In the name of God

Course Title:
Bio-Inspired Robotics

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(Thanks to Masoud Asadpour)

Lecture: Swarm Intelligence

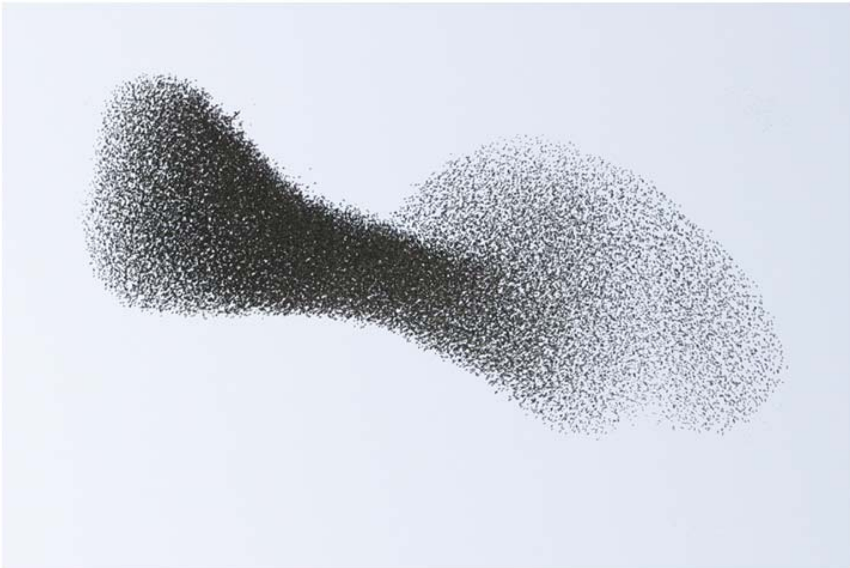
Some of the slides have been adapted from Eric Bonabeau, “Swarm Intelligence”
The text is mainly taken from Bonabeau et al., Swarm Intelligence: from natural to artificial systems

Swarm Intelligence

- Understanding the underlying mechanisms of swarm intelligence in animals helps us invent new computational techniques.
- In traditional computation techniques the computing task have to be:
  - well-defined
  - fairly predictable
  - computable in reasonable time with serial computers

Swarm Intelligence

- "The emergent, collective intelligence of groups of simple agents." (Bonabeau et al, 1999)
- "Dumb parts, properly connected into a swarm, yield smart results" (Kevin kelly)



Harmonious Flight

The ability of animal groups—such as this flock of starlings—to shift shape as one, even when they have no leader, reflects the genius of collective behavior—something scientists are now tapping to solve human problems.

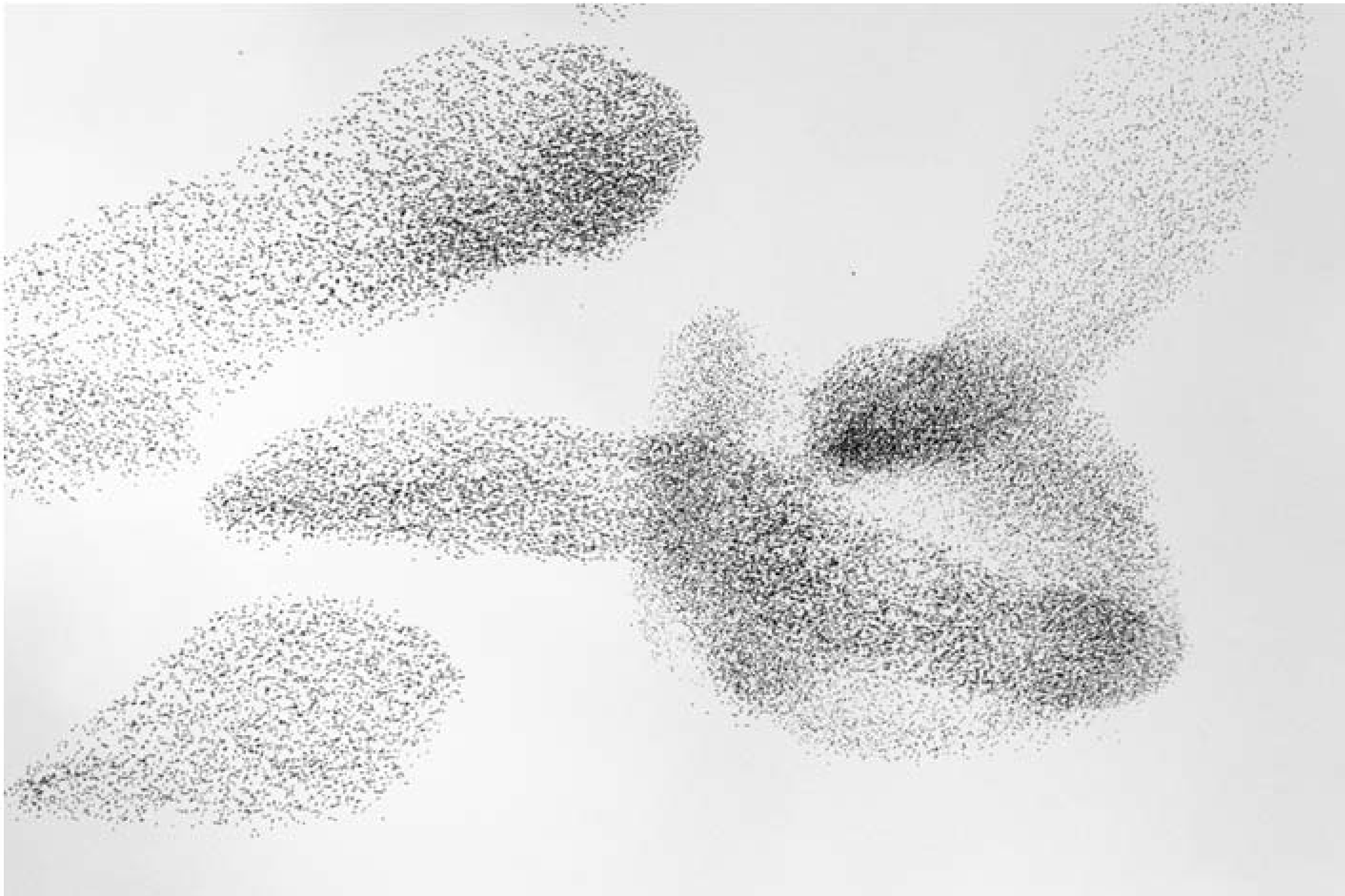
Photograph by Manuel Presti

The 14 photos seen in this and some of the following slides have been taken from a collection about swarm intelligence on National Geographic's web site

Conveyer-belt Behavior

Leafcutter ants (Atta colombica) in Panama carry bits of vegetation to their nest, where collaborating teams of ants transport, clean, cut up, crush, mold, and pack the material into compost piles. Still other ants tend the piles to grow fungi, the main food source for the colony's young. Because a colony of several million leafcutters relies upon cooperation to survive, biologists sometimes describe it as a superorganism.

Photograph by Christian Ziegler



Aerial Art

Flocks of starlings in Rome, Italy, twist and turn into curious shapes. The birds are not following leaders as they perform such maneuvers, biologists say, but rather acting as a group in which individual birds constantly change their position.

Photograph by Manuel Presti

Mass Escape

A peregrine falcon on the attack forces a flock of starlings to take evasive action, moving together as one.

Photograph by Manuel Presti

Instant Messaging

Because each individual is paying close attention to its neighbors, news travels fast through a school of bigeye jack near Cocos Island in the Pacific. The fish follow simple rules that keep the group alert: stick together, avoid collisions, and swim in the same direction.

Photograph by David Hall

On the Move

Wildebeests crossing the Mara River in Kenya may be able to follow a migration route even if only a few of them know the way, say researchers using a computer model of herd behavior. Never mind that the informed animals aren't trying to lead. The rest follow anyway.

Photograph by Winfried Wisniewski, Foto Natura

Modern-day Plague

Locusts beyond number rise in a single black cloud in Mauritania, devouring every crop in their path and leaving hunger or starvation in their wake. Finding ways to prevent such plagues depends on a deeper understanding of swarm theory and the surprising ways it affects our lives.

Photograph by Jean-François Hellio and Nicolas Van Ingen

Gathering Storm

Biologists in an Oxford lab show that when otherwise harmless juvenile locusts get too crowded, they will suddenly align themselves and march in the same direction, triggering a potentially devastating swarm.

Photograph by Peter Essick

Arboreal Light Show

A tree ablaze with fireflies in Indonesia blinks on and off as each insect adjusts its flashes to match the others. Such self-organized behavior resembles the synchronized firing of heart muscle cells or the rhythmic applause of a crowd—but seems more mysterious.

Photograph by Mitsuhiko Imamori, Minden Pictures

Communal Breadwinners

Army ants work together to find food to haul back to the group.

Photograph by Christian Ziegler

Water Ballet

Kids from a summer day camp watch a school of golden trevally swim by at the Georgia Aquarium in Atlanta. The ability of schools to stick together as they move through the water, which is beautiful to observe, still holds mysteries for biologists trying to understand the principles of collective motion.

Photograph by Peter Essick

Democratic Decisions

Even though swarming honeybees frequently differ about where to establish a new nest, the group usually chooses the best site. Bees reach this decision by gathering information, conducting independent evaluations, and holding a kind of vote.

Photograph by Peter Essick

Driving Force

Chicago traders swarm on the stock exchange floor, driving the price of soybean futures with the same practices—fact-finding, independent study, and voting—used by swarming honeybees in search of a new site to nest.

Photograph by Peter Essick

Mob Mentality

In high spirits, a well-dressed crowd at Ascot Racecourse near London celebrates a day of horse races with singing and patriotic flag waving. Individuals in a densely packed group tend to act differently from the way they would on their own, scientists say, not unlike a herd of animals. So event organizers need to take special care to keep participants from panicking as they exit such events.

Photograph by Peter Essick

Interesting characteristics of social colonies

- Flexible: the colony can respond to internal perturbations and external challenges
- Robust: Tasks are completed even if some individuals fail
- Decentralized: there is no central control in the colony
- Self-organized: paths to solutions are emergent rather than predefined

Self-organization

- A mathematical tool to model the behaviors of the social insects
- '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)

→ Emergent Behavior

Ingredients of a self-organized system

- The four ingredients of self-organization:
  - Positive feedback (amplification) e.g. bees dance to show the direction and distance of food sources to their nestmates
  - Negative feedback (for counter-balance and stabilization)
  - Amplification of fluctuations (randomness, errors, random walks) e.g. lost ant foragers can find new food sources
  - Multiple interactions (direct or indirect)

Stigmergy

- Self-organization in social insects often requires interactions among insects.
- Such interactions can be direct or indirect.
- Direct interactions are the "obvious" interactions: antennation, trophallaxis (food or liquid exchange), mandibular contact, visual contact, chemical contact (the odor of nearby nestmates), etc.
- 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.

http://en.wikipedia.org/wiki/Stigmergy

Stigmergy in Nature

- Stigmergy was first observed in social insects.
- Ants:
  - Ants exchange information by laying down pheromones on their way back to the nest when they have found food.
  - In that way, they collectively develop a complex network of trails, connecting the nest in the most efficient way to the different food sources.
- termites:
  - Termites use pheromones to build their complex nests by following a simple decentralized rule set.
  - Each insect scoops up a 'mudball' or similar material from its environment, invests the ball with pheromones, and deposits it on the ground.
  - Termites are attracted to their nestmates' pheromones and are therefore more likely to drop their own mudballs near their neighbors'.
  - Over time this leads to the construction of pillars, arches, tunnels and chambers.

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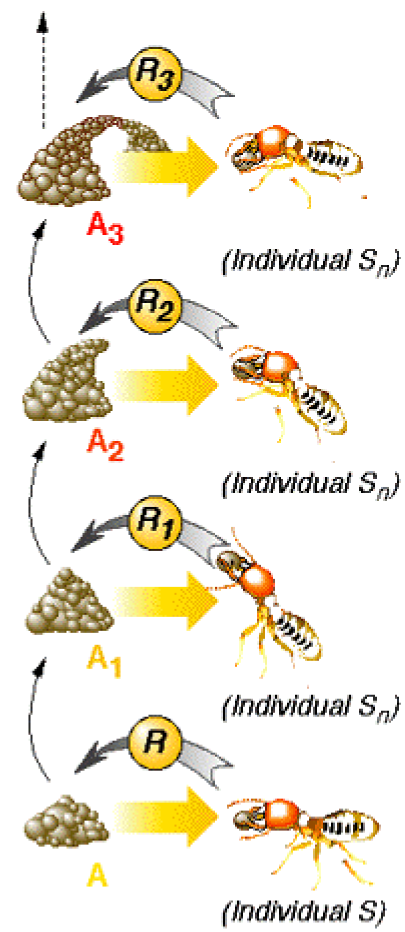
- termites:
  - Grassé showed that the coordination and regulation of building activities in termites do not depend on the workers themselves but are mainly achieved by the nest structure
  - a stimulating configuration triggers the response of a termite worker, transforming the configuration into another configuration that may trigger in turn another (possibly different) action performed by the same termite or any other worker in the colony.

Stigmergy in Termites Nest Building

- Assume that the architecture reaches state A, which triggers response R from worker S.
- A is modified by the action of S (e.g. S may drop a soil pellet), and transformed into a new stimulating configuration A1
- A1 may in turn trigger a new response R1 from S or any other worker Sn and so forth.
- The successive responses R1, R2, Rn may be produced by any worker carrying a soil pellet.
- Each worker creates new stimuli in response to existing stimulating configurations. These new stimuli then act on the same termite or any other worker in the colony.



http://www.javatroll.com/Ants/

Stigmergy in general

- Stigmergy is not restricted to eusocial creatures, or even to physical systems.
- On the Internet there are many emergent phenomena that arise from users interacting only by modifying local parts of their shared virtual environment.
- Wikipedia is a perfect example of this.
  - The massive structure of information available in a wiki could be compared to a termite nest
  - One initial user leaves a seed of an idea (a mudball) which attracts other users who then build upon and modify this initial concept eventually constructing an elaborate structure of connected thoughts

http://en.wikipedia.org/wiki/Stigmergy

Ants

- among the most successful insects ; 20,000 or more species
- Evolved to fill a variety of different ecological niches: predators, herbivores, leaf-cutters, seed-harvesters, aphid- tenders, and fungus-growers
- Found in: deserts, rainforests, mountains and valleys.
- Life stages: egg, larvae, pupae, adult
- A nest consists of: one or more fertile females (queen), fertile males, sterile or sub-fertile females (workers, soldiers, etc)
  - Fertilized eggs produce females, others become male
- Task hierarchy: young and queen caring, digging and other nest works, foraging or defense

Communication and interaction in ants

- Chemical: Pheromones for foraging, alarm, confusing enemies
- Trophalaxis: food or liquid exchange
- Touch: antennae, mandible
- Sound: generated by the gaster segments or mandibles of some ant species
- Vision: visual contact

Defense in ants

- Biting
- Stinging
- Trap-jaw mandibles
- Poisoning by formic acid
- Defense against disease:
  - Maintaining the hygiene of the colony
  - Transport of dead nest-mates
- Defense against flooding

Learning in ants

- Interactive teaching: Knowledgeable foragers of Temnothorax albipennis species directly lead naïve nest-mates to newly discovered food sources by tandem running
- Specialization: Controlled experiments with colonies of Cerapachys biroi suggest that these ants can specialize based on their previous experience.
  - An entire generation of identical workers was divided into two groups: One group was continually rewarded with prey, while it was made certain that the other failed
  - Members of the successful group intensified their foraging attempts while the unsuccessful group ventured out less and less.
  - One month later, 'workers that previously found prey kept on exploring for food, whereas those who always failed specialized in brood care'.

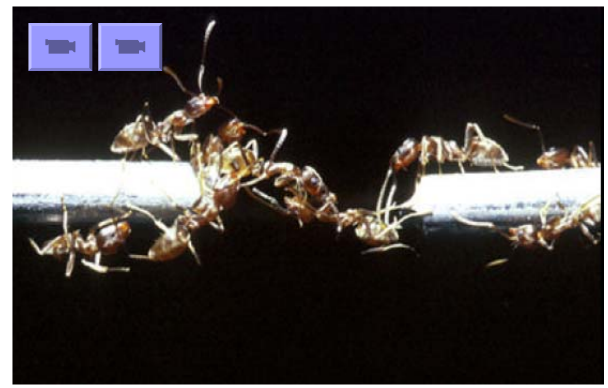
Nest building in ants

- Time scale:
  - Permanent: complex nests
  - Temporary: nomadic
  - Mixed: Army ants alternate between nomadic stages and stages where the workers form a temporary nest out of their own bodies!
- Places:
  - subterranean
  - on trees: Weaver ants (Oecophylla) build nests in trees by attaching leaves together, first pulling them together with bridges of workers and then sewing them together by pressing silk-producing larvae against them in alternation.

Navigation in ants

- visual landmarks: Desert ants Cataglyphis fortis make use of visual landmarks in combination with other cues to navigate.
- Dead reckoning: Sahara desert ants have been shown to navigate by keeping track of direction as well as distance travelled. They use this information to find the shortest routes back to their nests.
- Earth's magnetic field: Several species of ants have been shown to be capable of detecting and making use of the Earth's magnetic field.
- Polarized Light:
- Direction of the sun

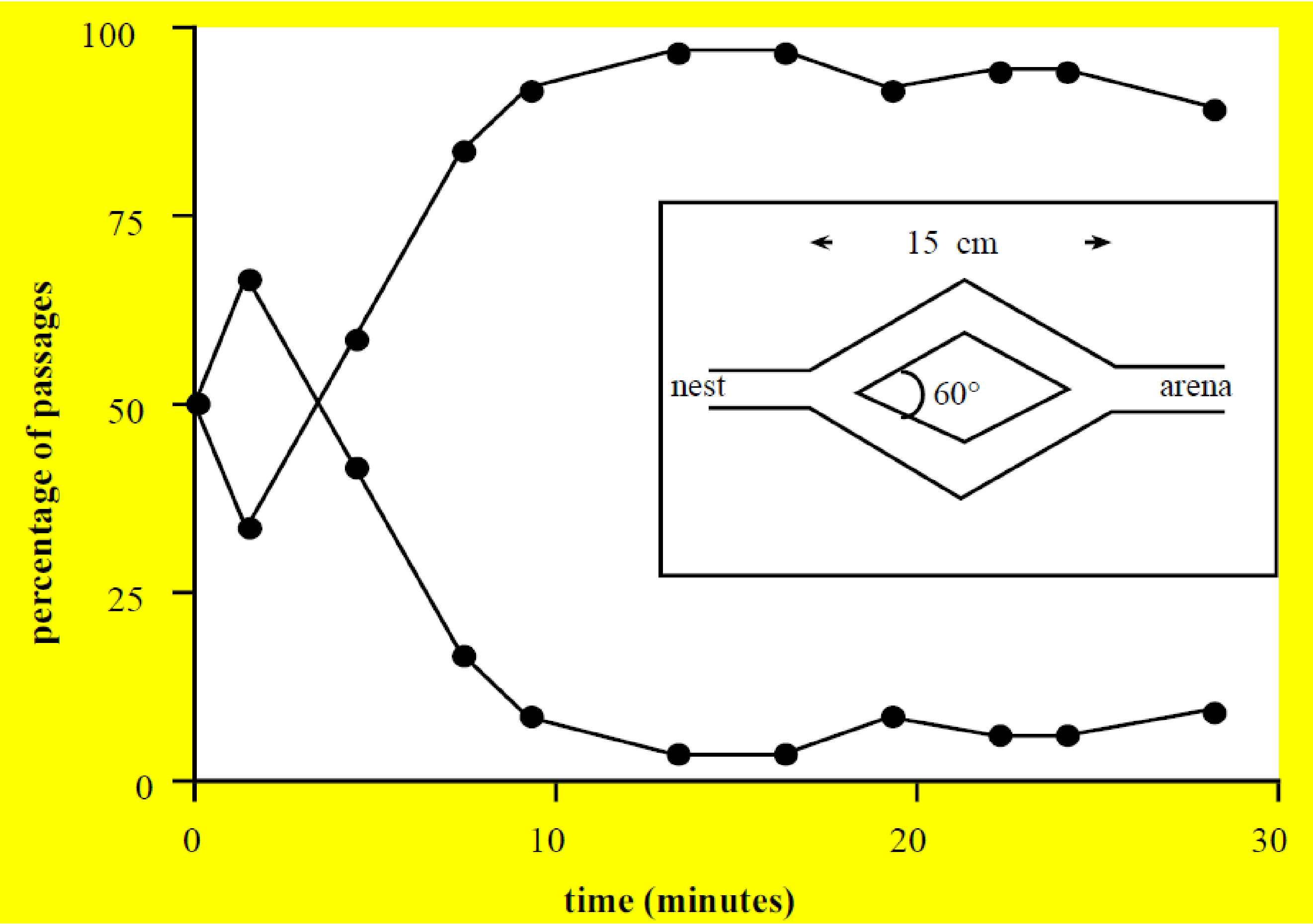
Locomotion of ants



- Walking: most ants travel by walking.
- Swimming: Some species form floating rafts that help them survive floods.
- Branchiation: Some species of ants form chains to bridge gaps over water, underground, or through spaces in vegetation.
- Submerging: Polyrhachis sokolova, can swim and lives in nests that are submerged underwater. They make use of trapped pockets of air in the submerged nests.
- Jumping: Harpegnathos saltator ants can jumps by the synchronized action of the mid and hind pair of legs.
- Gliding: most arboreal ants e.g. Cephalotes atratus are able to direct the direction of their descent while falling.
- Flying: Among females the Queens fly once when establishing a new colony but remove theirs after mating. Males can fly as well but they are alive only for some days.

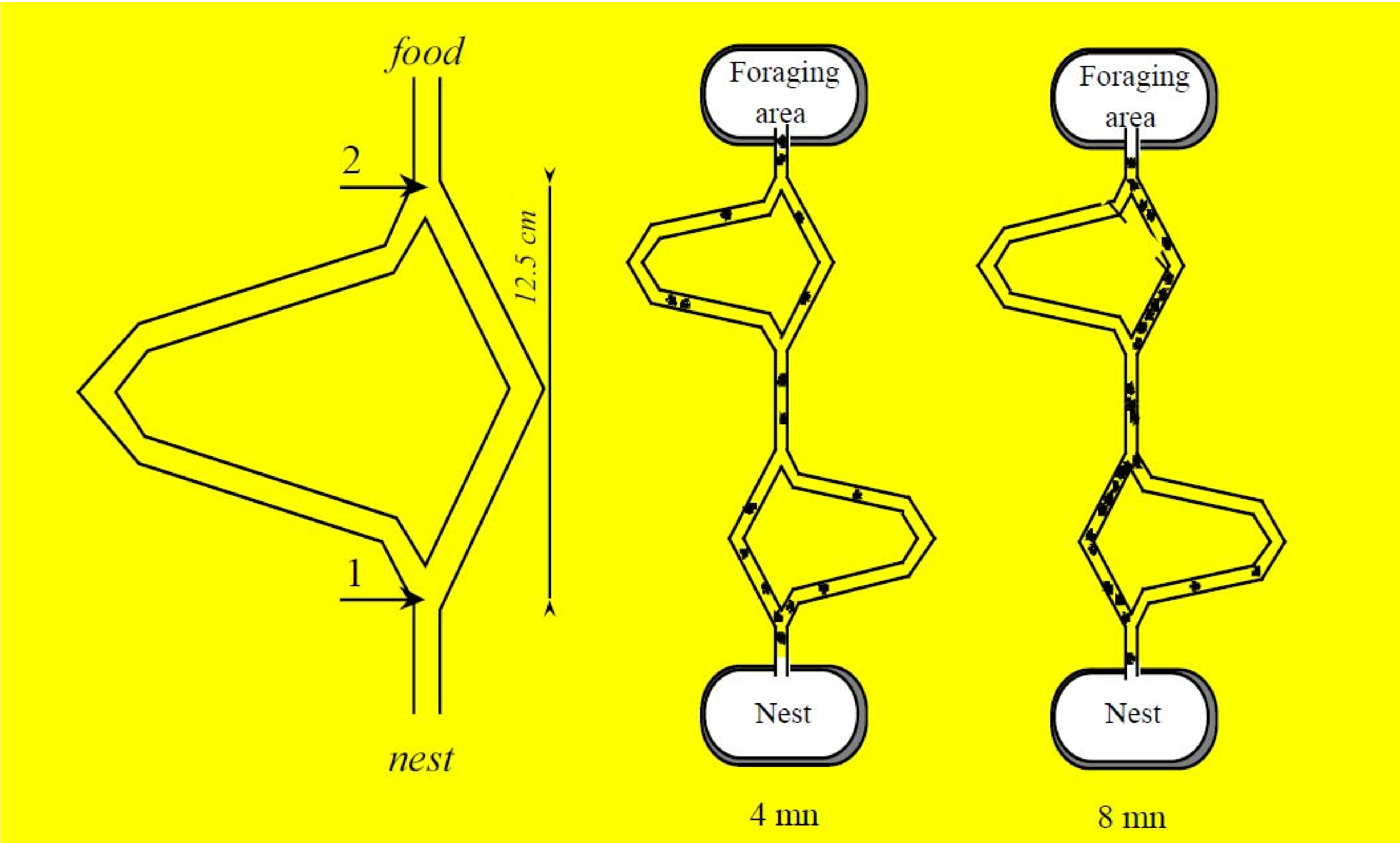
Shortest Path

Foraging in ants, symmetric paths



- Ultimately one of the branches is a winner, not both of them (collective decision)
- The winner is not clear from the beginning (i.e. quality of the paths is equal for the ants)

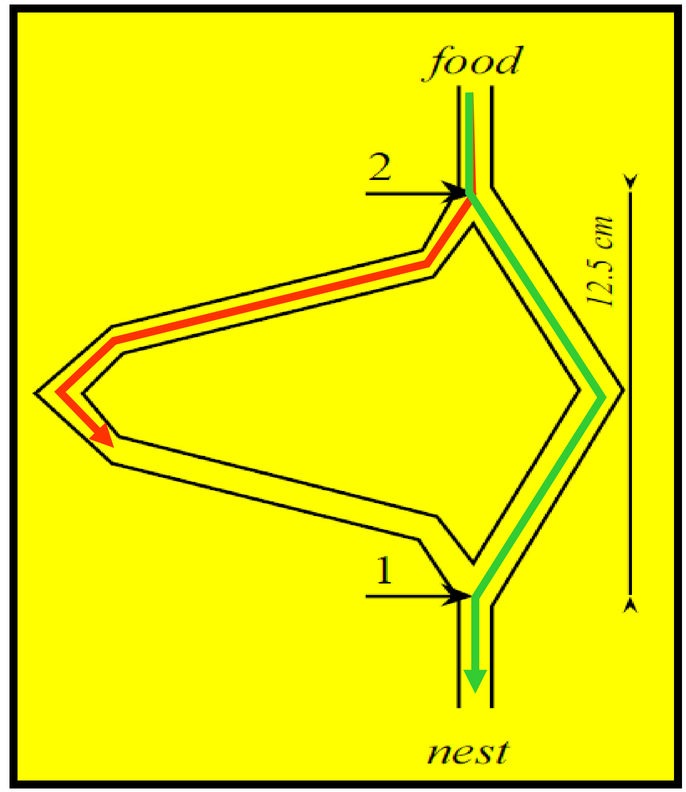
Foraging in ants, asymmetric paths



Shortest path problem

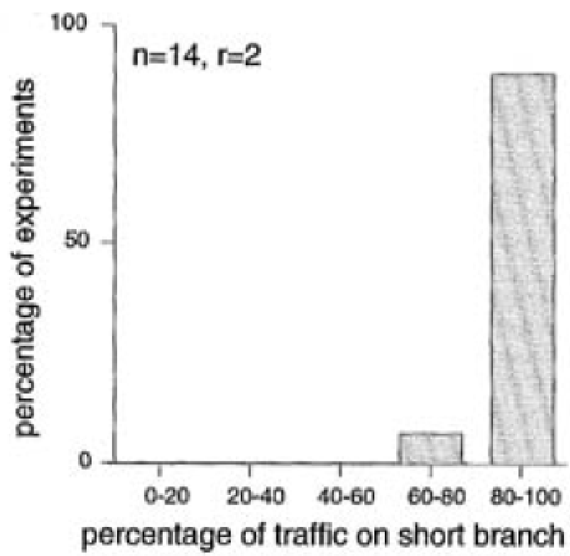
$$P_A = \frac{(k+A_i)^n}{(k+A_i)^n + (k+B_i)^n} = 1 - P_B$$

- Ai and Bi: the numbers of ants that have used branches A and B after i ants have used the bridge
- n: degree of nonlinearity
- k: degree of attraction of an unmarked branch, randomness of choice

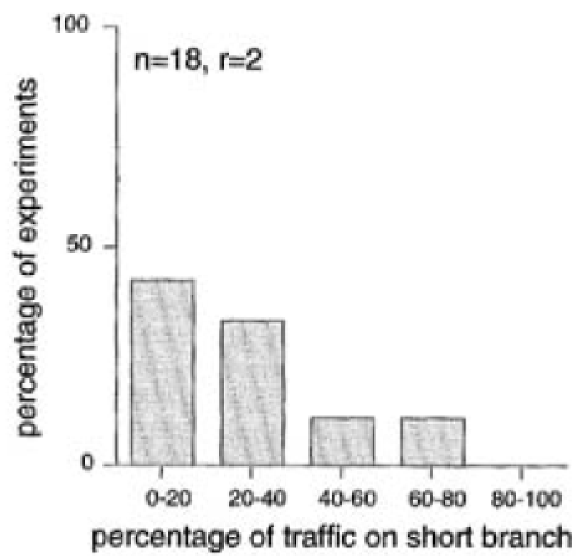


Effect of Initial Pheromone

- Distribution of the percentage of ants that selected the shorter path over n experiments. The longer branch is r times longer than the short branch.
- Pheromone are persistent for hours or months, so the real ants are trapped in local optimum sometimes.



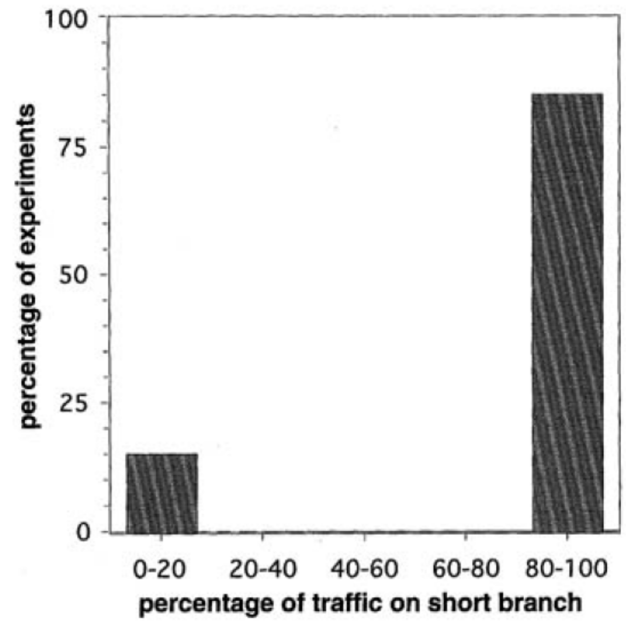
Both branches are presented from beginning of the experiment.

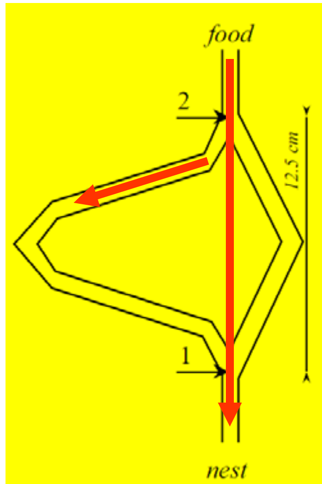


The short branch is presented to the colony 30 minutes after the long branch

Effect of Initial Pheromone ctd.

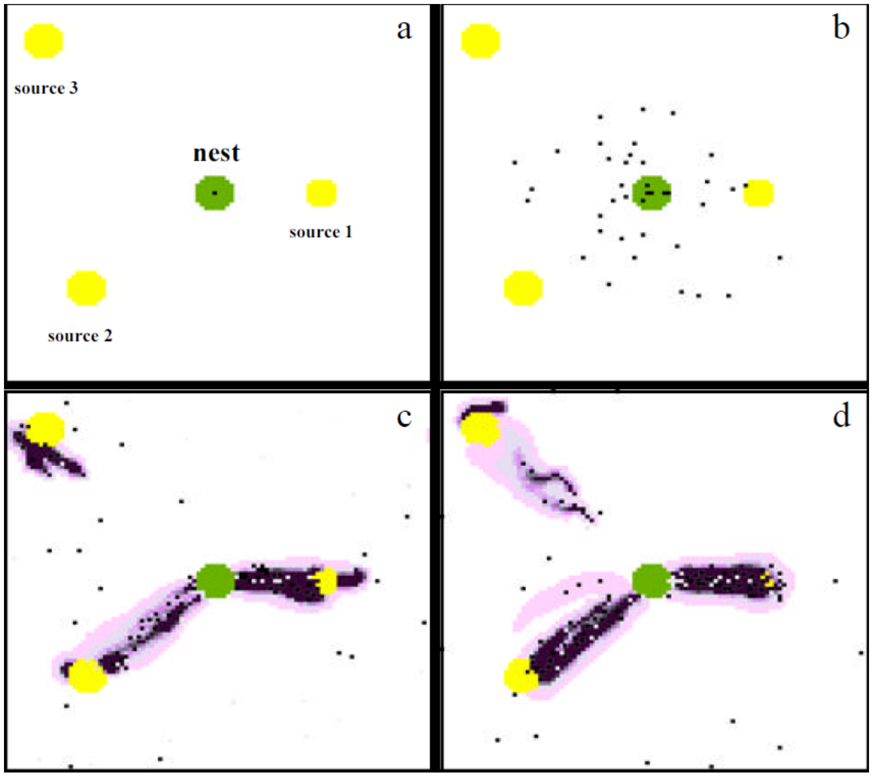
- Same experimental setup as previous slide but with another specie of ants.
- The short branch is presented after the long branch
- Why the ants are not trapped in local optimum?
- Solution: Memory
  - When an ants finds itself in the middle of the long branch, it often realizes that it is heading almost perpendicularly to the required direction
  - This induces it to make U-turns on the long branch





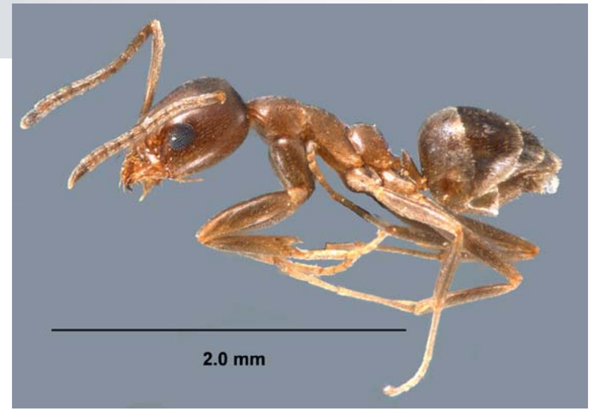
Foraging from multiple sources

- (a) Simulation of 3 food sources of identical quality presented to the colony at various distances from the nest. Pheromone decay occurs over short time scales.
- (b) ants (black dots), explore their environment randomly.
- (c) trails that connect the nest to the food sources are being established.
- (d) only the trails that connect the nest to the closest food sources are maintained, leading to the exploitation of two sources.
- The next closest source will be exploited later, when the first two exploited sources are exhausted.



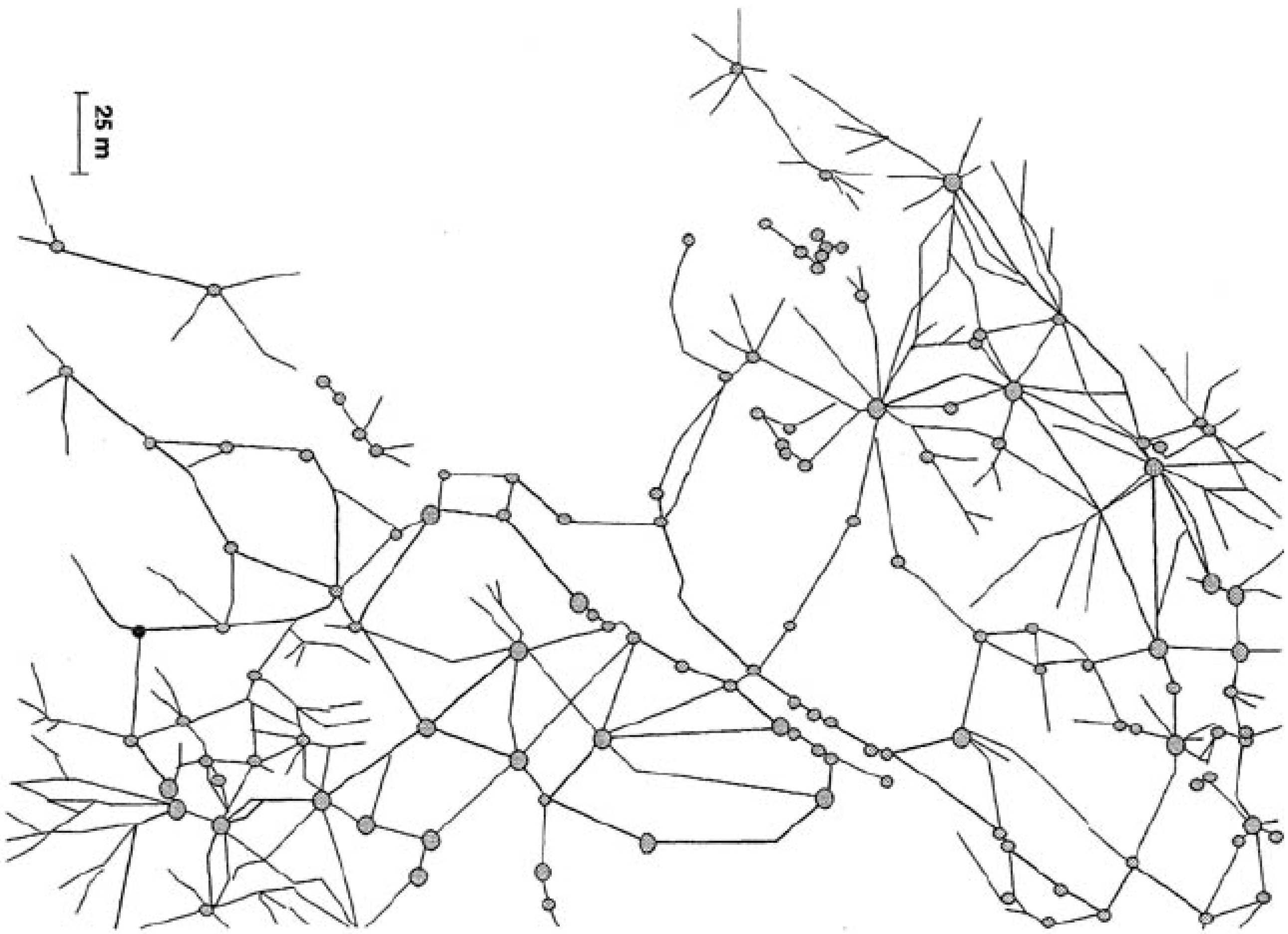
Minimum Spanning Tree

Inter-nest traffic



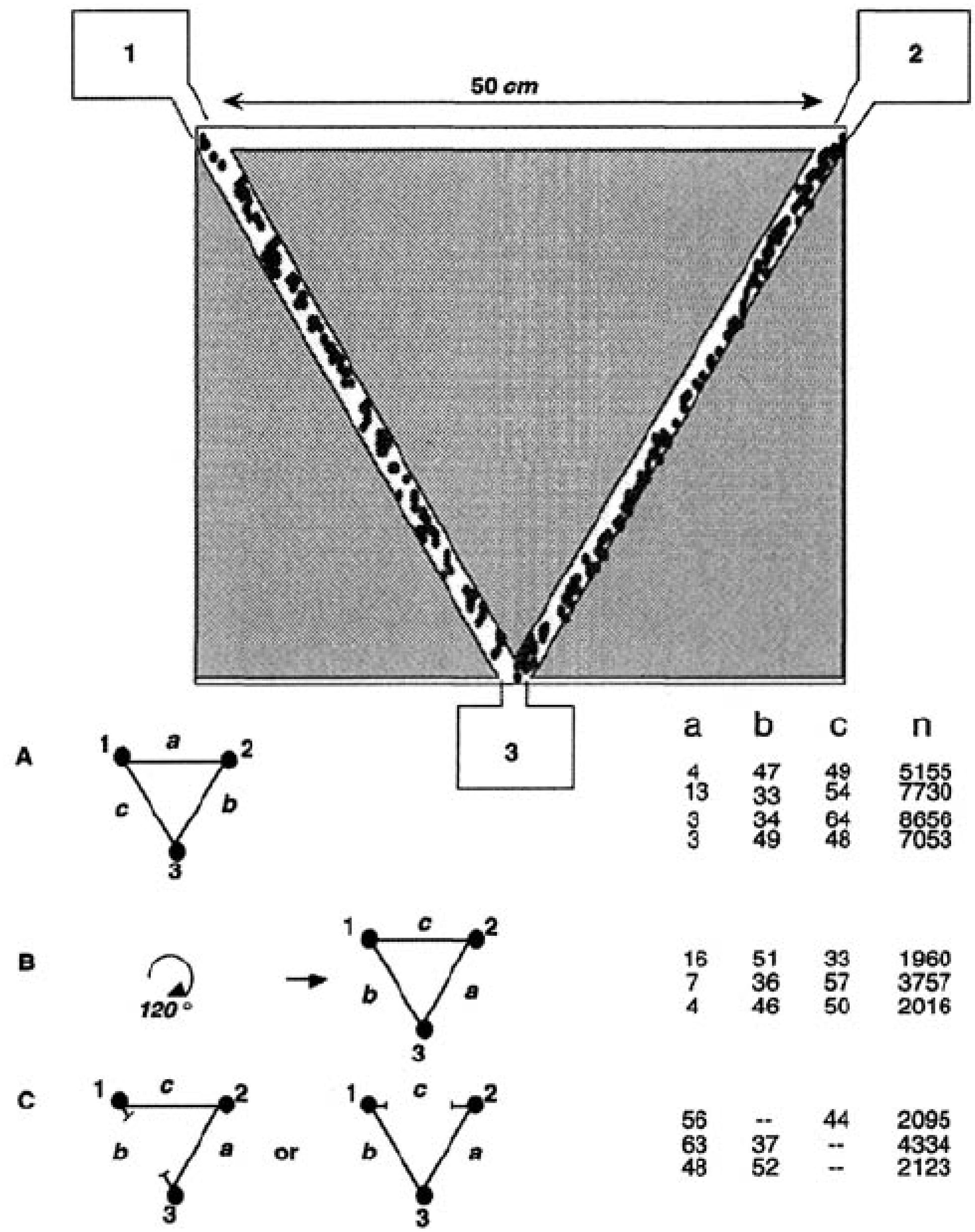
- Societies of Linepithema humile are composed of subsocieties connected by a permanent network of chemical trails.
- Workers, larvae and even queens are continuously exchanged between the nests of these subsocieties.
- Such exchanges enable a flexible allocation of the work force in the foraging area in response to environmental cues.
- Moreover, inter-nest trails are extended to include trails to permanent, long-lasting or rich food sources.

Inter-nest traffic pattern



Minimum Spanning Tree

- Top: Experimental design and results for a triangular network connecting three nests.
- Bottom: Drawings represent the qualitative solutions adopted. A solid line indicates heavy traffic, and an interrupted line a cut branch. The numbers indicate the quantitative results for each experiment, with the percentage of traffic on each branch (a, b, and c) and the total traffic (n) on the branches,
- (a) The triangular network was left for two weeks before counting the traffic (4 experiments). This experiment indicates that chemical, rather than visual, cues play a key role in the selection of branches,
- (b) The entire bridge system was rotated 120 degrees, the nests not being moved (3 experiments),
- (c) The most frequented branch was then cut (3 experiments).

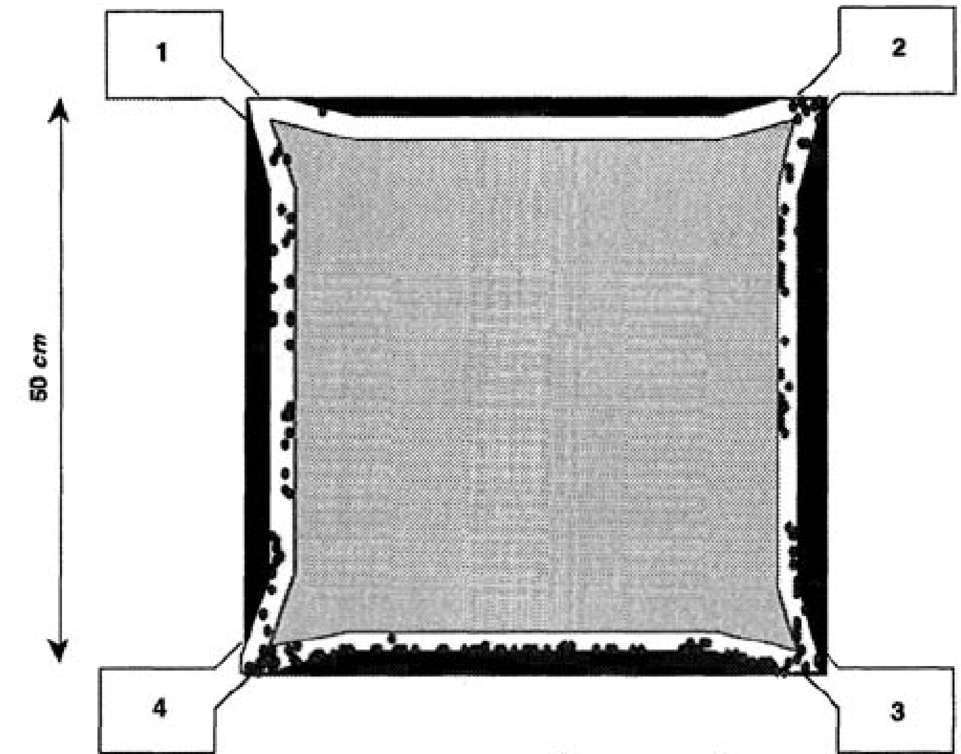


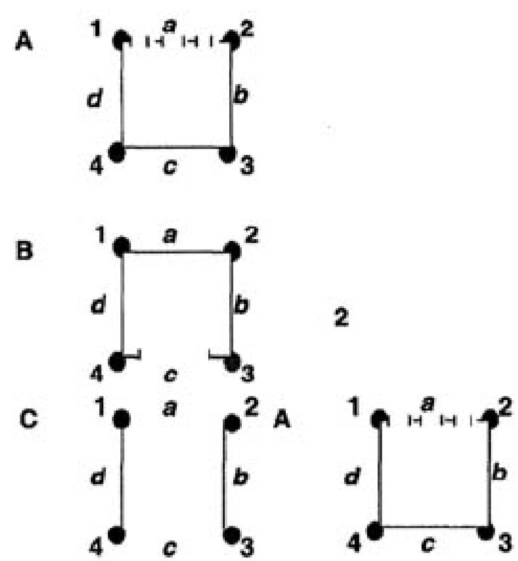
	a	b	c	n
A	4	47	49	5155
	13	33	54	7730
	3	34	64	8656
	3	49	48	7053
B	16	51	33	1960
	7	36	57	3757
	4	46	50	2016
C	56	--	44	2095
	63	37	--	4334
	48	52	--	2123

Aron et al., 1990

Minimum Spanning Tree

- Top: Experimental design and results for a square network connecting four nests.
- Bottom: "In light" means that the experiment has been performed with light. "In dark" means that the experiment has been performed in the dark. The absence of significant difference between experiments performed with and without light suggests that visual cues are not essential,
- (a) The square network was left for two weeks before counting the traffic; branch a is not exploited,
- (b) Branch c (the base of the U-shaped solution in A) was then cut.
- (c) Branches b and d were presented to the colony for two weeks, and then branches a and c were added; branch a is not exploited.





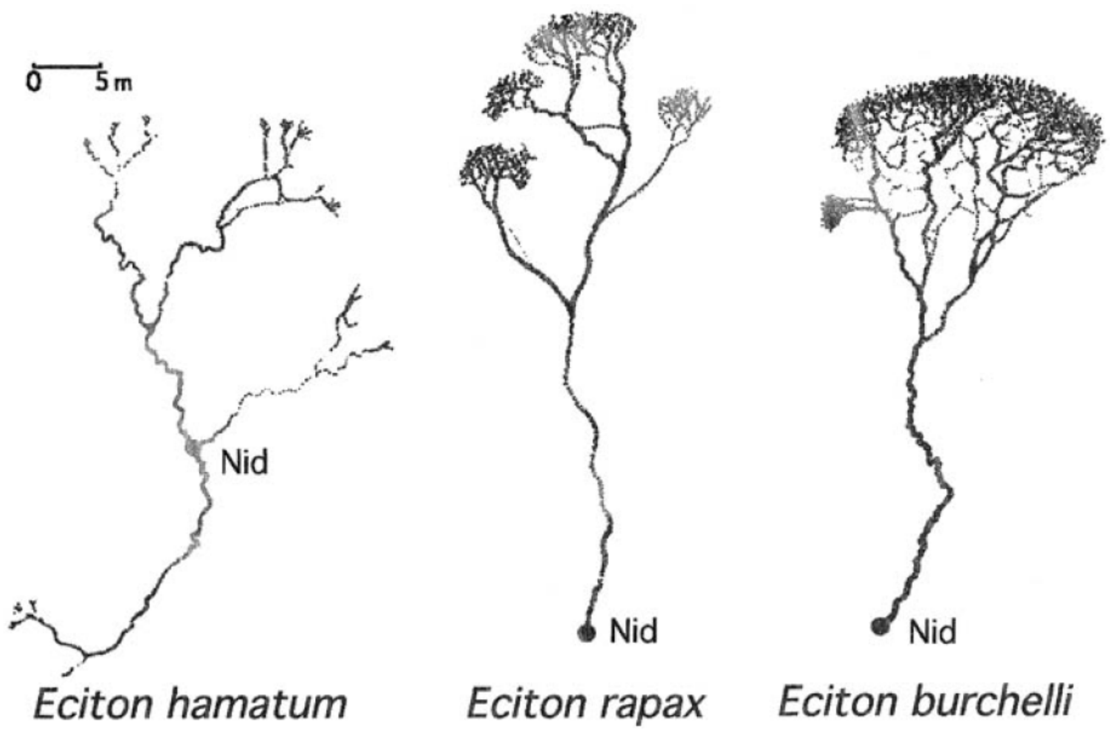
	a	b	c	d	n	
A	2	32	31	35	8150	in light
	3	45	32	20	4996	in light
	3	30	64	24	7839	in light
	2	32	35	30	6523	in dark
	2	24	41	32	10157	in dark
B	23	40	--	37	1642	in dark
	31	22	--	47	2740	in dark
C / 2 A	6	25	31	38	7974	in light
	4	27	28	41	8120	in light

Aron et al., 1990

The raid patterns of army ants

- The figure shows the swarm raid structures of three species of army ants
- E. hamatum feeds mainly on dispersed social insect colonies.
- Eciton burchelli feeds largely on scattered arthropods.
- E. rapax has an intermediary diet.
- These different diets correspond to different spatial distributions of food items: for E. hamatum, food sources are rare but large, whereas for E. burchelli, food can easily be found but in small quantities each time.

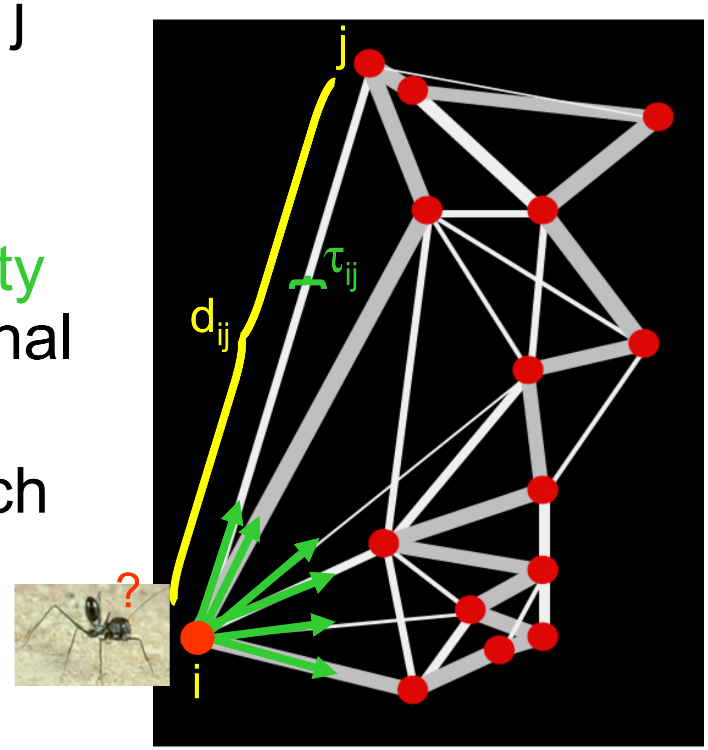
They have the same behavior but adapted to different niches



Travelling Salesman

Travelling Salesman using Ant Colony Optimization

- d_{ij}= distance between city i and city j
- τ_{ij}= virtual pheromone on link (i,j)
- m agents, each building a tour
- At each step of a tour, the probability to go from city i to city j is proportional to $(\tau_{ij})^{\alpha}(d_{ij})^{-\beta}$
- After building a tour of length L, each agent reinforces the edges it has used by an amount proportional to 1/L
- The virtual pheromone evaporates: $\tau \leftarrow (1-\rho)\,\tau$



Choosing the number of ants

- More ants:
  - More computation
  - Better solutions
- Using as many ants as there are cities in the problem, i.e. $m = n$, provides a good tradeoff.

Initialization of ants

- At the beginning of each tour, ants are either:
  - Placed randomly on the cities, or
  - At least one ant is placed on each city
- no significant difference in performance is observed

Variants of the transition rule

- Most of the time the city that maximizes $(\tau_{ij})^{\alpha}(d_{ij})^{-\beta}$ is selected (with probability q); however sometimes (with probability 1-q) a city is randomly selected.

Variants of the pheromone update rule

- Elitist ant: The ant that has found the best tour from the beginning of the trial is allowed to reinforce the pheromone in addition to the currently runing ants.
- Worst Tour: The worst tour is not allowed to update the pheromones
- Greedy update rule: Only the ant that generated the best tour since the beginning of the trial can be allowed to globally update the concentrations of pheromone on the branches. So only the set of edges that belong to this tour are updated.

Variants of the pheromone update rule (ctd.)

- Local update rule: the edge pheromone level is reduced when an ant visits an edge, making the visited edges less and less attractive as they are visited by ants, indirectly favoring the exploration of not yet visited edges.
- Ranking the m ants by tour length ($L_1(t)$, $L_2(t)$,... ,$L_m(t)$) and making ants update the edges with a quantity of pheromone proportional to their rank.

Quadratic Assignment

The Quadratic Assignment Problem (QAP)

- A set of n activities have to be assigned to n cities (or vice versa)
- $D = [d_{ij}]_{n,n}$ = distances between cities
- d_{ij} = the Euclidean distance between city i and city j,
- $F = [f_{hk}]_{n,n}$ = flows among activities (transfers of data, material, humans, etc.)
- f_{hk} = the flow between activity h and activity k.
- An assignment = a permutation π of {1,... ,n}, where $\pi(i)$ is the activity that is assigned to location i.
- Goal: find a permutation π_m such that the sum of the distances between their cities multiplied by the corresponding flows between their activities is minimized:

$$C(\pi) = \sum_{i,j=1}^{n} d_{ij} f_{\pi(i)\pi(j)}$$

Solving QAP using ACO

- QAP has shown to be NP-hard.
- Distance potential: the sum of the distances between a particular node and all the others. Lower distance potentials mean this node is more barycentric in the network.

$$f_h = \sum_{k=1}^{n} f_{hk} \quad h = \{1, \ldots, n\}$$

- Flow potential: the total flow exchanged between an activity and all the others. Higher flow potentials means this activity is more important in the system of flows exchanged.

$$d_i = \sum_{j=1}^{n} d_{ij} \quad \mathrm{h} = \{1, \ldots, n\}$$

- Solution with ACO: assign activity j to city i with a probability proportional to : $(\tau_{ij})^{\alpha}(d_i.f_j)^{-\beta}$

Problem solving with ant colony optimization algorithm

- The same method applies to all assignment-type problems
  - Quadratic assignment
  - Job-shop scheduling
  - Graph coloring
  - Vehicle scheduling
  - Network routing

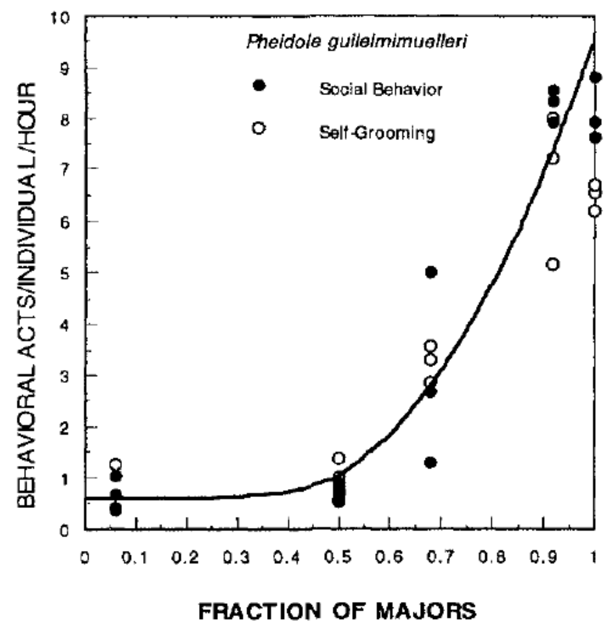
Division of labor

Division of Labor

- Division of labor: different activities are often performed simultaneously by specialized individuals.
- Plasticity: The ratios of workers performing the different tasks varies in response to internal perturbations or external challenges.

Elasticity in division of labor

- In most species of Pheidole genus, the worker population is divided into two morphological subcastes: the minor and major subcastes.
- Minors: take care of the quotidian tasks; smaller than the majors
- Majors: called soldiers, specialized for seed milling, abdominal food storage, defense, or some combination of them.
- Experimental results: When the fraction of minors in the colony becomes small, majors engage in tasks usually performed by minors and efficiently replace the missing minors.



Wilson, 1984

Response Threshold Model

- A model for division of labor
- S: the intensity of a stimulus associated with a particular task
  - E.g. task: larval feeding ➔ stimulus: larval demand through emission of pheromones
  - E.g. task: corpse clustering ➔ stimulus: dead nestmates

- θ: a response threshold
  - determines the tendency of an individual to respond to the stimulus s and perform the associated task.
  - the probability of response is low for $s \ll \theta$ and high for $s \gg \theta$.

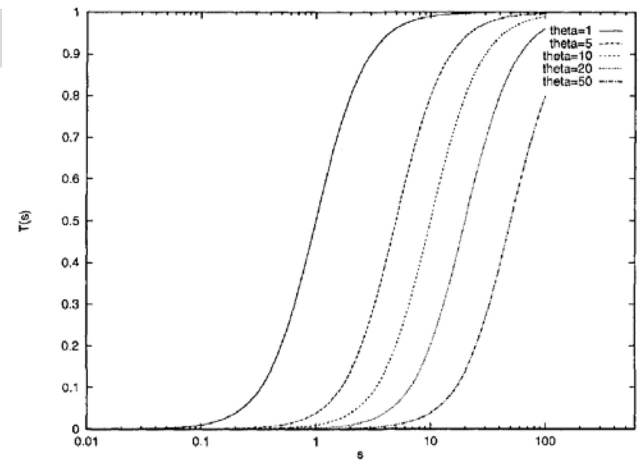
Response Function

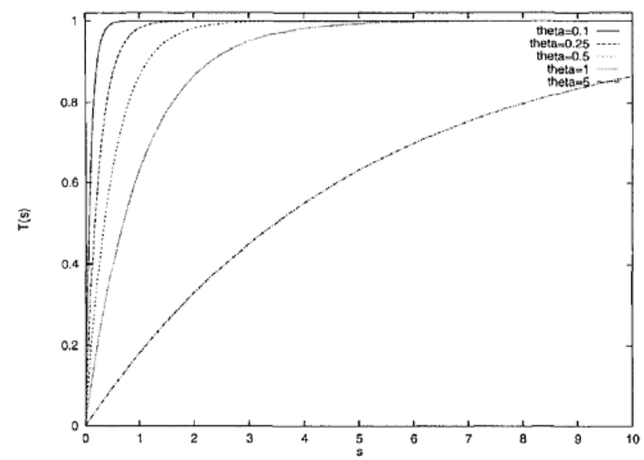
- $T_\theta(s)$: the probability of performing the task as a function of stimulus intensity
- Characteristics of a response function:
  - s << θ ➔ $T_\theta(s) \rightarrow 0$
  - s >> θ ➔ $T_\theta(s) \rightarrow 1$
  - $T_\theta(s)$ monotonically increases with s
- Sigmoid function:

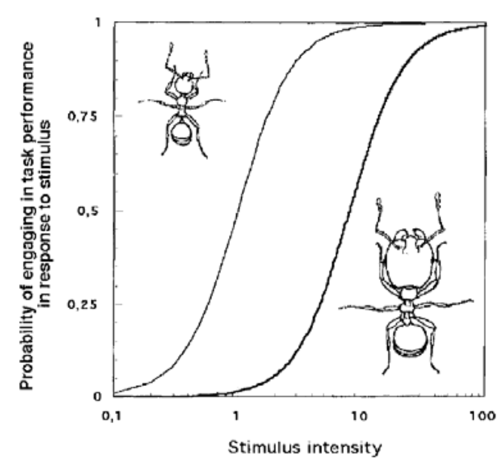
$$T_\theta(s) = s^n / (s^n+\theta^n)$$

- Exponential function:

$$T_\theta(s) = 1 - e^{-s/\theta}$$

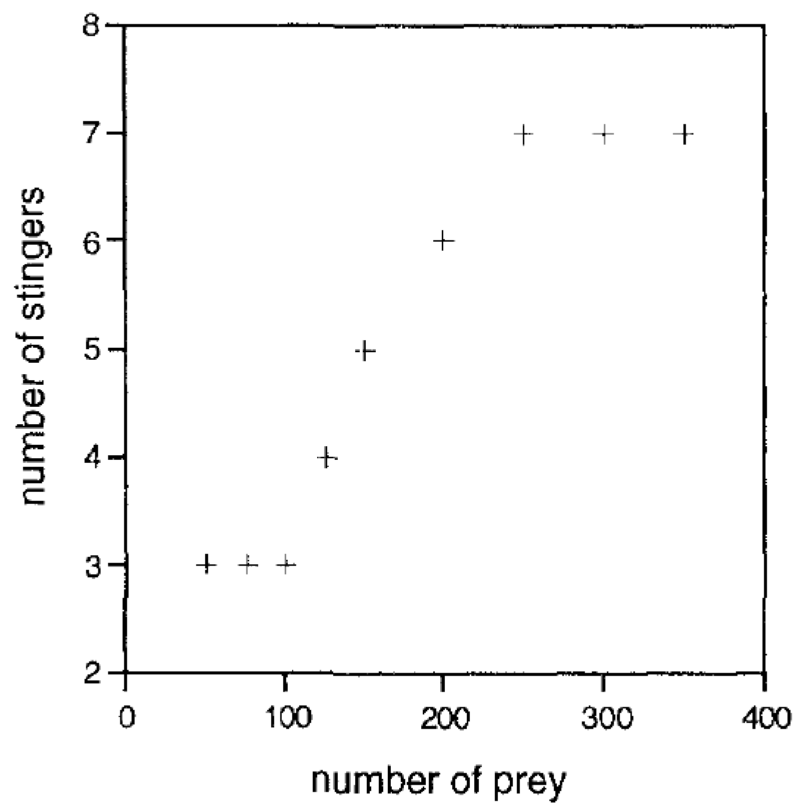






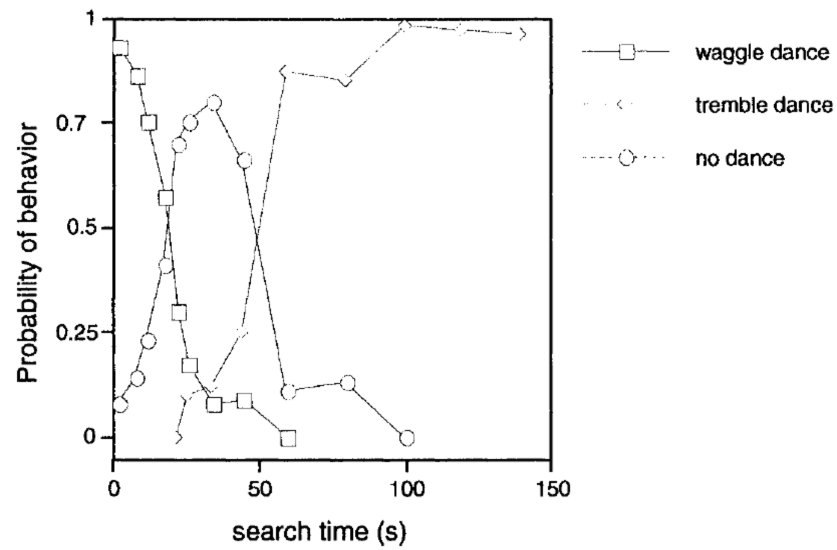
Response threshold in ants

- Two type of specialized ants in Ectatomma ruidum:
  - Stinger ants (or killer ants): kill the prey
  - Transporter ants: transport the dead prey
- when presented with an increasing number of prey, stinger ants start to help transporter ants and become involved in the retrieval process

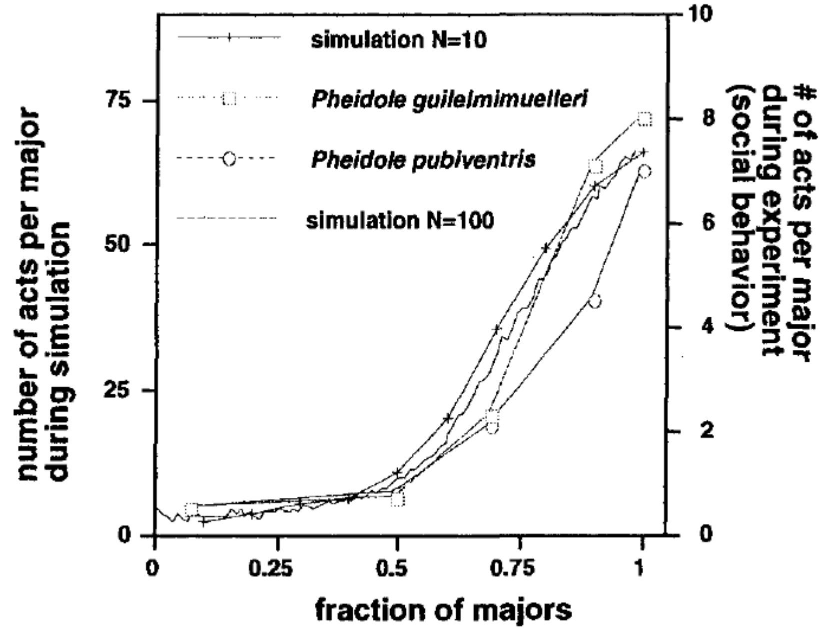


Response threshold in honey bees

- If it takes a forager too long to unload her nectar to a storer bee, she gives up foraging with a probability that depends on her search time in the unloading area. She will then start a tremble dance to recruit storer bees.
- If her in-hive waiting or search time is very small, she starts recruiting other foragers with a waggle dance.
- If her in-hive waiting or search time lies within a given window, she is likely not to dance at all and return to the food source.



Response threshold model for one task



- s: stimulus or demand
- X_i: the state of an individual I
  - $X_i = 0$ ➔ inactive
  - $X_i = 1$ ➔ performing the task
- θ_i: the response threshold of individual i.

- An inactive individual starts performing the task with a probability P per unit time:

$$P(X_i=0 \rightarrow X_i=1) = T_{\theta i}(s) = s^2 / (s^2+\theta_i^2)$$

- An active individual gives up task performance and becomes inactive with constant probability *p* per unit time:

$$P(X_i=1 \rightarrow X_i=0) = p$$

- Stimulus dynamics:

$$s(t+1) = s(t) + \delta - \alpha\, N_{act}/N$$

δ: increase in stimulus per unit time

α: efectiveness of task performance

N_{act}: number of active individuals

N: total number of individuals

Response threshold model for several tasks

- m tasks, n individuals, T types
- s_j : demand for task j
- n_i : total number of individuals of type i
- f_i : n_i / n
- N_{ij} : the number of workers of type i engaged in task j performance,
- x_{ij} : N_{ij} / n_i
- θ_{ij} : response threshold of workers of type i to task j .
- The average deterministic differential equations describing the dynamics of the x_{ij}'s are given by:

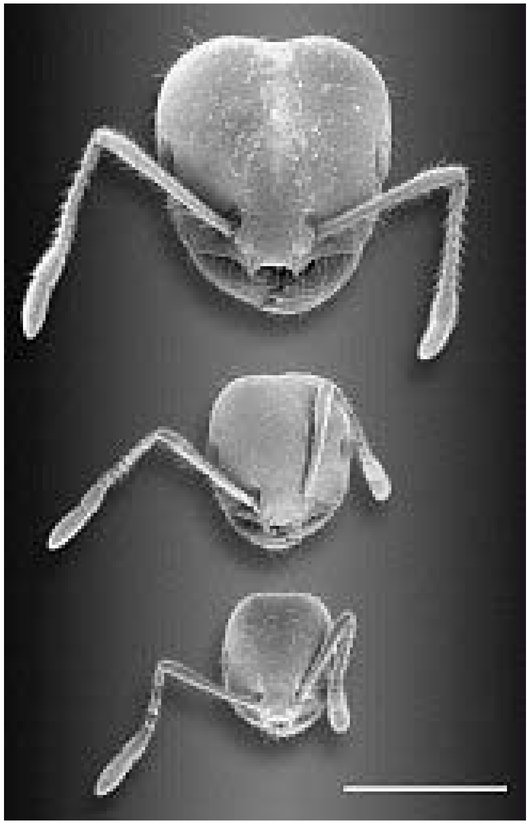
$$\partial_t x_{ij} = \frac{s_j^2}{s_j^2 + \theta_{ij}^2}\left(1 - \sum_{k=1}^{m} x_{ik}\right) - p x_{ij}$$

$$\partial_t s_j = \delta_j - \alpha \sum_i f_i x_{ij}$$

Specialization

Specialization

- Specialization allows greater efficiency of individuals in task performance because they "know" the task or are better equipped for it.
  - Temporal polyethism: Individuals of the same age tend to perform identical sets of tasks.
  - Worker polymorphism: Some workers have different morphologies. e.g. the soldier or major caste which is observed in several species of ants.
  - Individual variability: Even within an age or morphological caste, differences among individuals in the frequency and sequence of task performance may exist.



Specialization model

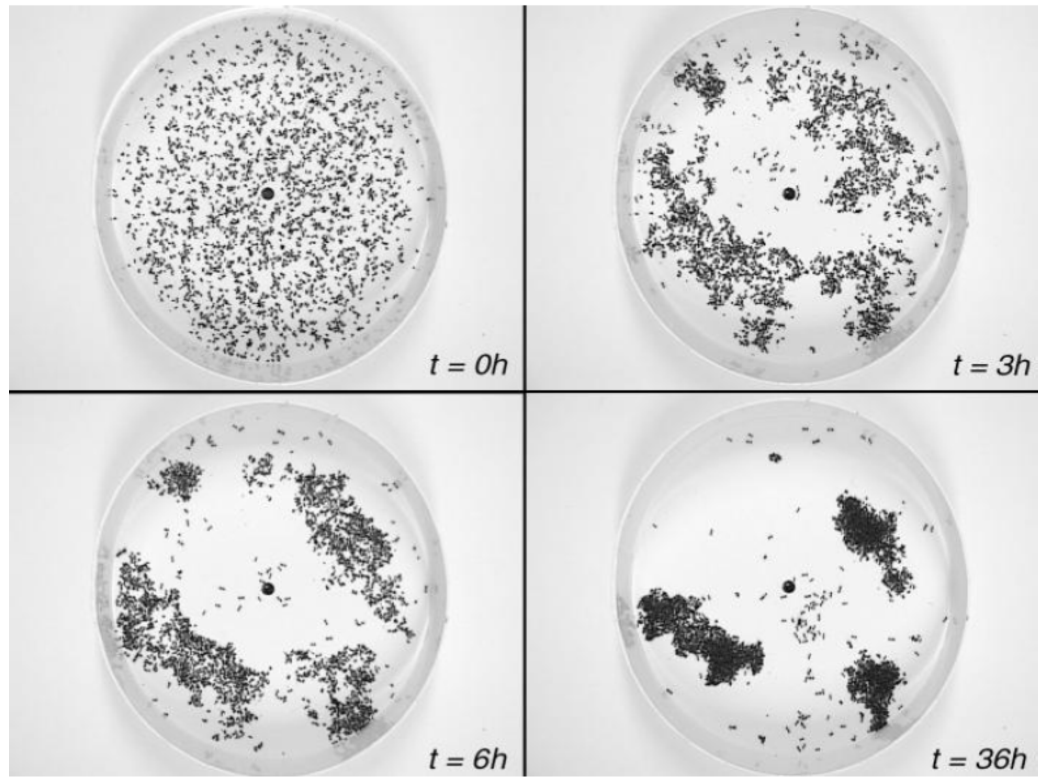
- The simple response threshold model can not explain the specialization phenomena observed in many social animals.
- Solution: allow response thresholds vary in time following a reinforcement process:
  - The threshold decreases when the corresponding task is performed during Δt:
    $$\theta_{ij} \leftarrow \theta_{ij} - \xi \Delta t$$
  - The threshold increases when the corresponding task is not performed during Δt:
    $$\theta_{ij} \leftarrow \theta_{ij} + \varphi \Delta t$$

Response threshold of individual i to task j

Clustering and Sorting

Corpse clustering in ants

- 1500 corpses are randomly located in a circular arena (diameter 25 cm), where Messor sancta workers are present.
- The figure shows four successive pictures of the arena:
  - the initial state,
  - 2 hours,
  - 6 hours, and
  - 26 hours after the beginning of the experiment.



Clustering model

- M agents walking randomly in the environment.
- An isolated item is more likely to be picked up by an unladen agent:

$$P_p=[k_1/(k_1+f)]^2$$

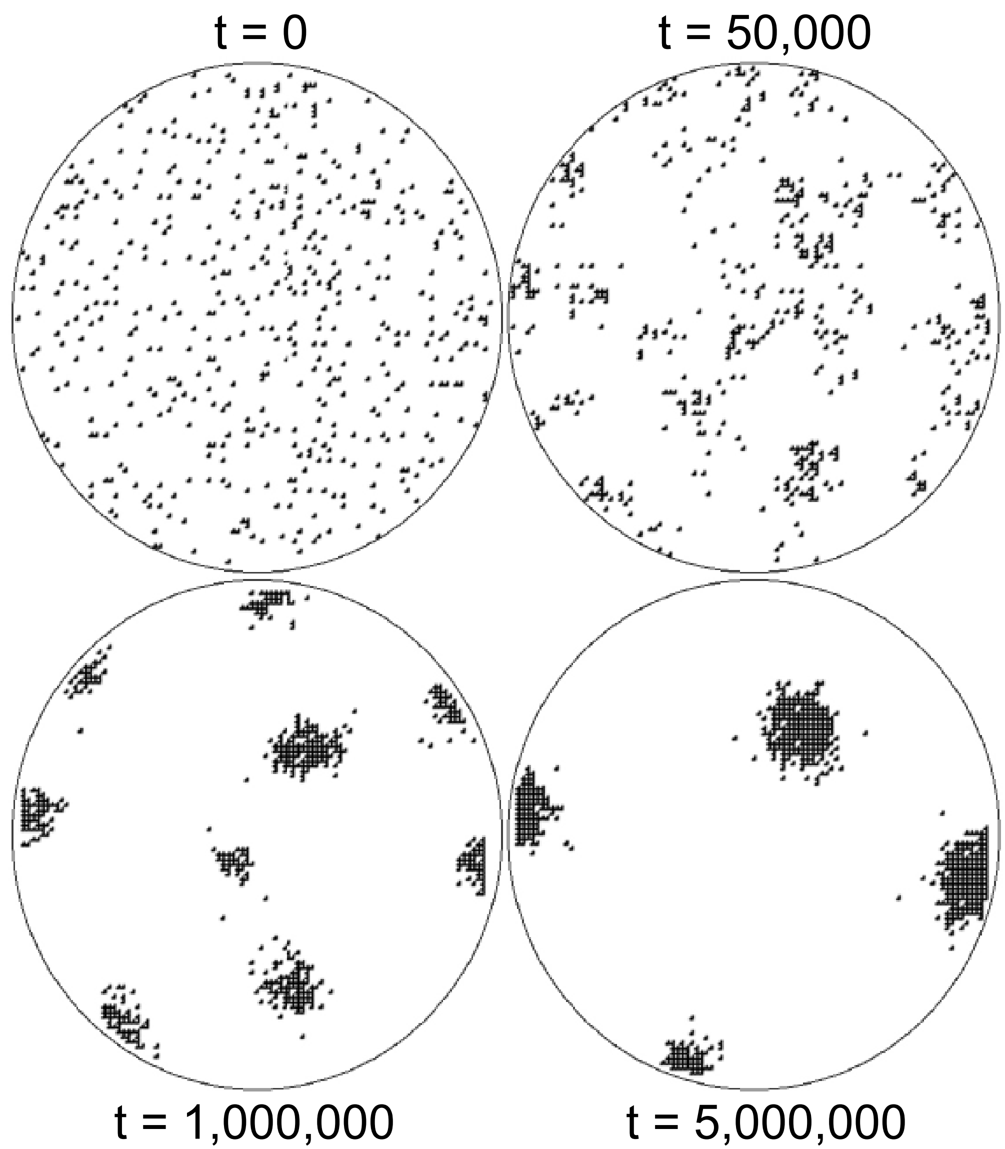
f = density of items in neighborhood

- A laden agent is more likely to drop an item next to other items:

$$P_d=[f/(k_2+f)]^2$$

Clustering in simulation

- Simulated circular arena
  - diameter = 200 grid sites
  - total area: 31,416 sites
  - The initial state, with 5,000 items placed randomly in the arena
- T = 50, k_1 = 0.1, k_2 = 0.3, 10 agents.



Brood sorting in ants

- The same principle as clustering can be applied to sort items of several types (i=1,...,n).
- f is replaced by f_i, the fraction of type i items in the agent's neighborhood:

$$P_p=[k_1/(k_1+f_i)]^2$$

$$P_d=[f/(k_2+f_i)]^2$$

Graph Partitioning

- Let $G = (V, E)$ be an undirected graph, $V = \{v_i , i = 1 , . . . , N\}$ is the set of N vertices and E the set of edges.

- Let the adjacency matrix be denoted by $A = [a_{ij}]$; $a_{ij} \neq 0$ if and only if $(v_i, v_j) \in E$.

- We shall only treat the cases where $a_{ij} = 0$ or 1, which correspond to $(v_i, v_j) \notin E$ and $(v_i, v_j) \in E$, respectively. The case of weighted edges can be readily derived.

Graph Partitioning (ctd.)

- Let δ_i be the degree of vertex i, that is, the number of edges that connect to v_i. More generally, $\delta_i = \sum_j a_{ij}$. Let δ be the diagonal matrix, the elements of which are the δ_i 's.

- Each vertex of the graph is initially assigned a set of random coordinates in Z^n

- Problem: change the vertices' coordinates in Z^n so that:
  1. clusters present in the graph are located in the same portion of space,
  2. intercluster edges are minimized, and
  3. different clusters are clearly separated.

Distance between two vertices

$$d(v_i, v_j) = \frac{\left| D\left(\rho(v_i), \rho(v_j) \right) \right|}{\left| \rho(v_i) \right| + \left| \rho(v_j) \right|}$$

$$\rho(v_i) = \left\{ v_j \in V ; a_{ij} \neq 0 \right\} \cup \left\{ v_i \right\}$$

$$D(A, B) = (A \cup B) - (A \cap B)$$

Local Density

$$f(v_i) = \begin{cases} \frac{1}{s^2} \sum_{v_j \in Neigh_{(s\times s)(r)}} \left[1 - \frac{d(v_i, v_j)}{\alpha}\right] & if\ f > 0 \\ 0 & otherwise \end{cases}$$

- s x s defines the neighborhood range in x and y directions
- r is the current position
- α defines the scale for dissimilarity
- $f(v_i)$ is a measure of the average distance within the graph of vertex v_i to the other vertices v_j present in the neighborhood of v_i

Pick up / Drop probabilities

- Probability of picking up a node

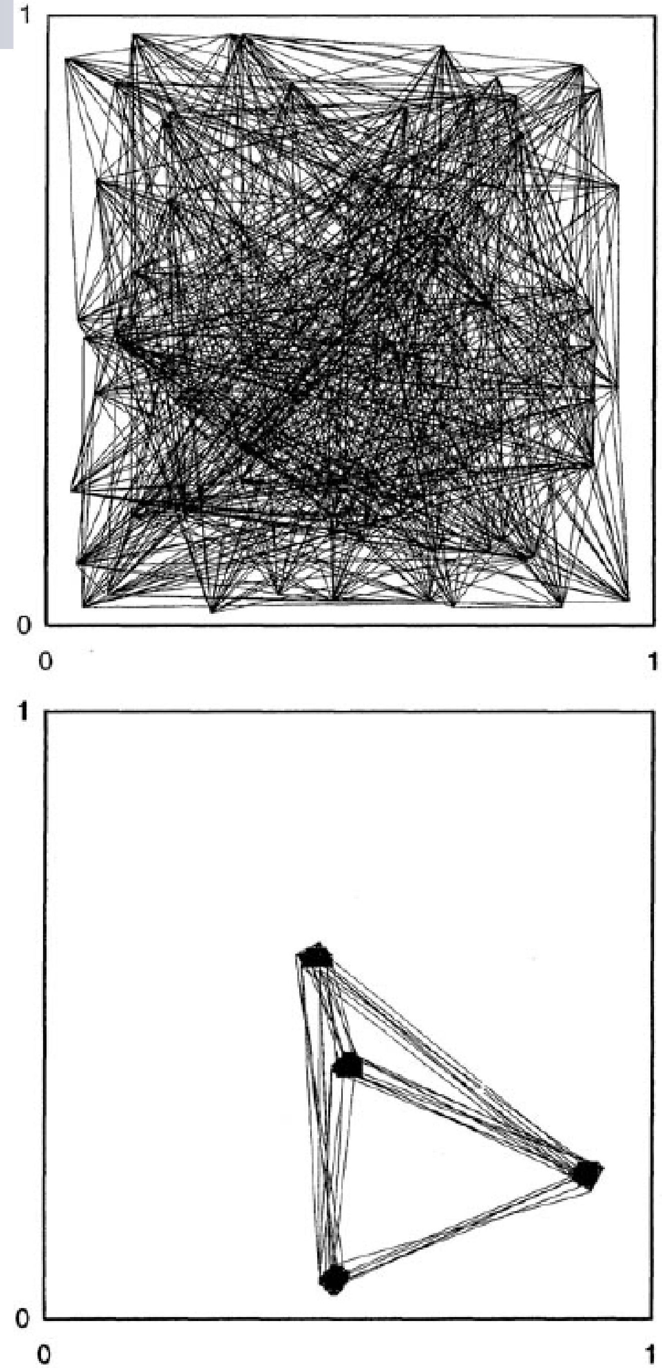
$$p_p(v_i) = \left(\frac{k_1}{k_1 + f(v_i)} \right)^2$$

- Probability of dropping a node

$$p_d(v_i) = \left(\frac{f(v_i)}{k_2 + f(v_i)} \right)^2$$

Example

- (a) Initial distribution of vertices on the portion of plane [0,1] x [0,1] for a random graph:
  - 4 clusters, each of them has 25 vertices,
  - 0.8: existence probability of an edges between vertices in a cluster
  - 0.01: existence probability of an edges between vertices in different clusters
- (b) The algorithm, with 10 agents, is able to find "natural" clusters in this graph. Vertices distribute themselves in space in such a way that exactly 4 clusters of vertices appear, which correspond to the 4 clusters of the graph.

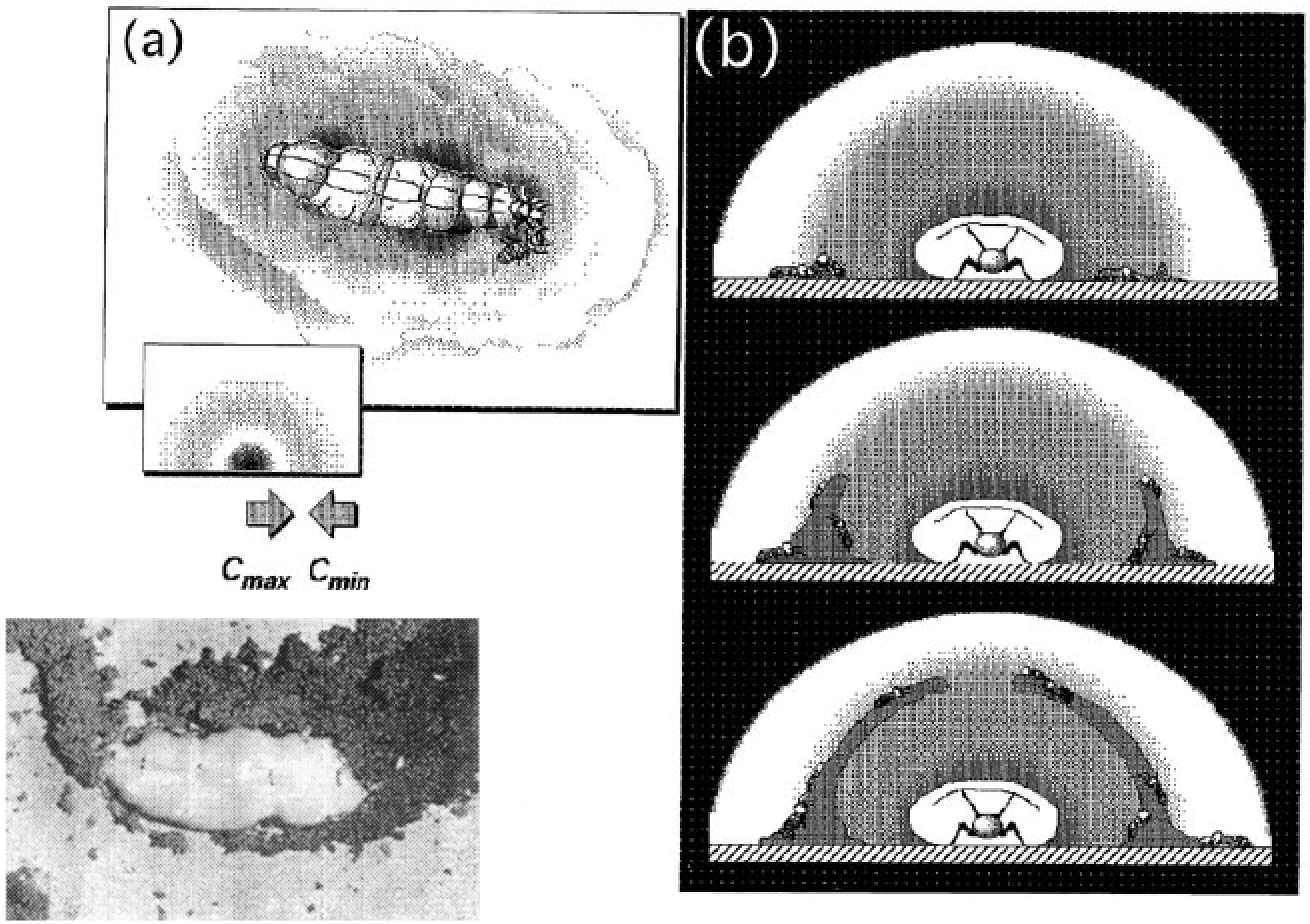


Templates and Nest Building

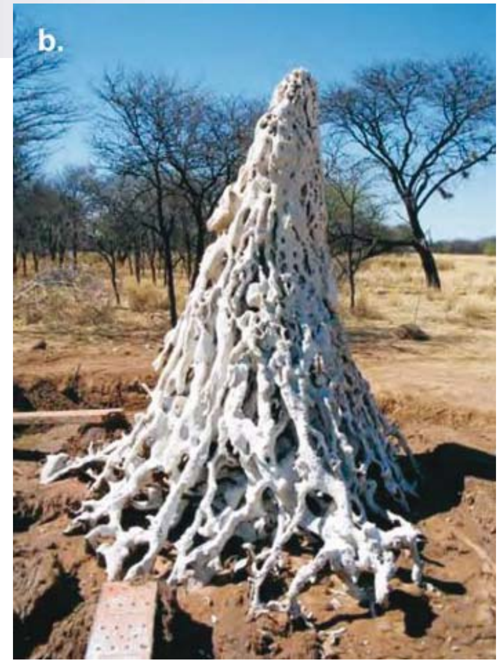
Template

- What happens if some corpses of dead ants are placed nearby each other at the beginning? ➔ predictable patterns
- A template is a pattern that is used to construct another pattern; a kind of prepattern in the environment used by animals to organize their activities ➔ snowball effect
- This prepattern can result from natural gradients, fields, or heterogeneities that are exploited by the colony. E.g.:
  - Some ants build walls around the brood pile
  - Construction of the royal chamber in termites based on the emission of pheromone from the queen

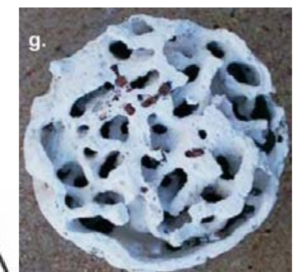
Building the royal chamber in termites

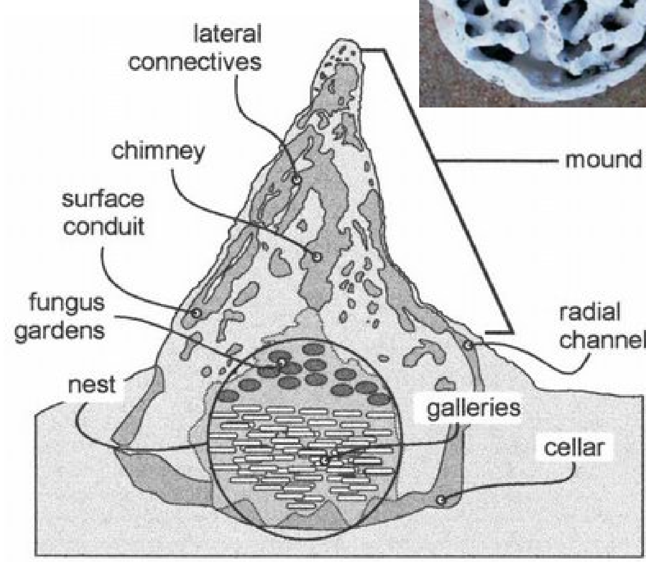


Termites Nest



- Some species of termites (Macrotermes) build complex nests, comprised of:
  - roughly cone-shaped outer walls that often have conspicuous ribs containing ventilation ducts which run from the base of the mound toward its summit,
  - brood chambers within the central "hive" area, which consists of thin horizontal lamellae supported by pillars,
  - a base plate with spiral cooling vents,
  - a royal chamber, which is a thick-walled protective bunker with a few minute holes in its walls through which workers can pass,
  - fungus gardens, draped around the hive and consisting of special galleries or combs that lie between the inner hive and the outer walls, and,
  - finally, peripheral galleries constructed both above and below ground which connect the mound to its foraging sites.
- The structure of fine tunnels and ducts inside the mound play an important role in regulating temperature, as well as moisture levels and the replenishment of oxygen, without drawing any energy from the outside world,

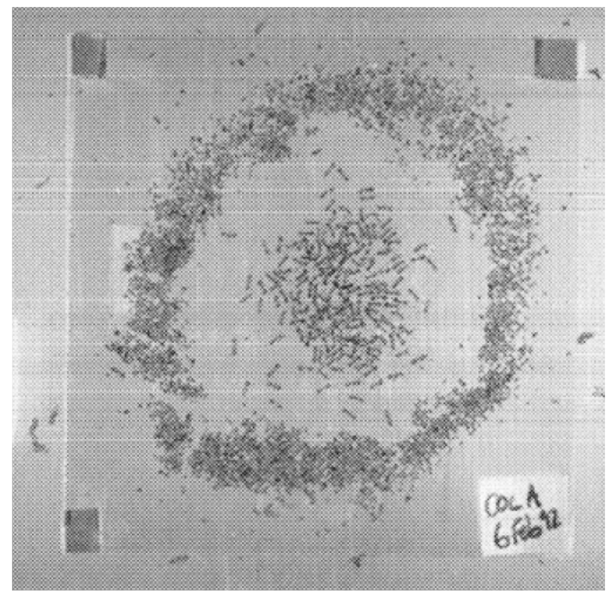




http://pruned.blogspot.com/2007/05/landscapes-as-organs-of-extended.html

Wall building in ants

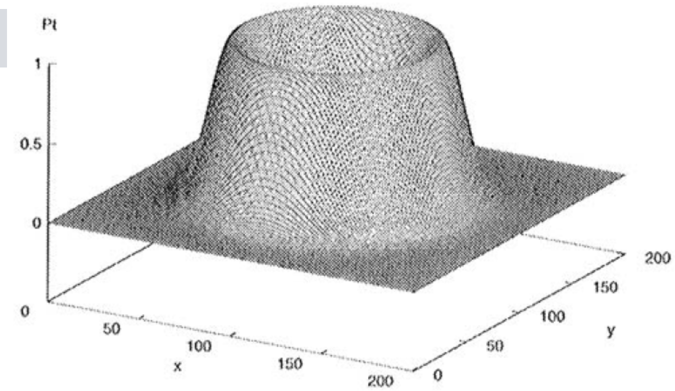
- The Leptothomx albipennis ants construct simple perimeter walls in a two-dimensional nest.
- The walls are constructed at a given distance from the tight cluster of ants and brood, which serves as a chemical or physical template.
- The template mechanism allows the size of the nest to be regulated as a function of colony size.
  - Each worker always has about 5 mm2 of floor area in the nest.



Important factors in wall building

- Deposition behavior is influenced by two factors:
  - the local density of grains
  - the distance from the cluster of ants and brood.
- The probability of depositing a brick is:
  - highest when both the distance from the cluster is appropriate and the local density of bricks is large;
  - lowest when the cluster is either too close or too far and when the local density of bricks is small.
- When the distance from the cluster does not lie within the appropriate range, deposition can nevertheless be observed if bricks are present;
- Conversely, if the distance from the cluster is appropriate, deposition can take place even if the number of bricks is small.

Wall building model



- Probability of depositing a grain of sand:

$$p_d \, p_t$$

$$p_d = [f/(k_2+f)]^2$$

  - p_d depends only on f the perceived fraction of grains in the agent's neighborhood
  - p_t is the template effect; exhibits a maximum at some distance from the center of the cluster

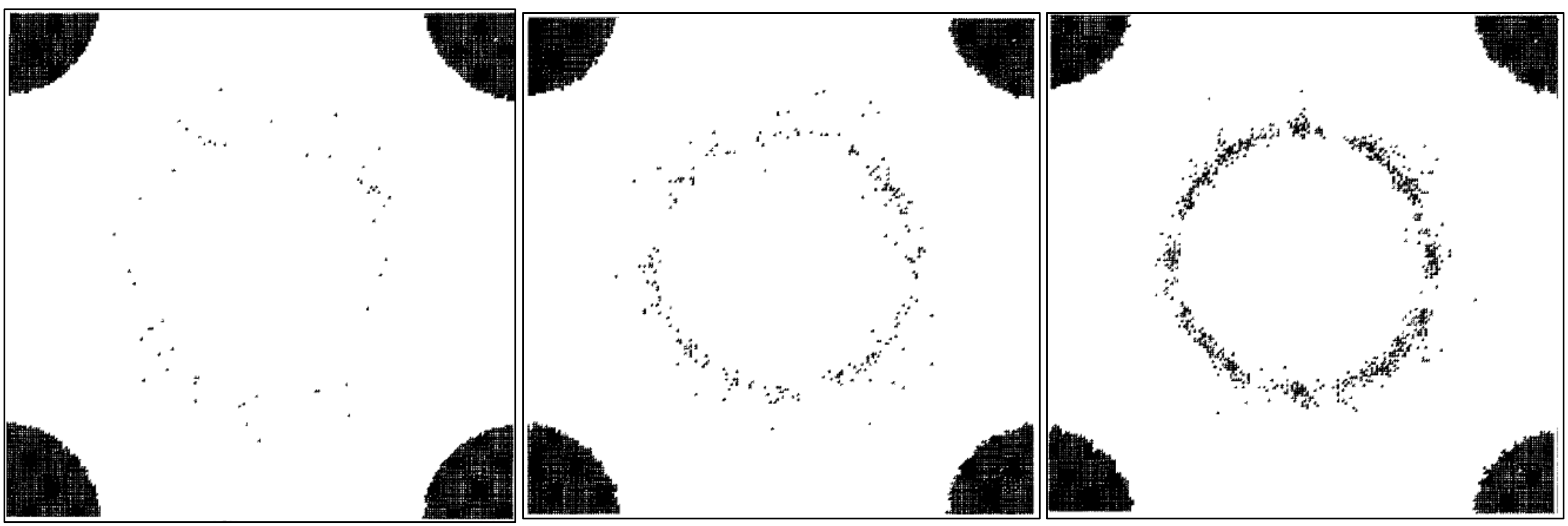
- Probability of picking up a grain of sand:

$$p_p \, (1-p_t)$$

$$p_p = [k_1/(k_1+f)]^2$$

Simulation of wall building

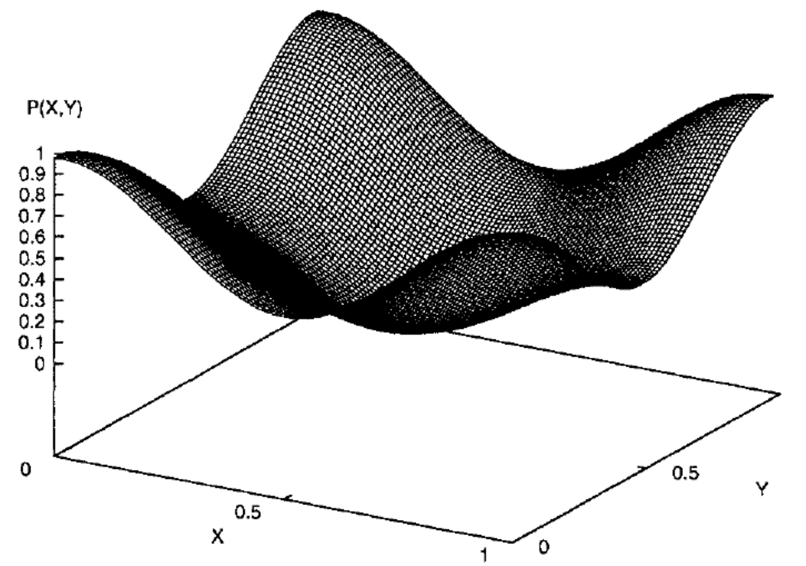
- 10 agents , k1=0.1, k2=0.3



T=50 T=1,000 T=10,000

Graph partitioning and Templates

- A template probability should be added to the probability of picking up and dropping
- E.g. forcing the clusters to be defined on [0,0] [0,1] [1,0] [1,1] :



$$P_t(x,y) = a\left[e^{-\frac{x^2+y^2}{\sigma^2}} + e^{-\frac{(x-1)^2+y^2}{\sigma^2}} + e^{-\frac{(x-1)^2+(y-1)^2}{\sigma^2}} + e^{-\frac{x^2+(y-1)^2}{\sigma^2}} - b\right]$$

Self Assembly

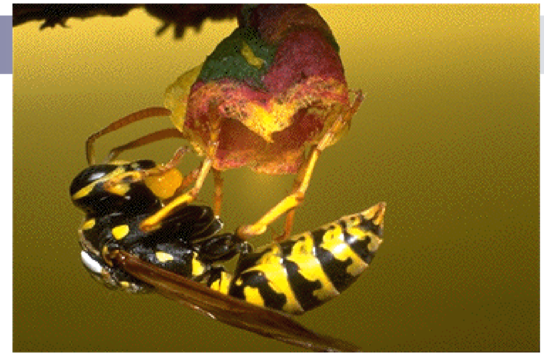
Wasp Nest

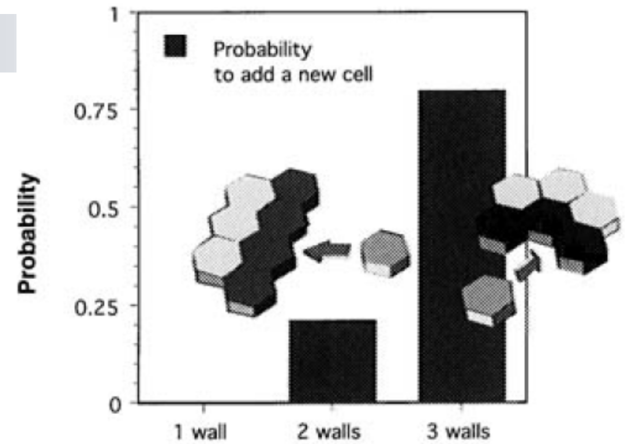
- Tropical wasps build complex nests, comprised of a series of horizontal combs protected by an external envelope and connected to each other by a peripheral or central entrance hole



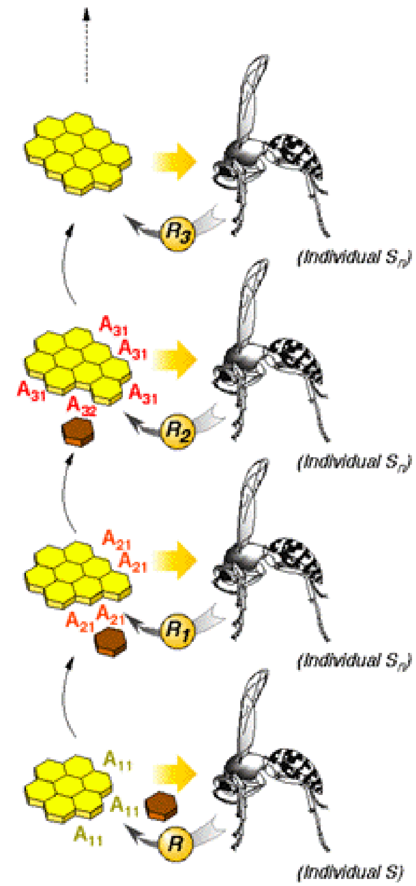
http://www.javatroll.com/Ants/realNest.html

Nest building in Wasps





- Cells are not added randomly to the existing structure
- wasps have a greater probability to add new cells to a corner area where three adjacent walls are present, than to initiate a new row by adding a cell on the side of an existing row.
- Therefore, wasps are influenced by previous construction, and building decisions seem to be made locally on the basis of perceived configurations in a way that possibly constrains the building dynamics.



http://www.javatroll.com/Ants/

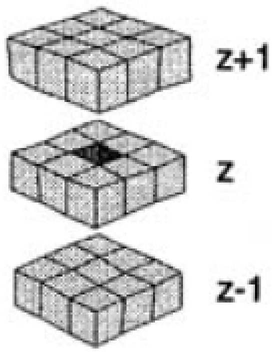
Model of nest building in wasps

- The deposit of an elementary building block (a brick) by an agent depends solely on the local configuration of bricks in the cells surrounding the cell occupied by the agent.
- When a stimulating configuration is encountered, the agent deposits a brick with probability one (brick deposits are deterministic). No brick can be removed once it has been deposited.

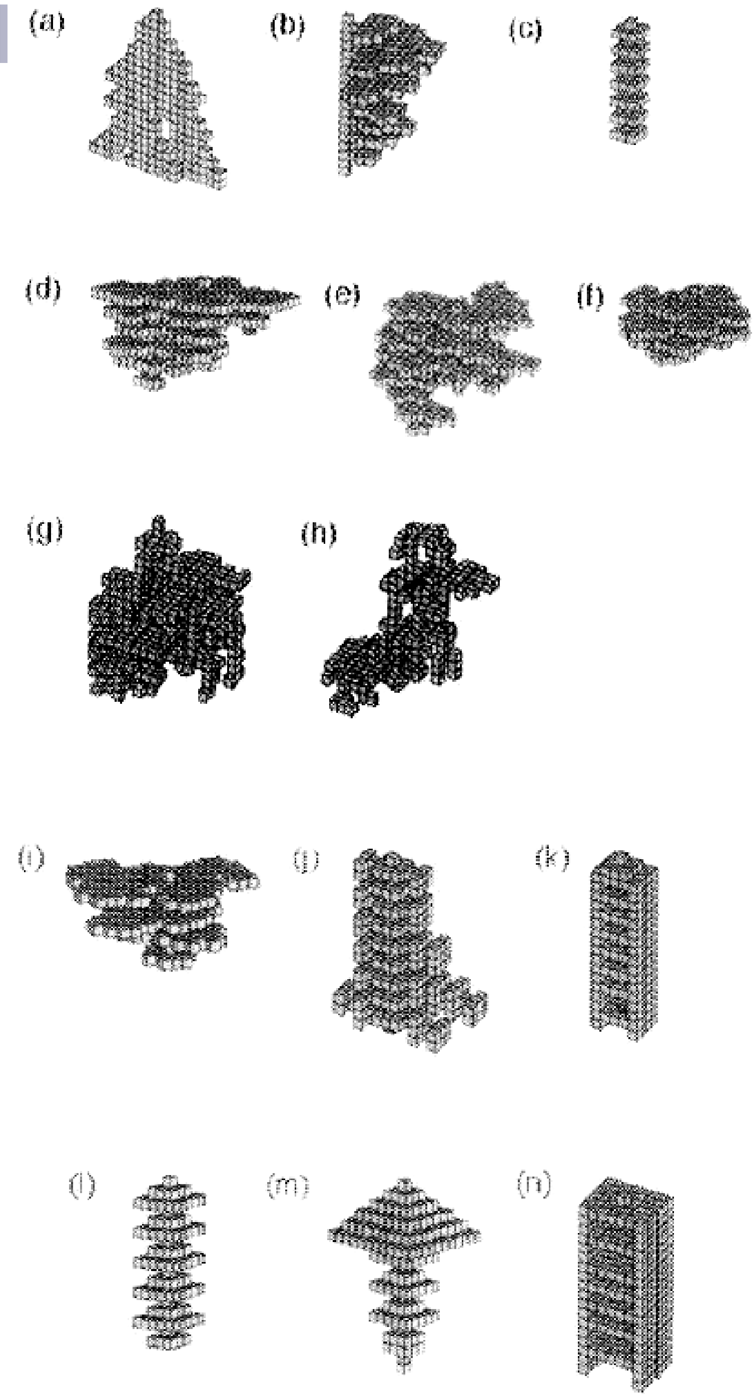
- Microrule: the association of a stimulating configuration with a brick to be deposited
- Algorithm: any collection of compatible microrules.
  - Two microrules are not compatible if they correspond to the same stimulating configuration but result in the deposition of different bricks.
  - An algorithm is characterized by its microrule table, a lookup table comprising all its microrules, that is, all stimulating configurations and associated actions.

Construction Algorithm

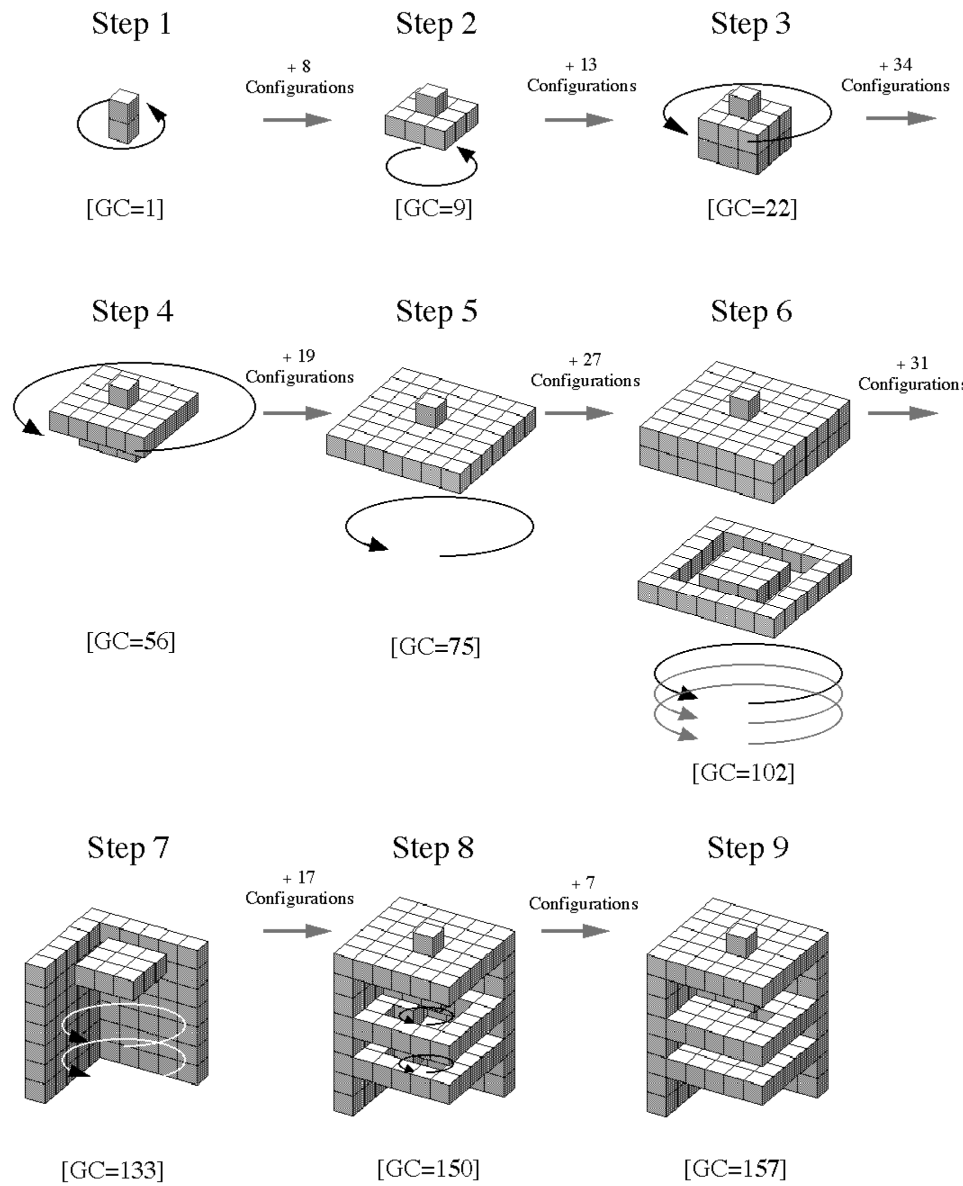
```
/* Initialization */
Construct lookup table /* identical for all agents */
Put one initial brick at predefined site /* top of grid */
For k = 1 to m do
    assign agent k a random unoccupied site /* distribute the m agents */
End For

/* Main loop */
For t = 1 to tmax do
    For k = 1 to m do
        Sense local configuration
        If (local configuration is in lookup table) then
            Deposit brick specified by lookup table
            Draw new brick
        Else
            Do not deposit brick
        End If
        Move to randomly selected, unoccupied, neighboring site
    End For
End For
```



Some simulation results



Coordinated microrules



http://www.javatroll.com/Ants/

Cooperative Transport

Cooperative Transportation

Cooperative vs. solitary transport

- In Pheidologeton diversus, single worker ants usually carry burdens (grasping them between their mandibles, lifting them from the ground and holding them ahead as they walk forward) rather than drag them.
- By contrast, in cooperative transport, one or both forelegs are placed on the burden to aid in lifting it, mandibles are open and usually lay against the burden without grasping it.

Movement patterns of group - transporting ants

- Corresponds to their positions around the perimeter of a burden with reference to the direction of transport :
  - workers at the forward margin walk backward, pulling the burden,
  - while those along the trailing margin walk forward, apparently pushing the burden;
  - ants along the sides of the burden shuffle their legs sideways and slant their bodies in the direction of transport

From solitary to group transport

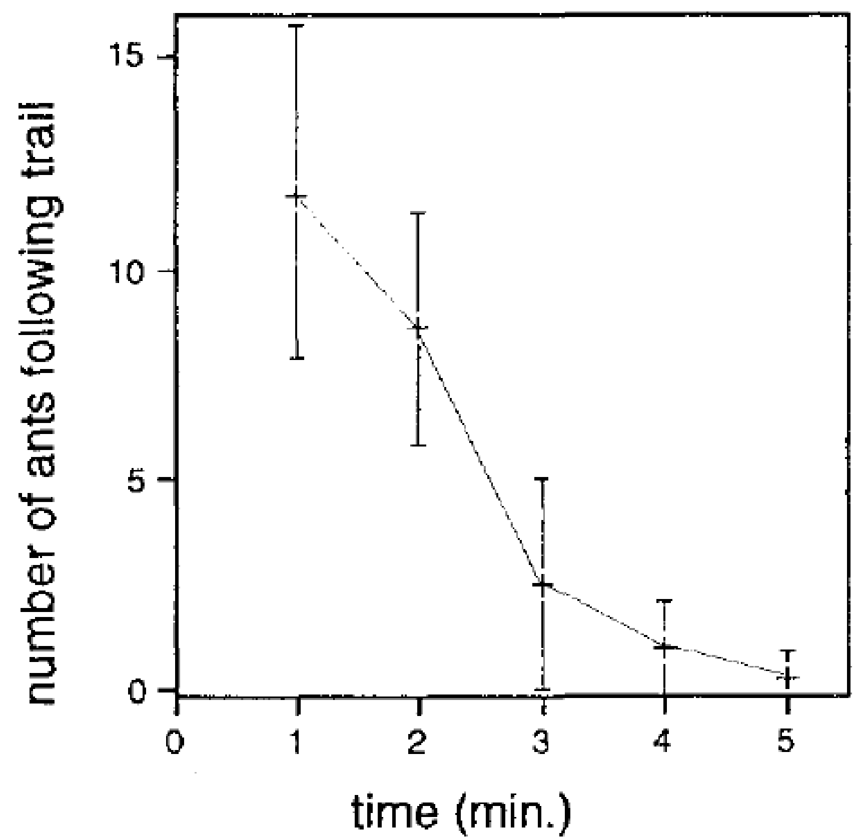
- Carry: A single ant first tries to carry the item.
- Drag: If the item resists motion, drags it.
- Realign: The ant spends a few seconds testing the resistance of the item to dragging before realigning the orientation of its body without releasing the item; modifying the direction of the applied force may be sufficient to actually move the item.
- Reposition: In case realignment is not sufficient, the ant releases the item and finds another position to grasp the item.
- Recruitment: If several repositioning attempts are unsuccessful, the ant eventually recruits nestmates.

Recruitment of Nestmates

- Recruitment for collective transport falls within two categories:
  - short-range recruitment (SRR)
  - long-range recruitment (LRR)
- SRR: In SRR, a scout releases a poison gland secretion in the air immediately after discovering a large prey item; nestmates already in the vicinity are attracted from up to 2 m.
- LRR: If SRR does not attract enough nestmates, a scout lays a chemical trail with a poison gland secretion from the prey to the nest. Nestmates are stimulated by the pheromone alone (no direct stimulation necessary) to leave the nest and follow the trail toward the prey.

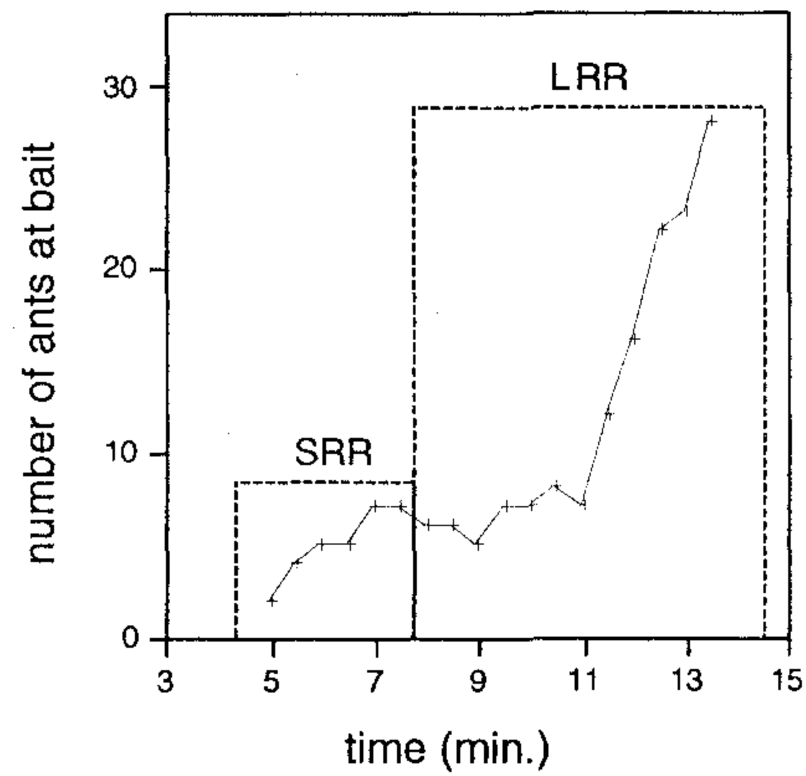
Short Range Recruitment

- Number of ants (Novomessor albisetosus) following an "artificial" poison gland pheromone trail as a function of time.
- The number of ants following the trail was counted during the minute after introduction.



Long Range Recruitment

- A freshly killed grasshopper was pinned to the ground 6m from the nest of a Novomessor cockerelli colony.
- Soon after the first worker discovered the prey, other workers were attracted (SRR).
- When the first scouts returned to the nest laying a trail, the number of nestmates at the site increased significantly (LRR).



Number of ants

- Experiments show that the ants do not estimate the size or weight of the prey but rather adapt their group sizes to the difficulty encountered in first moving the prey.
- Decisions rely on how difficult it is to carry the prey, and not simply on weight.
  - A prey item that resists (either actively or passively) stimulates the ant(s) to recruit other ants
  - Recruitment ceases as soon as a group of ants can carry the prey in a well-defined direction

Coordination

- Coordination in collective transport seems to occur through the item being transported.
- A movement of one ant engaged in group transport is likely to modify the stimuli perceived by the other group members, possibly producing, in turn, orientational or positional changes in these ants.
- The coordination mechanism used by ants in cooperative transport is not well understood, and has never really been modeled.

Deadlock Recovery

- Deadlock situations:
  - Forces are applied by ants in opposite directions and cancel one another
  - The group has encountered an obstacle or any significant heterogeneity on the substrate
- Solution: like a single ant
  - Realigning (more) and Repositioning (less)
  - Recruitment of special forces: If a group of ants is still unable to move the prey item for a certain time, specialized workers with large mandibles may be recruited in some species to cut the prey into smaller pieces

Particle Swarm Optimization

Idea

- Social influence and social learning enable a person to maintain cognitive consistency.
- People solve problems by talking with other people about them.
- As they interact their beliefs, attitudes, and behaviors change.
- The changes could typically be depicted as the individuals moving toward one another in a sociocognitive space.
- The particle swarm simulates this kind of social optimization

Overview

- A problem is given, and some way to evaluate a proposed solution to it exists in the form of a fitness function.
- A communication structure or social network is also defined, assigning neighbors for each individual to interact with.
- Then a population of individuals defined as random guesses at the problem solutions is initialized. These individuals are candidate solutions. They are also known as the particles, hence the name particle swarm.
- An iterative process to improve these candidate solutions is set in motion.

Overview (ctd)

- The particles iteratively evaluate the fitness of the candidate solutions and remember the location where they had their best success.
- The individual's best solution is called the particle best or the local best.
- Each particle makes this information available to their neighbors. They are also able to see where their neighbors have had success.
- Movements through the search space are guided by these successes.

Particles

- The swarm is typically modeled by particles in multidimensional space (R^m).
- Particles have a position and a velocity.
- The particles fly through hyperspace and remember the following information:
  - A global best that is known to all and immediately updated when a new best position is found by any particle in the swarm
  - Neighborhood best that the particle obtains by communicating with a subset of the swarm.
  - The local best, which is the best solution that the particle has seen
- Members of a swarm communicate good positions to each other (to all particles or a subset of the swarm).
- They adjust their own position and velocity based on these good positions.

Update rule

- The particle position and velocity update equations in the simplest form that govern the PSO are given by:

$$x_{i,j} \leftarrow x_{i,j} + v_{i,j}$$

$$v_{i,j} \leftarrow c_0\, v_{i,j}$$
$$+\ c_1\, r_1\, (\text{global best}_j - x_{i,j})$$
$$+\ c_2\, r_2\, (\text{local best}_{i,j} - x_{i,j})$$
$$+\ c_3\, r_3\, (\text{neighborhood best}_j - x_{i,j})$$

Initial Swarm

- 20-40 particles (even 10 is sometimes enough)
- One common choice is to take for all i and j = 1, … , m
  - $x_{i,j} \in U[x_{jmin}, x_{jmax}]$
  - $v_i = 0$, or $v_{i,j} \in U[(x_{jmin}-x_{jmax})/2, (x_{jmax}-x_{jmin})/2]$

where x_{jmin} , x_{jmax} are the limits of the search domain in each dimension

U represents the Uniform distribution (continuous).

Coefficients: c_0

- Update rule:

$$x_{i,j} \leftarrow x_{i,j} + v_{i,j}$$

$$v_{i,j} \leftarrow c_0\, v_{i,j}$$
$$+ c_1\, r_1\, (\text{global best}_j - x_{i,j})$$
$$+ c_2\, r_2\, (\text{local best}_{i,j} - x_{i,j})$$
$$+ c_3\, r_3\, (\text{neighborhood best}_j - x_{i,j})$$

- c_0 is an inertial constant. Good values are usually slightly less than 1.
- Proposed value: 0.7-0.8

Confidence Coefficients: c_1, c_2, c_3

- Update rule:

$$x_{i,j} \leftarrow x_{i,j} + v_{i,j}$$

$$v_{i,j} \leftarrow c_0\, v_{i,j} + c_1 r_1 (\text{global best}_j - x_{i,j}) + c_2 r_2 (\text{local best}_{i,j} - x_{i,j}) + c_3 r_3 (\text{neighborhood best}_j - x_{i,j})$$

- c_1, c_2 and c_3 are constants that say how much the particle is directed towards good positions. They affect how much the particle's global best, personal best, and it's neighbors best influence its movement.
  - c_1 : Social component, confidence to society
  - c_2 : Cognitive component, self confidence
  - c_3 : Social component, confidence to neighbors in society
- In the canonical PSO: $c_3 = 0$; also c_1 and $c_2 \approx 2$
- In different formulations usually either $c_1 = 0$ or $c_3 = 0$
- Proposed values: 1.5-1.7

Common Error

- Update rule:

$$x_{i,j} \leftarrow x_{i,j} + v_{i,j}$$

$$\begin{aligned} v_{i,j} \leftarrow\ & c_0\, v_{i,j} \\ & + c_1\, r_1\, (\text{global best}_j - x_{i,j}) \\ & + c_2\, r_2\, (\text{local best}_{i,j} - x_{i,j}) \\ & + c_3\, r_3\, (\text{neighborhood best}_j - x_{i,j}) \end{aligned}$$

- What is wrong if we draw one random number e.g. for r_1 and multiply it to all components of the vector (Global Best – X_i) ?

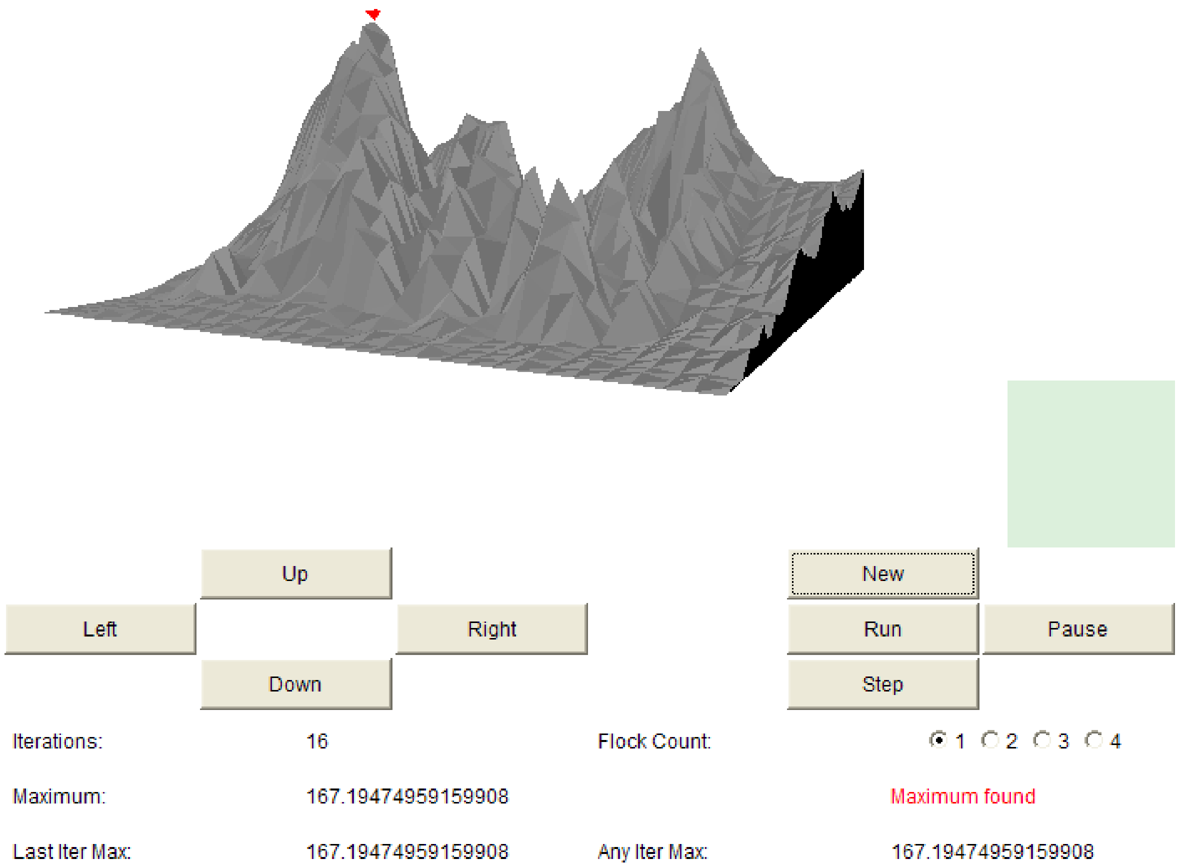
Interval Confinement

- If the particle's position goes beyond the borders of the search space:
  - Set it's position to the nearest value of the border point
  - Set it's velocity to 0
- What happens if only the first rule is applied?
- Other options?

Information Links

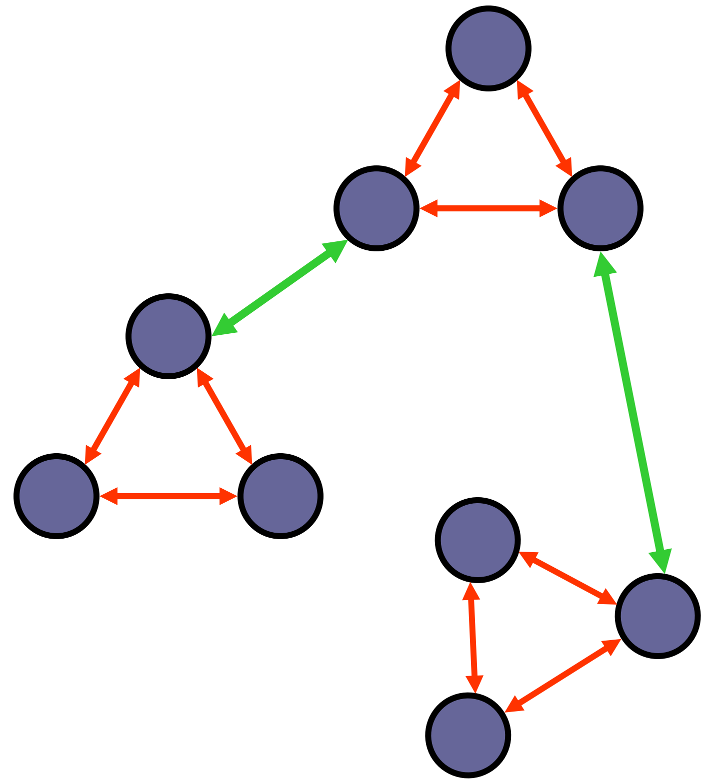
- Each particle informs K others
- The information links are
  - Fixed at the beginning or
  - Defined randomly with each iteration
- For m = 20 , K = 3 is enough

PSO Java Applet



http://www.projectcomputing.com/resources/psovis/index.html

Tribes



- A tribe consists of some particles which are fully connected by information links
- The inter-tribe information links are numerous
- While intra-tribe connections are few (but not zero)

Repulsive PSO

- Update rule:

$$x_{i,j} \leftarrow x_{i,j} + v_{i,j}$$

$$v_{i,j} \leftarrow c_0\, v_{i,j}$$
$$+ c_1\, r_1\, (\text{global best}_j - x_{i,j})$$
$$+ c_2\, r_2\, (\text{local best}_{i,j} - x_{i,j})$$
$$+ c_3\, r_3\, (\text{neighborhood best}_j - x_{i,j})$$
$$-\ c_4\, r_4\, (\text{local best of another particle}_j - x_{i,j})$$

- Another particle is randomly chosen
- The goal is to disperse the particles