Bio-Inspired Artificial Intelligence

Lecture 9: Swarm Intelligence & Swarm Robotics

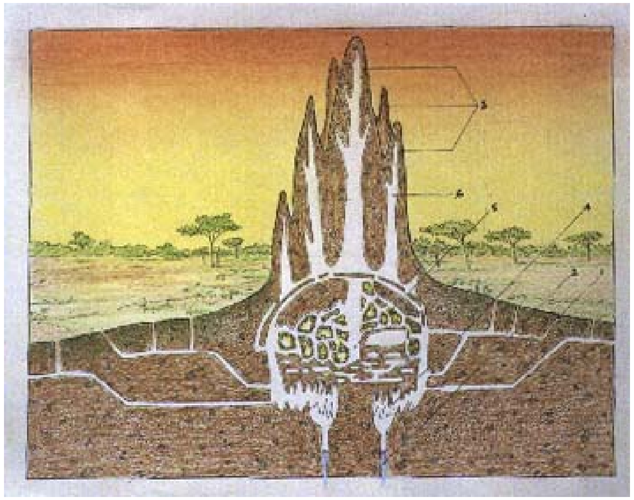
Knowledge Technology

http://www.informatik.uni-hamburg.de/WTM/

Motivation

- Mounds can reach a diameter of 30m and/or a height of up to 9m
- Up to ~2 million termites, 1 queen (up to 36000 eggs/day)

- Mound consists of 6 main parts:
  - Outer wall
    (up to 60cm thick)
  - Brood chambers
  - Base plate (often)
    with cooling vents
  - Royal chamber
  - Fungus gardens
  - Peripheral galleries



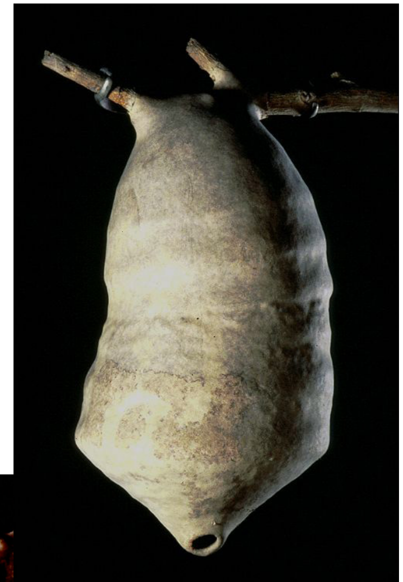
- 1.200l air consumed/day (Lüscher, 1961)
  but only 500l volume in big mounds
  → Very good venting/air-conditioning!
- Termites are usually up to 12.7mm

Motivation

- How can robots achieve that?
  - If we equip NAO robots with the same software, they should be able to build a house (150m high, roughly 50 floors)!
- Features of termite swarm:
  - Architectures ***without architects***
  - No central organization
  - Termites don’t have blueprint of mound
  - Small sensing range, only ***local knowledge***
- If humans want to achieve that:
  - 4 times Empire State building
  - 1km wide
  - And it has to be built in heavy fog without walkie-talkies or plans being passed on!

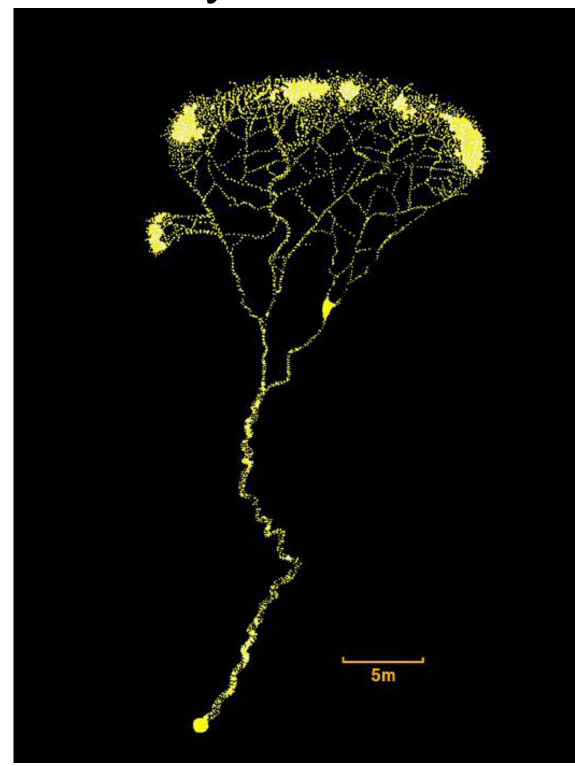
Other Examples

Harvester Ants



Wasps

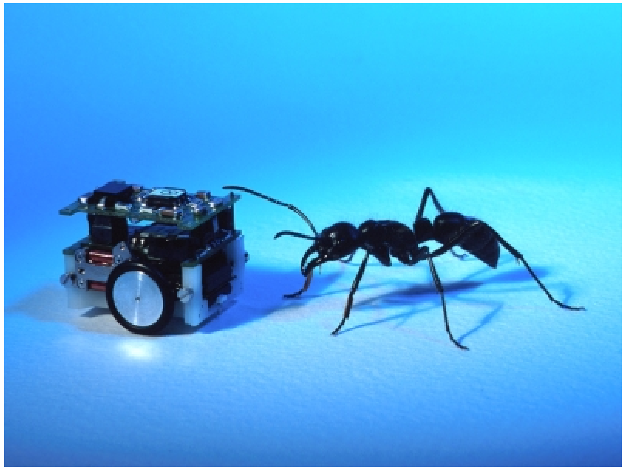
Army Ant Trails



Pictures taken from Guy Theraulaz

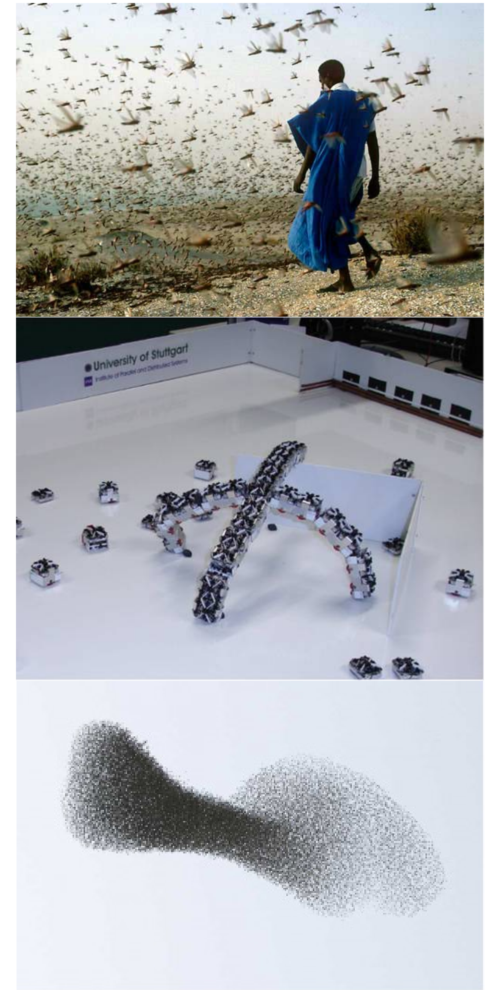
Outline

- What is a swarm?
- How does a swarm work?
- Properties of swarm approaches
- Mechanisms
  - Template based
  - Stigmergy
    - Wasp Nest Building
  - Positive/Negative reinforcement
    - Shortest path, ACO
  - Flocking
    - Boids, PSO
- Swarm Robotics



What exactly is a Swarm?

- Not all groups of agents are swarms!
- A swarm is a group of agents that fulfils most or all of the following:
  1. Agents are not centrally controlled
  2. Group consists of a large number of agents
  3. Group consists of few homogeneous subgroups
  4. Agents are relatively incapable and/or inefficient
  5. Agents have only local sensing and communication capabilities



Pictures from National Geographic, Symbion Project and Photograph by Manuel Presti

How does a swarm work?

- Usually 100+ to millions of agents with only local information without any central control
- Intelligent behaviour as a sum of large number of local interactions between agents and agent and environment
- ***Emergent Behaviour***
  - Behaviour that is not directly programmed in individuals
  - Only „emerges“ through local interactions
- ***Self-Organisation***

  “a process in which patterns at the global level of a system emerge solely from numerous interactions among the lower level components of the system” (Deneubourg et. al, 1987)

How does a swarm work? (2)

- Several mechanisms can be observed in biological swarm systems:
  - Usage of templates or patterns (based on chemicals)
  - Feedback loops
    - Positive Feedback (amplification)
    - Negative Feedback (competition, exhaustion, saturation,..)
  - Amplification of fluctuations (Randomness)
  - Stigmergy
  - Local and simple communication, usually not audio-visual
  - Probabilistic nature

Properties of a Swarm System

- Desirable properties that can be observed in biological systems:

1. Robustness
   - Behaviour is ***robust to changes*** in the environment
   - Robust to failure through high ***redundancy***
   - No single point of failure as in centrally controlled system
   - (Single agents more robust due to simplicity)

2. Scalability
   - Agents can be usually added or removed without problem
   - Mechanisms often ***independent of group size***

Properties of a Swarm System (2)

3. Flexibility
    - Interactions with ***local environment*** define behaviour
    - Dynamic task allocation / differentiation
    - Swarm automatically ***adapts*** to changes in dynamic environments

- All these properties highly desirable for robotic systems
    - Single robot has to be complex for complex tasks which results in high maintenance and risk of failure
    - ***Dynamic environments*** are difficult to prepare for
    - BUT advantages come with a loss of external control

Properties of a Swarm System (3)

- What domains are swarm systems good for? Tasks that

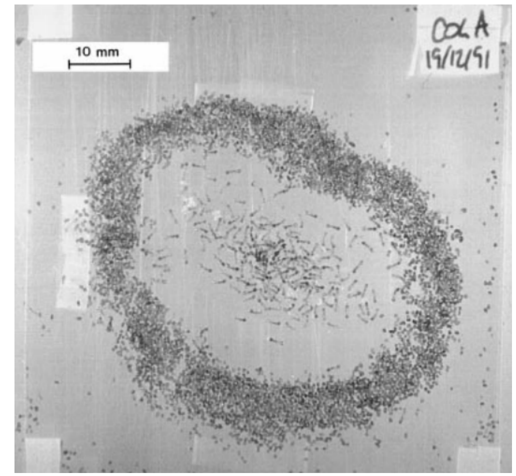
1. cover a region
   - Exploration, large area search or observation
2. can be executed in parallel
   - Collective foraging, building, harvesting
3. are dangerous or need redundancy
   - Work in desaster areas, e.g. cleaning of toxic waste, where the loss of agents is likely
4. scale up or down dynamically
   - Dynamic task allocation can lead to near optimal use of resources through dynamic redistribution

Classification of Collective Behaviour

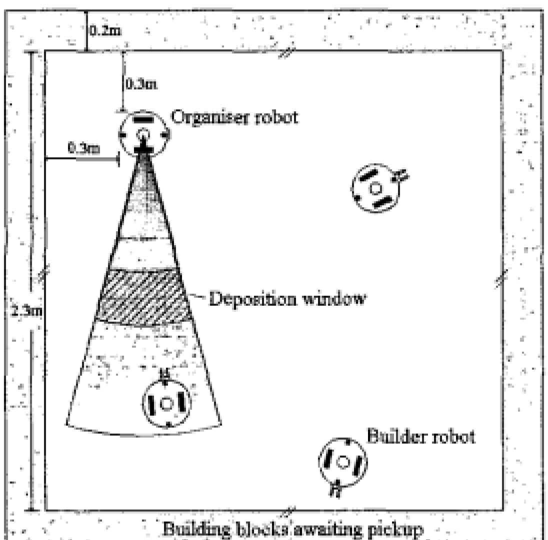
- Collective behaviours can be categorized
- Simon Garnier et.al. (2007) propose 4 categories:
  - **Coordination** (appropriate organisation in space and time)
  - **Cooperation** (individuals achieve tasks together which could not be done by single one)
  - **Deliberation** (group is faced with several options and chooses collectively at least one)
  - **Collaboration** (different activities are simultaneous performed by groups of specialized individuals)

Templates and Patterns

- Social insects often use template mechanisms based on chemicals
  - Examples: Bee queen chamber, ant nest building
- Templates can be emulated e.g. by light
  - Often centrally controlled information



Franks & Deneubourg 1997



- R.L. Steward & R.A. Russell (2004)
- Group consists of builder and organiser robots
- Builder robots react to light intensity in pattern created by organiser robots

Stigmergy

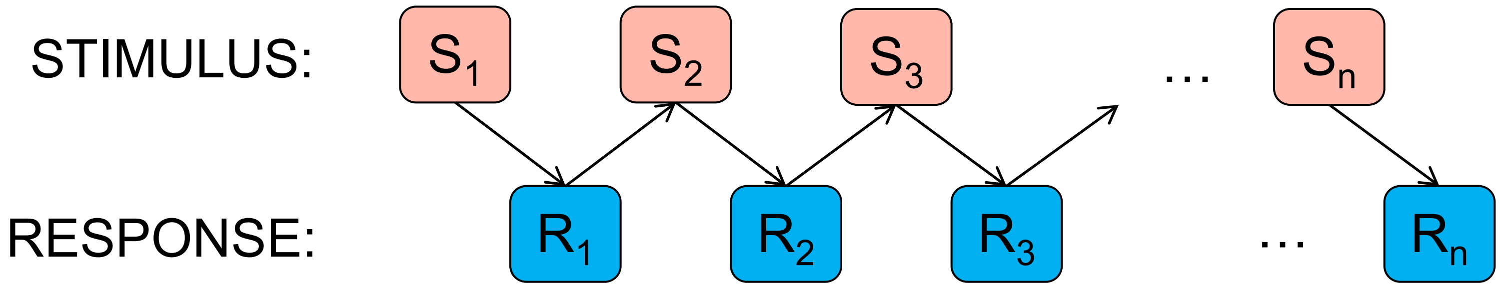
- Term coined by Pierre-Paul Grassé (1895-1985)
- Derived from Greek words
  - Stigma (= Sign), Ergon (= Action)
- "Stimulation of workers by the performance they have achieved."

Stigmergy is a method of ***indirect communication*** in a ***self-organizing*** emergent system where its individual parts communicate with one another by ***modifying their local environment***.

(Wikipedia)

Stigmergy (2)

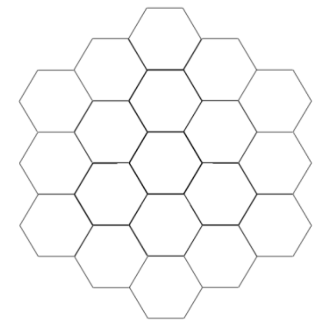
- Agents leave signs (clues) in the environment which determine subsequent actions of same (or other) agent



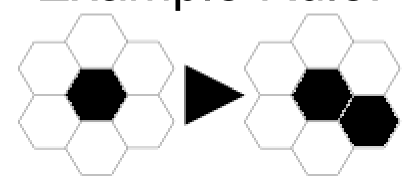
- Stigmergy can be used to coordinate collective work
- “Indirect communication” through environment
- Concept also used in human domain, think of post-its, wikis…

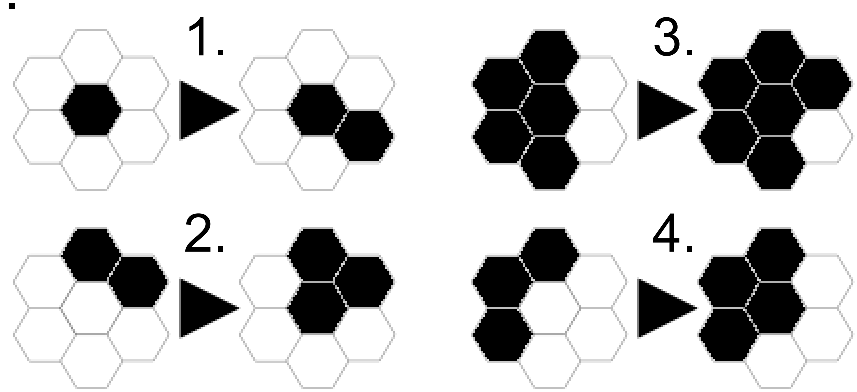
Stigmergy Example

- Queen bee wants to have a circular nest
  - Workers can only see 6 adjacent cells
  - Use of pattern matching and rule set
  - Rules have a priority
- Workers walk around whole nest and try to apply rules
- How many rules are needed?
- What happens if workers don't have global knowledge about building sites with highest priority?



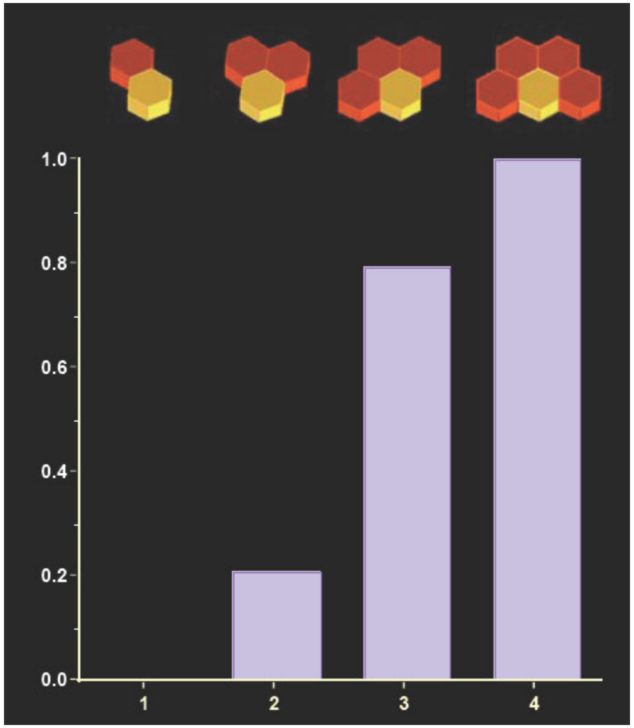
Example Rule:





Wasp Nest Building

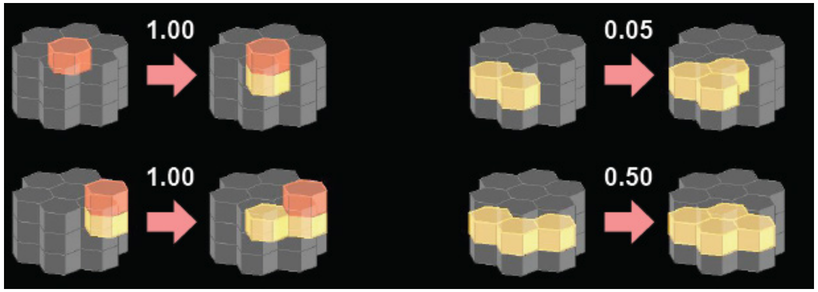
- Experiments by Karsai I. & Theraulaz G. (1995)
  - Wasps were numbered to follow individuals
  - Coloured paper was used as substitute for wood pulp and plant fibres
  - Colours were changed after certain intervals
- Probability to build cell increases with number of adjacent walls
- Simulation experiments:
  - Virtual wasps were used in 3D environment to simulate building behaviour
  - Uses the idea in the previous slide, only in 3 dimensions



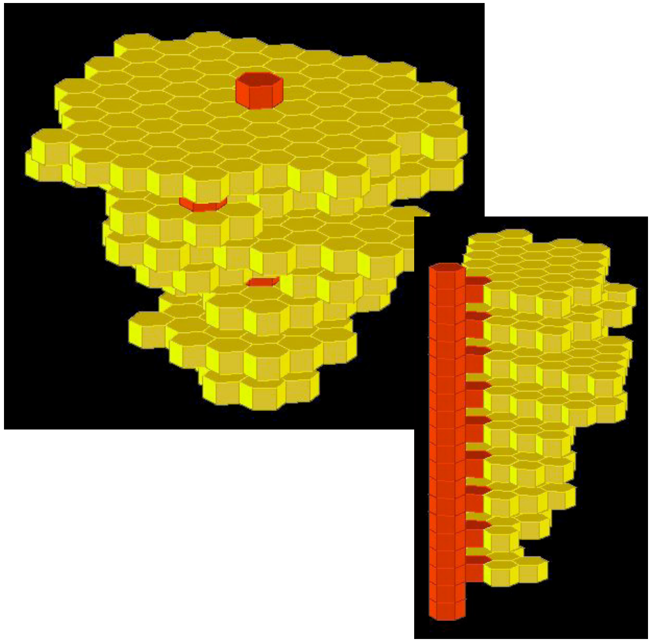
Karsai I. & Theraulaz G. (1995). Nest building in a Social Wasp: Postures and Constraints (Hymenoptera: Vespidae). *Sociology* **26** (1): 83-114.

Wasp Nest Building (2)

- 3D patterns were used, e.g.:



Results:

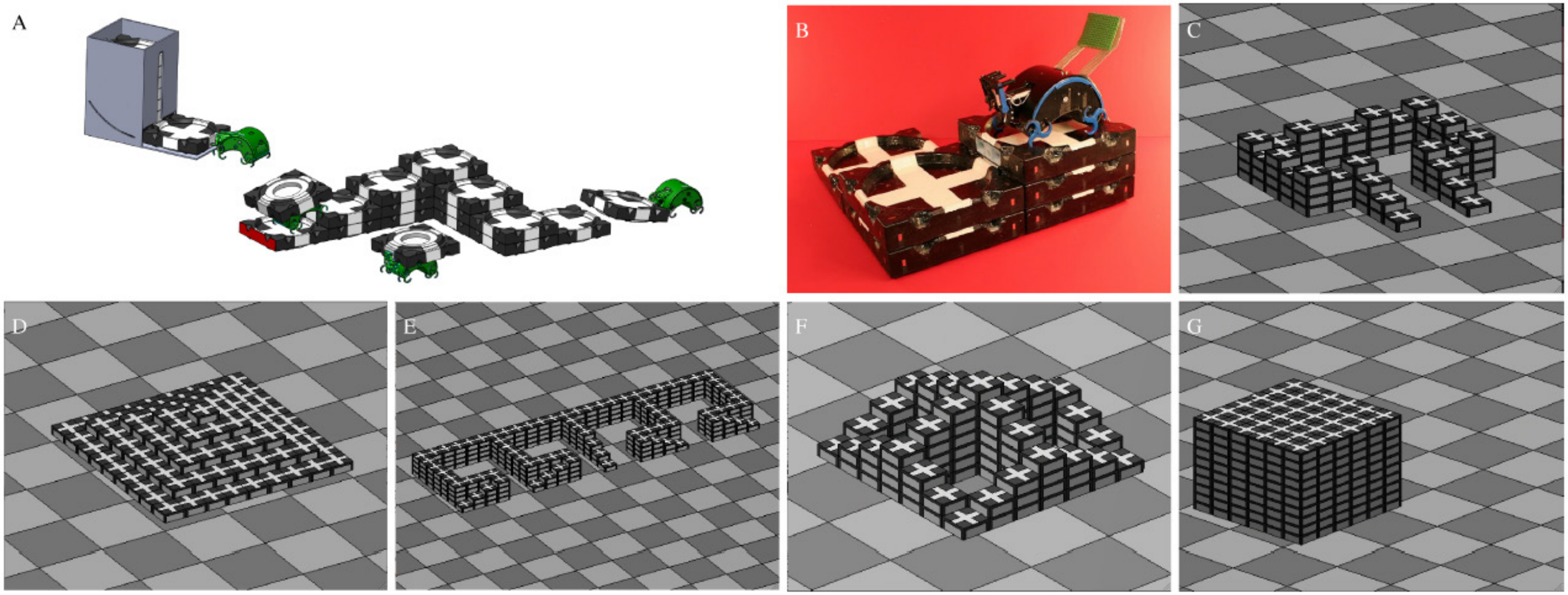


Examples from real wasps:

Pictures from Guy Theraulaz

Collective Building

- TERMES 3D Collective Construction System

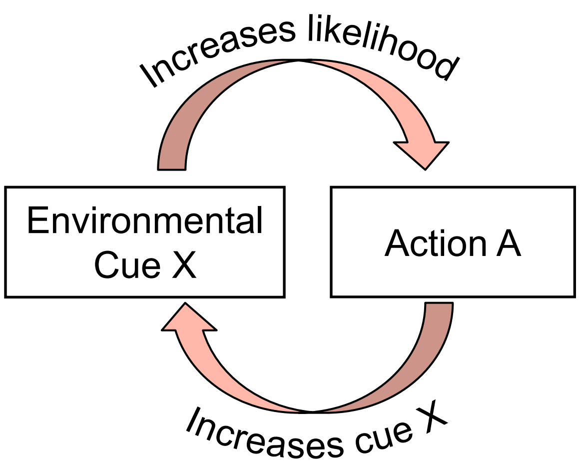


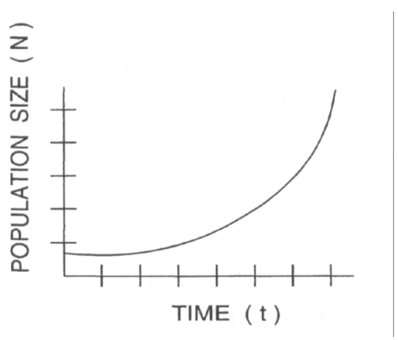
- Building plan is user defined with intermediate steps
- Other approaches use communication of blocks or RFID markers

Positive/Negative Reinforcement

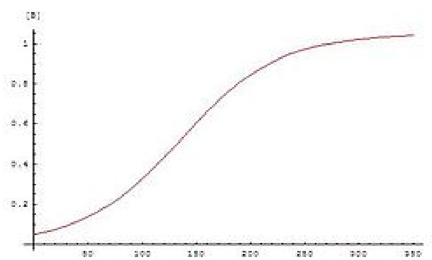
- Behaviour modulated by interplay between positive and negative feedback loop

Positive



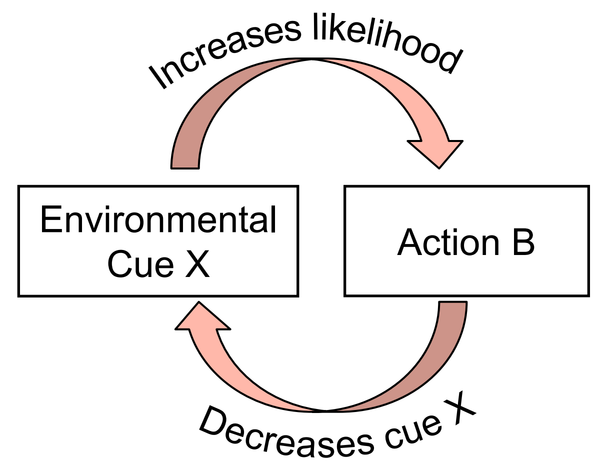


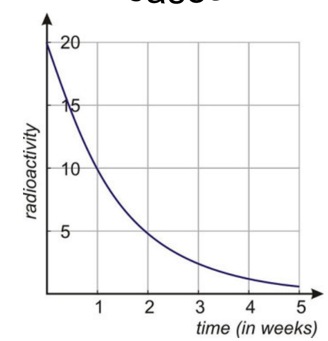
Combined:



Likelihood of Action

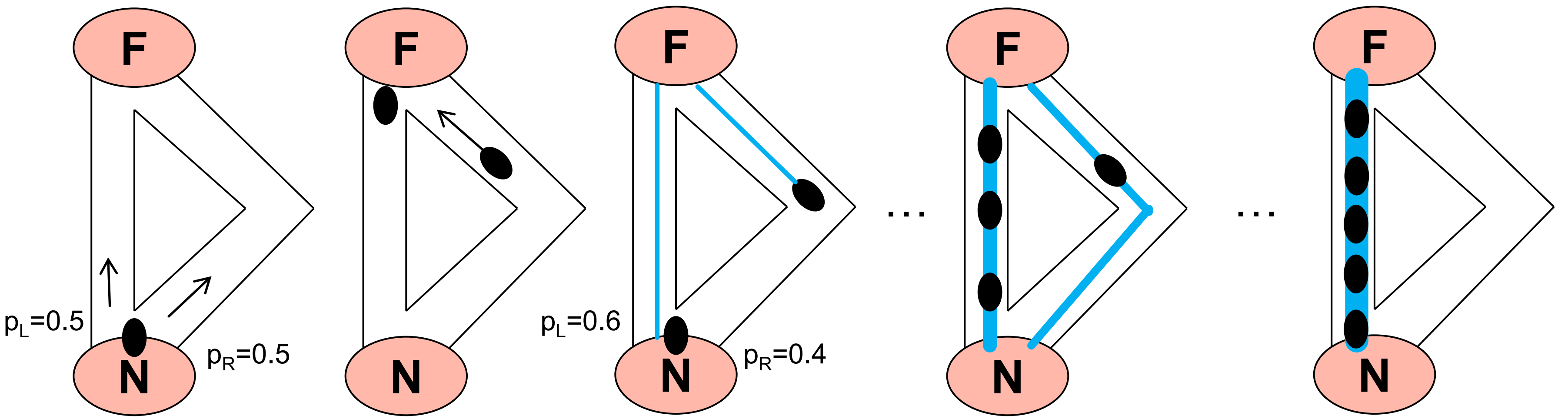
Negative





Collective Shortest Path

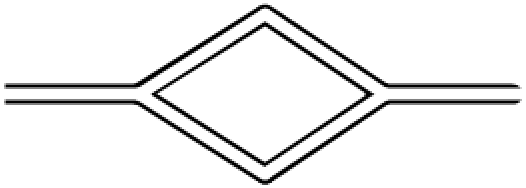
- How do ants form trails?



- Decision of ants are probabilistic
- Through ***positive reinforcement*** of pheromone the probability to choose the shortest path is increased
- Negative reinforcement? → ***e.g. decay of pheromone***

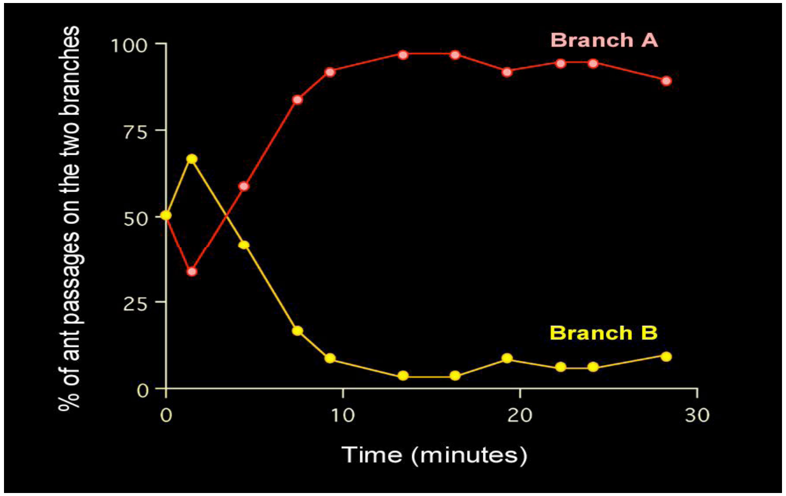
Collective Shortest Path (2)

- Properties of ant trail following:
  - Very ***robust*** to disturbances or broken paths
  - “Optimal path” gets chosen through collective decision process
- What happens in case of two equally optimal paths?



1. Both paths get explored at first
2. By chance one path gets used more often
3. After a while one path is preferred due to higher pheromone concentration.

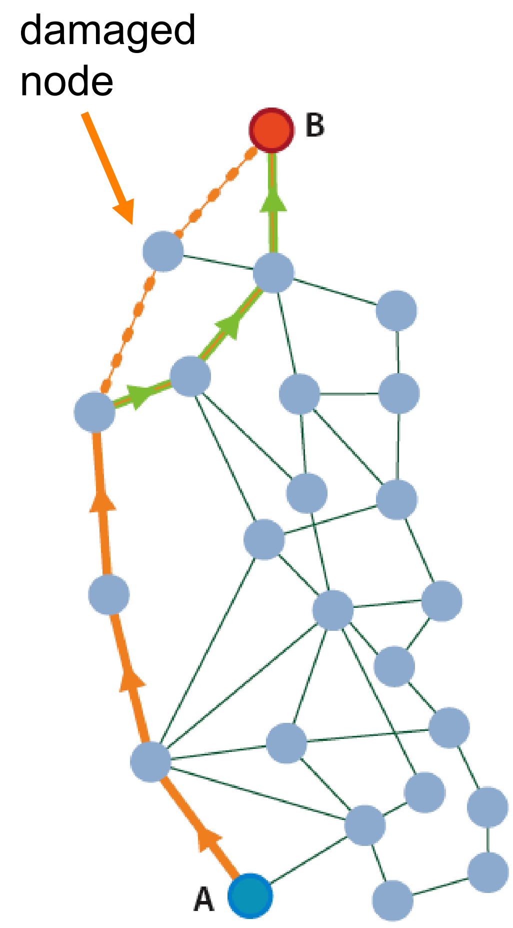
→ ***Amplification of fluctuations!***



J.-L. Deneubourg, S. Aron, S. Goss, and J. M. Pasteels. The self-organizing exploratory pattern of the Argentine ant. *Journal of Insect Behavior*, 3:159–168, 1990.

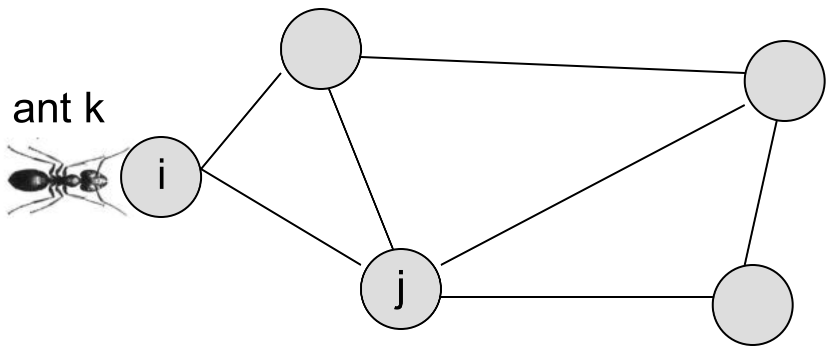
Ant Colony Optimisation

- Developed by Dorigo et al. (1994)
- Use stigmergy and reinforcement to find shortest path in network
- Applicable to all problems that can be formulated as Travelling Salesman
- Can be used for communication networks
- Advantages:
  - Dynamic re-routing
  - Does not assume network is static
  - Robustness to failure of nodes



ACO

- Uses a population of ants
- Each ant moves around network by transitions from state i (current state) to j (next state)
- Transition rule:



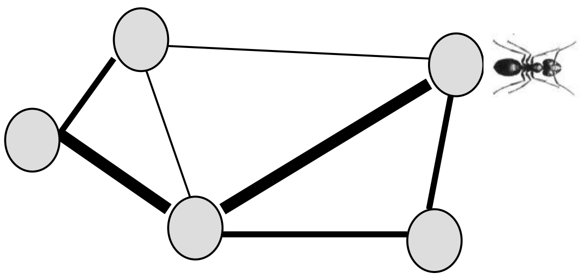
$$p_{ij}^{k}(t) = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha} \cdot [\eta_{ij}]^{\beta}}{\sum_{k \in allowed_k} [\tau_{ik}(t)]^{\alpha} \cdot [\eta_{ik}]^{\beta}} & \text{if } j \in allowed_k \\ 0 & \text{otherwise} \end{cases}$$

  - η = visibuility/attractiveness of edge, τ = pheromone on edge
  - α, β to determine influence

ACO (2)

- ***Update*** after ant completed a tour
  - p is a coefficient with (1-p) representing evaporation

Trail update: $\tau_{ij}(t+n)=\rho\cdot\tau_{ij}(t)+\Delta\tau_{ij}$



with $\Delta\tau_{ij} = \sum_{k=1}^{m} \Delta\tau_{ij}^{k}$

and $\Delta\tau_{ij}^{k} = \begin{cases} \dfrac{Q}{L_k} & \text{if k - th ant uses edge (i, j) in its tour (between time t and t + n)} \\ 0 & \text{otherwise} \end{cases}$

where Q is a constant and L_k the length of tour of ant k

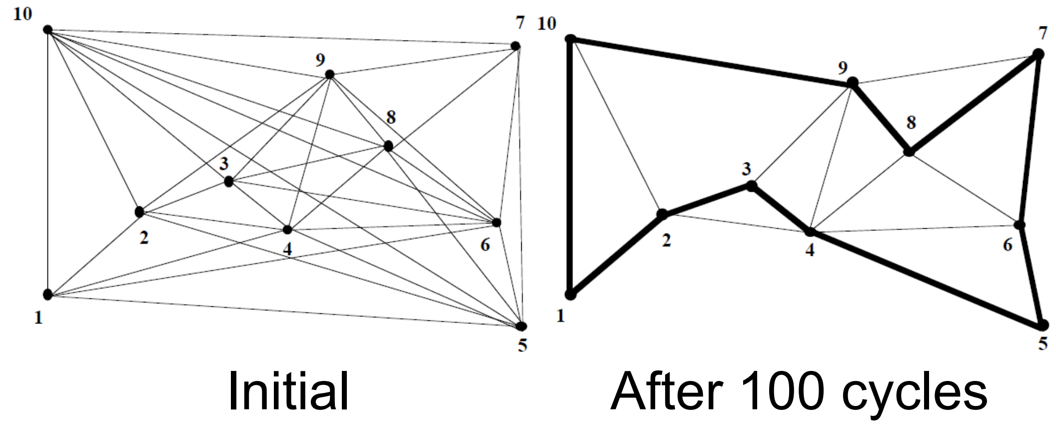
ACO (3)

- Ant searches can be repeated until best solution found
- Suggested initialisation:
  - Initialise pheromone to small quantity c
  - Set p < 1 to avoid accumulation, e.g. 0.1
  - $\alpha \leq 1 \leq \beta$

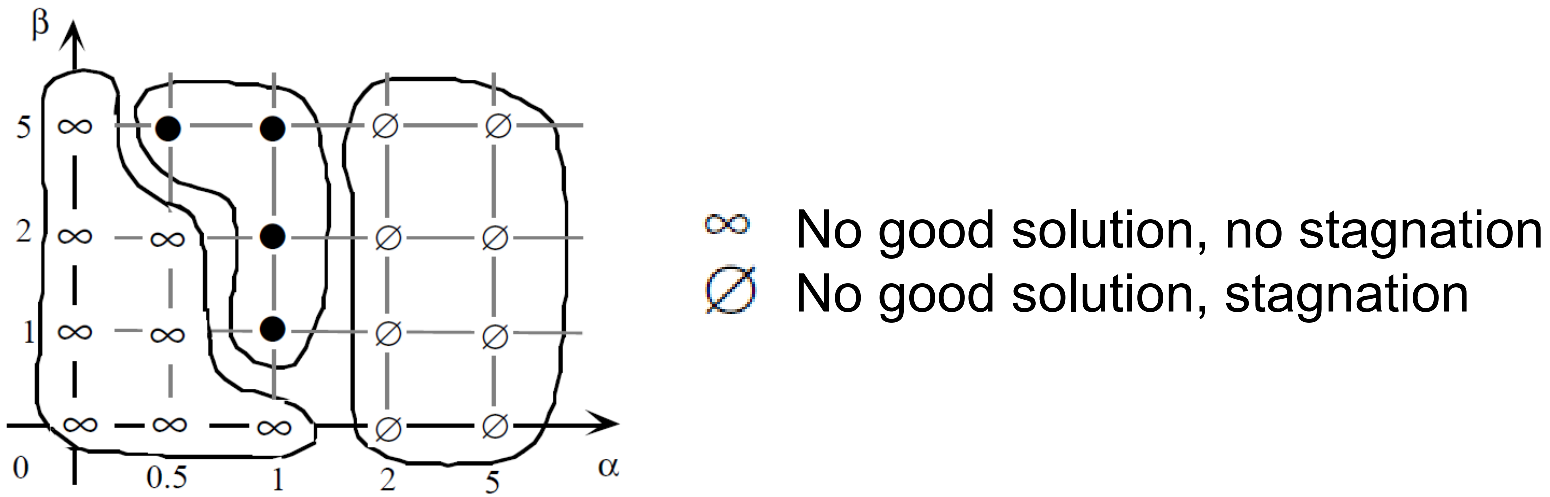
- Performance of ACO
  - Usually finds best solution on small problems (< 30 nodes)
  - On larger problems still good solution
  - Can be coupled with other search techniques to find best solution
  - Problems can be dynamic

ACO (4)

- Example result:

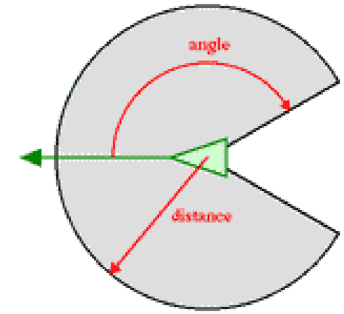


- Good values for α, β ?

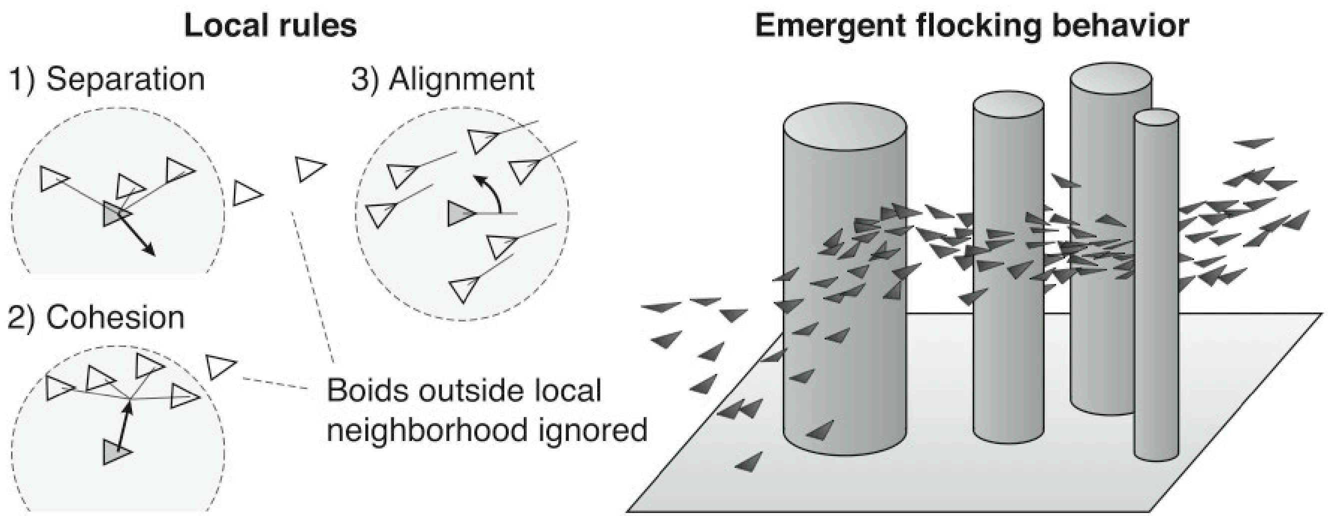


Flocking

Simulated Flocking: Boids



- Reynolds' "Boids" (1987)
  - Agents (=Boids) can sense angle and distance of/to neighbours



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

Particle Swarm Optimisation

- Optimization algorithm inspired by birds' flocking to find the best food area.

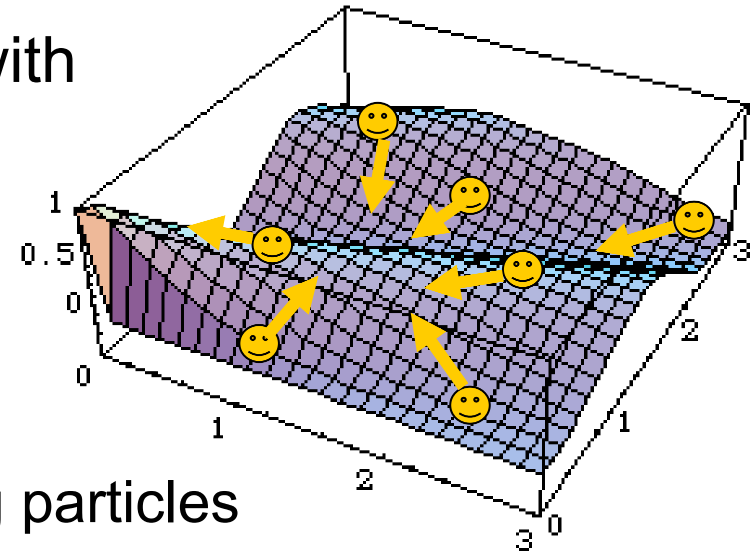
A caricature scenario:
The flock wants to find the area with the highest concentration of food (insects). Birds do not know where that area is, but each bird can shout o their neighbors how many insects are at its location. Birds also remember their own location where they found the highest concentration of food so far.

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

PSO

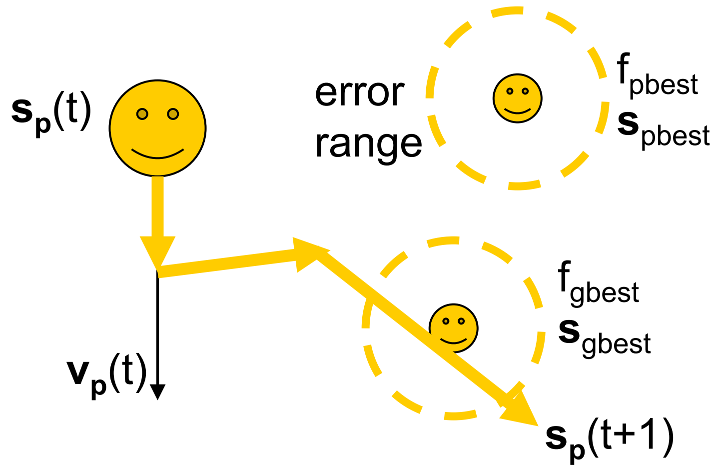
- Proposed by Kennedy and Eberhart (2001)
- Optimisation search space with dimension n
- Flock now vector of particles p with
  - Position s
  - Velocity v
  - Performance f
- All particles
  - perceive f and s of neighbouring particles
  - can select best neighbour (gbest)
  - remembers own best position so far (pbest)



Kennedy and Eberhart (2001) Swarm Intelligence. Morgan Kauffman

PSO (2)

- A particle computes next position by taking into account
  - Fraction of own current velocity v
  - Direction to own previous best
  - Direction to best neighbour
  - Some error for *gbest* and *pbest*



$$\mathbf{v}_p(t+1) = a \times \mathbf{v}_p(t) + b \times R \times (\mathbf{s}_{pbest} - \mathbf{s}_p(t)) + c \times R \times (\mathbf{s}_{gbest} - \mathbf{s}_p(t))$$

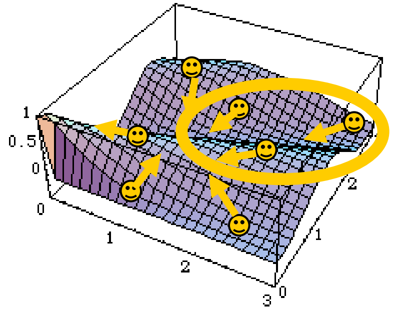
$$\mathbf{s}_p(t+1) = \mathbf{s}_p(t) + \mathbf{v}_p(t+1)$$

where a, b, c are learning constants between 0 and 1
R is a random number between 0 and 1

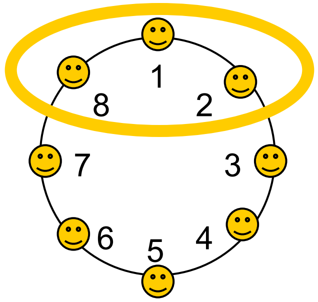
PSO (3)

- Initialisation
  - Initial random s and v, set *pbest* to initial position
  - Typically 20 particles for problems with dimensionality 2 – 200
  - Neighbourhood size, typically 3 to 5

Geographical neighborhood



Social neighborhood



- Iterate until solution *max(pbest)* acceptable or no further improvement
- Often difficult to encode parameters of problem to be solved to generate search space

Back to Termites…

- Termites “actively” leave cues in the environment
- Can use chemical cues
- Mainly 3 types of pheromones used:
  - Cement pheromone (left in building material)
  - Trail pheromone
  - Queen template pheromone (around queens body)
- Also other environmental cues in the mound have to be taken into account, like air flows, temperature, ….
- Often several classes (workers, soldiers, …)
- Complicated dynamical system with high dimensionality!

Division of Labour

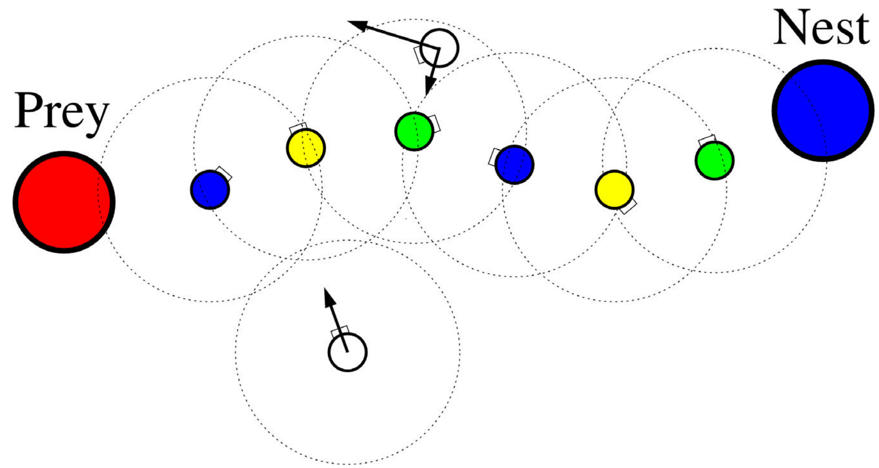
- Simple agent does not have all abilities needed
- Group has to work together to achieve goal

- ***Heterogeneity***: Differences in the swarm
  - Morphological differences (actuators, sensors, shape)
  - Behavioural / Functional differences (sorter, forager, etc)

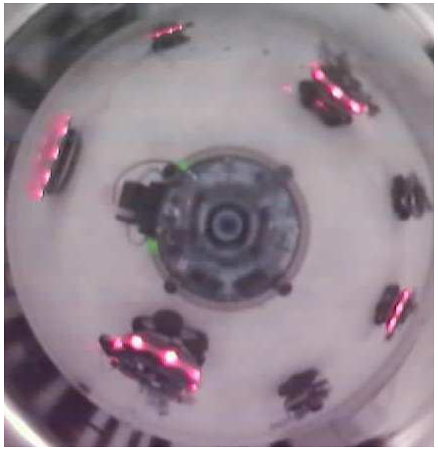
- ***Dynamic task allocation***
  - Size of sub groups changes over time
  - Specialists within the group have to be utilised
  - In social insects often overlapping abilities (soldiers can still carry, but not as good/fast)

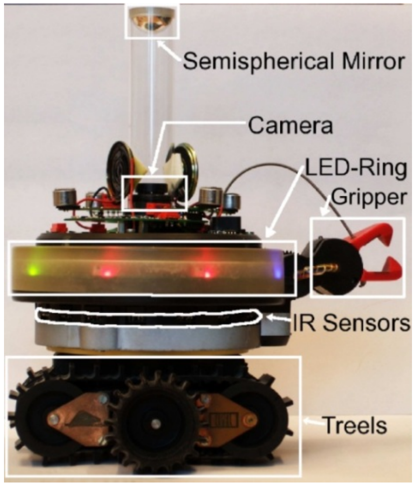
Swarm Robotics

- Not many applications yet
- Mostly proof of concept to explore possibilities

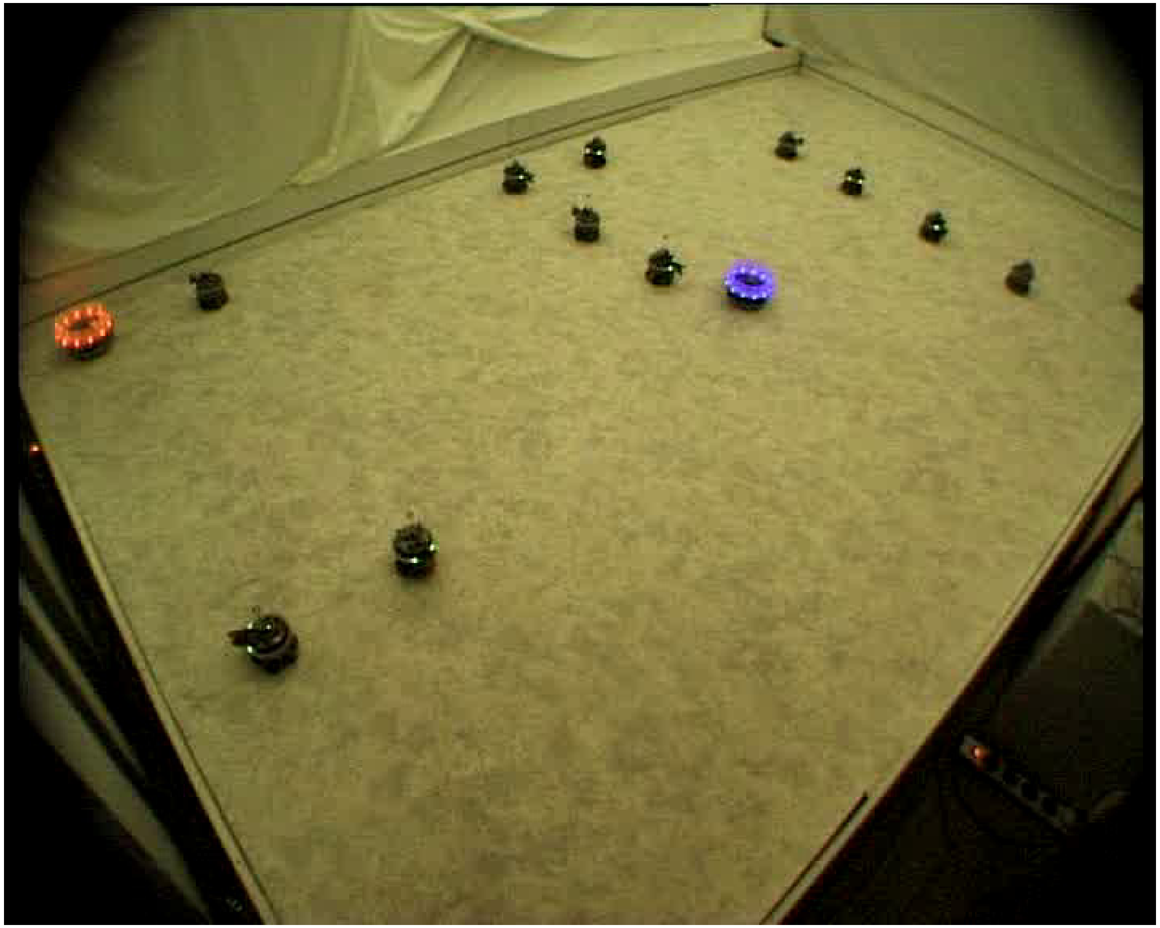


- Example: Chaining
  - Limited sensing range
  - Trying to overcome inability of pheromone laying
  - Cooperative transport



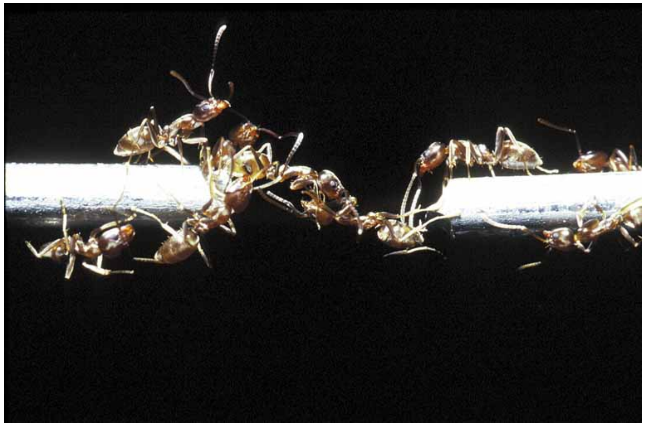


Chaining and Transport



Physical Cooperation

- Examples from biology
  - Passing a gap to large for one individual
  - Plugging potholes
  - Building



Physical Cooperation in Robots

Problems with Swarm Approaches

- Complexity moved from design of individual agent to design of ***meaningful individual behaviour*** in order to get emergent behaviour and self organisation
- ***Loss of control***
  - e.g. we want a house built by plan, not only with certain properties
- Loss of efficiency through probabilistic behaviour
  - Deterministic solution with less agents often preferable to more robust solution with redundancy (cost?)
- Single agents really simple in case of robotics?
  - Many mechanisms from biology not usable in robots, e.g. chemical trails

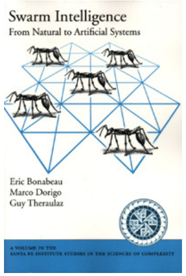
Summary

- Swarm systems have many desirable properties
  - Robustness, Scalability, Flexibility
- Self-Organisation through local interactions
  - Stigmergy, positive/negative reinforcement, flocking
- Algorithms that exploit mechanisms for optimisation:
  - Ant Colony Optimisation, Particle Swarm Optimisation

- Definition of individual behaviour to “construct” global behaviour far from trivial
- Swarm robotics still hot topic in research
- Many areas: Collective construction, mapping, exploration, sensor fields, collection, especially with small robots

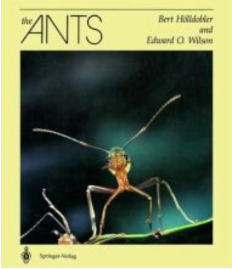
Further Reading

- Swarm Intelligence, 1999



Eric Bonabeau, Marco Dorigo and Guy Theraulaz
New York, NY: Oxford University Press, Santa Fe Institute Studies in the Sciences of Complexity

- The Ants, 1990



Bert Hölldobler, Edward Osborne Wilson

Harvard University Press