et al., 2005; Gross et al., 2006

Example: Search & Rescue

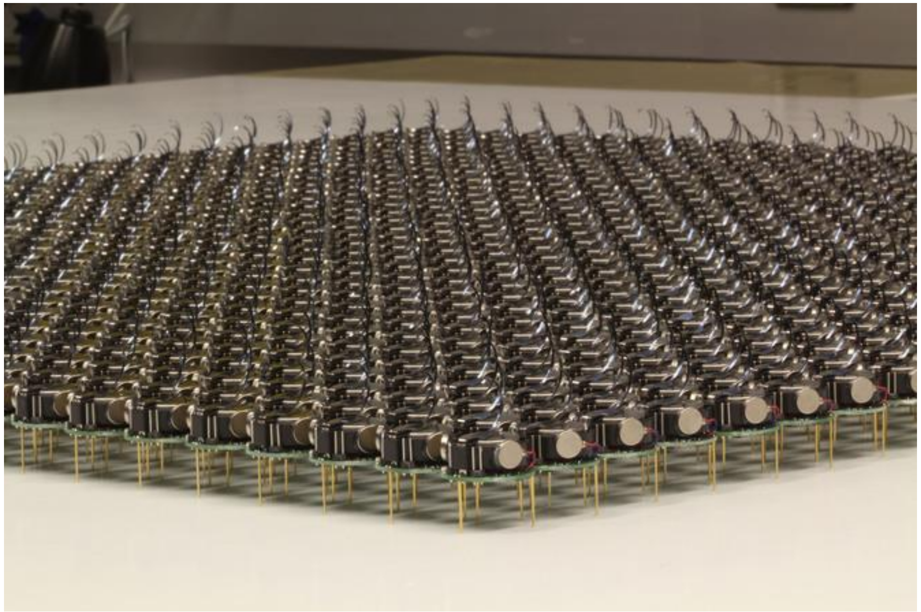
Example: Search & Rescue (Cont.)

Construction and Assembly

- Self Assembly
- Construction of buildings

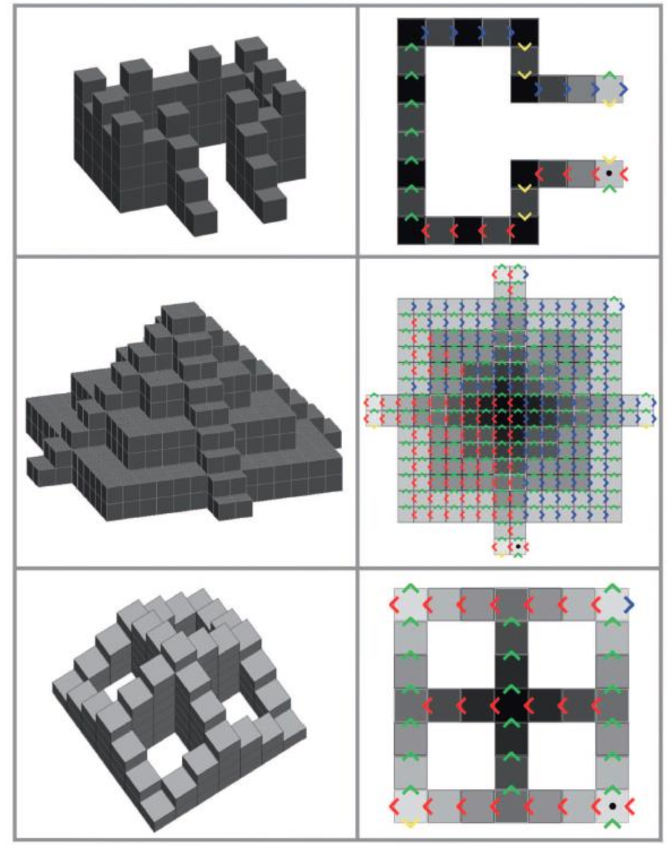
Self-Assembly with Kilo-Bots

- Use can define desired shape (pixel image)
- Kilobots localize through communication
- Can also compute gradient to distance of the origin
- Shape following until position is reached

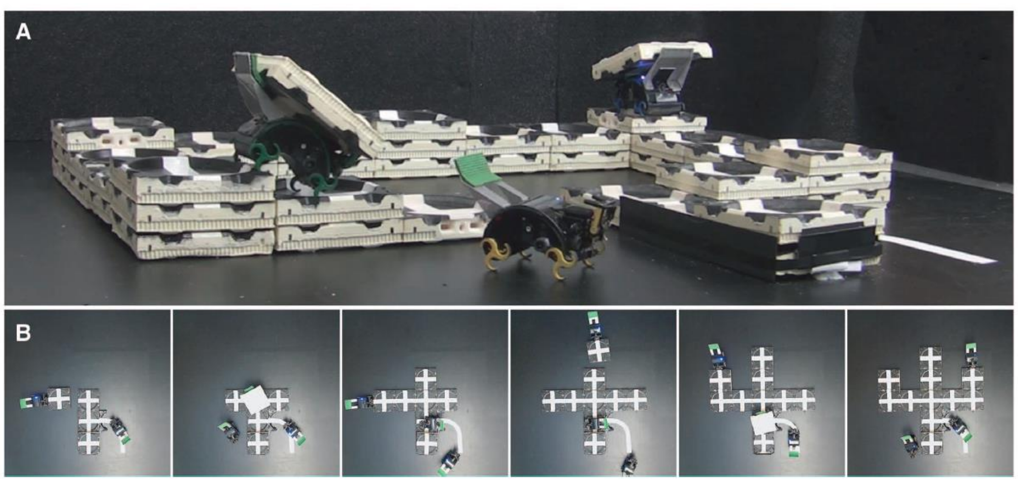


Self-Assembly with Kilo-Bots

Robot Termites



- User can specify desired structure
- Only local observations
- Each robot only uses local rules and predefined pathes that are computed from the structure
- Communication via stigmergy



Robot Termites

Summary

- Swarm intelligence can create interesting behaviors with very simple methods
  - Exploration, Transportation, Construction….
  - Exploit huge amount of parallelism
- Hard to design local control laws to achieve desired global behaviour
- There is a huge gap between analytical methods such as Dec-POMDPs and swarm intelligence
  - Swarm intelligence can be used for 1000 of agents
  - Dec-POMDPs automatically constructs desired behavior
- How can we close this gap?

Course Overview

- Introduction, Characteristics, Agents, Utility Theory…
- Game Theory, Nash Equilibria and Other Solution Concepts
- Finding Solution Concepts
- Games in Extensive Form, Sequential Games
- Coordination between Agents
- Learning with a Single Agent
- Learning with Multiple Agents
- Evolutionary Algorithms and Dynamics of Learning
- Partial Observable Markov Decision Processes (POMDP)
- Decentralized POMDPS
- Swarm Intelligence

Wow … we really managed☺

Next time, we will reserve more time for the later chapters of the lecture and cut a bit the first part

What next…?

You can do a huge amount of Machine Learning lectures at TUDa

Next Semester:

- Robot Learning (Jan)
- Machine Learning 2: Probabilistic Graphical Models (me☺)
- Integrated Project (Jan and me)
- Advanced ML seminar
  - Limited participants, but audience is always welcome
- Data Mining und Maschinelles Lernen (Fürnkranz)

Master and Bachelor Thesis

Topics from Multi-Agent Systems / Robot Learning / Machine Learning

Checkout our homepage!