COMP 4766/6912: Autonomous Robotics

Introduction to Swarm Robotics

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July 20, 2018

Outline

Initial Definitions

What is a swarm? What is swarm intelligence (SI)?

What is a Swarm?

A swarm is a group of mobile agents (e.g. animals or robots; real or virtual) which exhibit the following properties:

1. There is no centralized control or synchronization between agents
2. The agents sense and communicate locally

Lets take a look at some examples of swarms...

A swarm of honeybees looking for a new nest

Leafcutter ants retrieving building materials

Termite mounds taller than a Computer Scientist!

Chains of robots showing the path from point A to B

Spontaneous lane formation in human crowds

What is a Swarm? (Again)

A swarm is a group of mobile agents (e.g. animals or robots; real or virtual) which exhibit the following properties:

1. There is no centralized control or synchronization between agents
2. The agents sense and communicate locally

Property 1 implies that no one agent is in charge. Agents can have special roles and they can influence each other, but no agent can make decisions for the whole group.

Property 2 implies that no agent has a complete picture of the environment.

What is Swarm Intelligence?

Swarm intelligence (SI) refers to the ability of a swarm to solve a problem collectively.

- We assume that a single agent cannot solve this problem on its own (at least not very well)
- We won't get bogged down on what it means to be intelligent—if the swarm can be interpreted to be solving a collective problem, then that is sufficient

Advantages of SI over other problem-solving methods:

- Robustness to failure or malfunction of individual agents and external disturbances
- Flexibility to tackle many similar problems
- Scalability to tackle large and small problems

Examples

Are the following examples of swarms? Swarm intelligence?

Example	Swarm?	SI?
Ants foraging for food	Yes	Yes. Solving the problem of obtaining food for the whole group
Planes landing and taking off at an airport	No. Movements of planes controlled by tower	N/A
People moving without pattern through a crowded mall	Yes	No. Individuals are solving individual problems, not a collective problem
People forming into lanes as they travel through the mall	Yes	Yes. Individuals are solving their own problems but in a way that helps the whole group

Examples of SI in Biology

We will look at some initial examples of SI in biology. This will motivate our discussion on the principles of SI.

Example of SI in Biology: Ant "Cemetery" Construction

Workers ants carry dead ants out of the nest and place them in clusters that merge and grow larger over time.

Biologists believe that this behaviour is not centrally coordinated and that ants can only sense and communicate locally. Hence, the ant colony acts as a swarm. The collective problem being solved is cleaning, so this is an example of SI. (Deneubourg et al., 1990)

LEFT: Computational model, RIGHT: Real ant behaviour

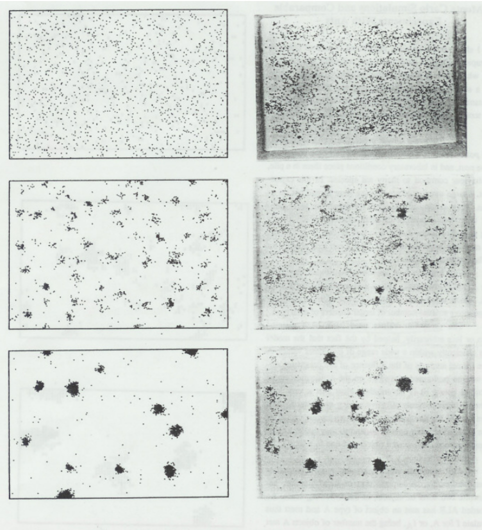


Fig. 1. Clustering after 1, 100000 and 2000000 steps. 100 ALRs, 1500 objects, $k^+=0.1$, $k^-=0.3$, m=50, e=0, space=290x200 points. Small evenly spaced clusters rapidly form, and later merge into fewer larger clusters.

Fig. 2. Clustering in a colony of *Pheidole pallidula*. 4000 corpses were placed on a 50x50cm arena, and photos taken at time 0, 20 and 68 hrs. Small evenly spaced clusters rapidly form, and later merge into fewer larger clusters.

(Deneubourg et al., 1990)

Deneubourg et al's Model

- Each agent applies a random walk and is able to measure the local density of objects
- If an isolated object is encountered, it has a good chance of picking it up:

$$p(\text{pick up}) = \left(\frac{k_1}{k_1 + density} \right)^2$$

- If the agent is carrying an object and encounters a dense collection of objects, it has a good chance of dropping it:

$$p(\text{drop}) = \left(\frac{density}{k_2 + density} \right)^2$$

- **NetLogo demo**

Example of SI in Biology: Honeybee Comb Structure

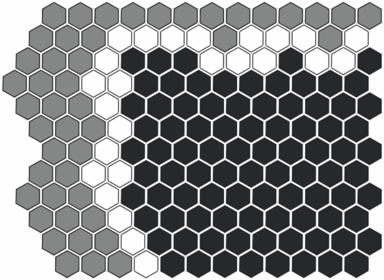


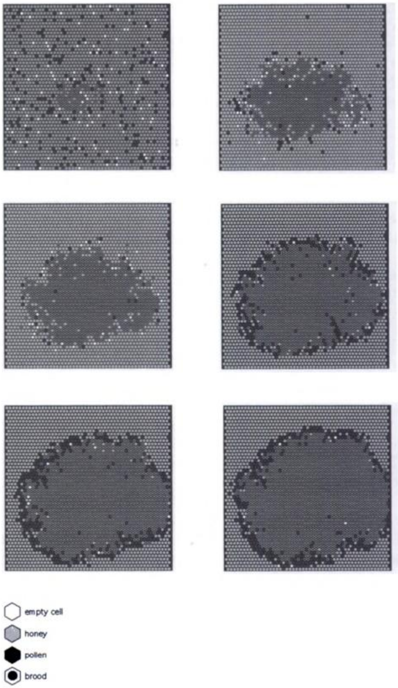
Fig. 2. The typical pattern of honey (grey cells), pollen (white cells), and brood (black cells) as seen on a honeybee's comb. Shown is the top-left corner of the comb

There is a characteristic pattern of concentric brood, pollen, and nectar cells.

The problem being solved is to distribute the brood, pollen, and nectar to allow ready access to needed materials.

- **Agents**: Queen, brood, workers.
- **Assumptions**:
  1. Queen lays eggs in a roughly random pattern in empty cells away near other brood cells
  2. Workers put pollen and nectar randomly in empty cells
  3. Workers obtain 4 times as much nectar as pollen
  4. Pollen consumed more quickly than nectar
  5. Pollen and nectar closest to brood cells consumed first

  A computer model built on these assumptions yields this result...



empty cell
honey
pollen
brood

Self-Organization (SO)

We will look next at self-organization (SO), a crucial property of SI systems.

Self-Organization (SO)

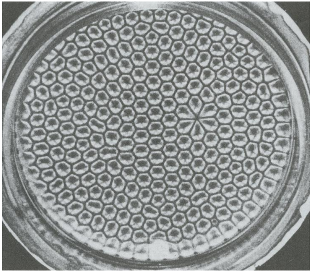
> *"Self-organization is a set of dynamical mechanisms whereby structures appear at the global level of a system from interactions among its lower-level components. The rules specifying the interactions among the system's constituent units are executed on the basis of purely local information, without reference to the global pattern..." (Bonabeau et al., 1999):*

We have seen 'structures' and 'global patterns' in both examples of SI shown so far.

This definition is reminiscent of our overall definition for SI. However, SO is perhaps a broader concept that doesn't specify anything about a problem being solved, merely that the local interactions among components creates some kind of global pattern.

SO in Non-Biological Systems

Self-Organization can be observed in non-biological systems, for example in the formation of Bérnard convection cells (left) or regularly space ridges in dunes (right).



The difference in biological systems is that the interacting components in biology are typically much more complex than in non-biological systems (oil molecules, sand grains). Also, physical laws are in effect for both, but biological systems also adhere to behaviours that are learned and/or genetically programmed.

Mechanisms for SO

SO is supported by the following mechanisms:

Positive feedback (amplification) Mechanisms that encourage certain quantities or patterns to grow. Recruitment of other members of the swarm to join in some activity is an example.

Negative feedback (inhibition) Mechanisms that encourage certain quantities or patterns to shrink. Negative feedback can be explicit such as when one agent causes another to inhibit their behaviour, or it can be an implicit result of resource limits.

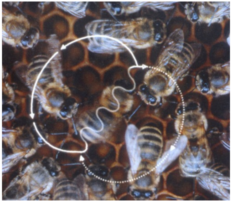
Multiple interactions The global structure or pattern arises over time through multiple interactions between components/agents.

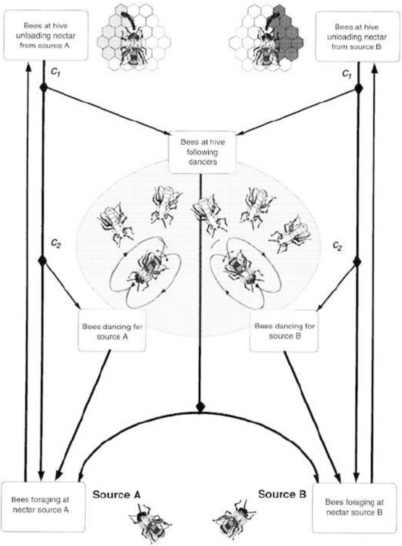
We will see instances of these mechanisms in the following examples...

Example: Honeybee Foraging

Honeybees gather nectar from flowers then return to the hive, give up the nectar to another bee. The bee will then do one of the following:

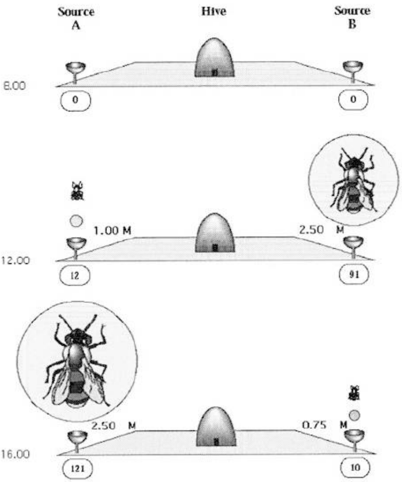
- Perform a 'waggle dance' (see right) indicating the direction and distance of the nectar source which tends to recruit other bees to that source.
- Continue to forage from her previous source without dancing.
- Abandon her previous source and follow another bee's waggle dance, leading her to that source.





This schematic illustrates the choices (c_1 and c_2) open to a bee returning to the hive from a food source.

These choices are influenced by the perceived quality of the two food sources. Bees returning from high-quality food sources have a higher probability of dancing to support that source.



Performing the waggle dance to lead other bees to the same food source is an example of positive feedback that amplifies the selection of a large food source over a small one.

In this experiment food source B is more plentiful in the morning (8:00-12:00) but food source A is more plentiful in the afternoon (12:00-16:00). Consequently, B attracts more bees in the morning and A attracts more in the afternoon.

Stigmergy

Stigmergy is indirect communication between agents that occurs through the environment.

Stigmergy

The term **stigmergy** was coined by biologist Pierre-Paul Grassé who was an expert on termites. Stigmergy is indirect communication between agents that takes place through modifying the environment and perceiving the modifications made by other agents. Importantly, it is not that messages are left from one agent to others, but that a change is made to the environment that affects the behaviour of other agents somehow (Bonabeau et al., 1999).

Grassé developed his theory of stigmergy to explain the collective construction of termite mounds, which are massive complex, and take generations of termites to construct. He pictured the process like this...

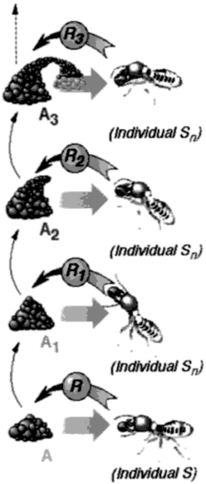


FIGURE 1.13 Assume that the architecture reaches state A, which triggers response R from worker S. A is modified by the action of S (for example, S may drop a soil pellet), and transformed into a new stimulating configuration A_1, that may in turn trigger a new response R_1 from S or any other worker S_n and so forth. The successive responses R_1, R_2, R_n 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. Such a process, where the only relevant interactions taking place among the agents are indirect, through the environment which is modified by the other agents, is also called *sematectonic* communication [329]. After Grassé [158]. Reprinted by permission © *Masson*.

An example of stigmergy that we have already seen is in the construction of cemetary clusters in ants. In Deneubourg et al.'s model for this behaviour, the ants react only to the local density of objects (i.e. dead ants), picking up isolated objects with high probability and depositing them with high probability when the density is high (in or near a cluster).

Question

STIGMERGY:

Which of the following are examples of stigmergy (select all that apply)?

a	Leaving a mess in your apartment with the expectation that your roommate will notice it and clean it up.
b	Leaving a mess in your apartment and a message to your roomate that he should clean it up.
c	A bricklayer continuing an incomplete wall started by another worker.
d	A foreman giving verbal instructions to a roofer as to where the next shingle should be placed.

Select all of the above that apply

Answer

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Another Question!

HONEYBEE FORAGING:

Honeybees forage and return to the hive to perform or follow waggle dances. Is this an example of stigmergy?

a	Yes. The bees are communicating by modifying part of the environment.
b	No, because the bees are communicating directly.
c	No, because the waggle dance is not communication.
d	Yes. This is stigmergy because the only way insects communicate is through stigmergy.

Answer

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Pheremones

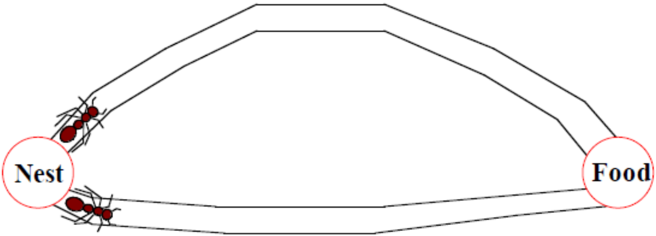
In many cases, insects deposit chemical signals called **pheremones** which can indicate something about a certain place or thing. The classic example of pheremone use is in ant foraging.

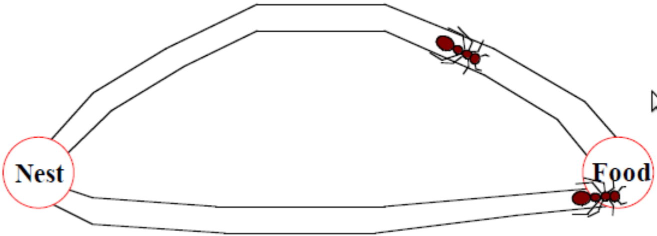
PLAY NOVA VIDEO

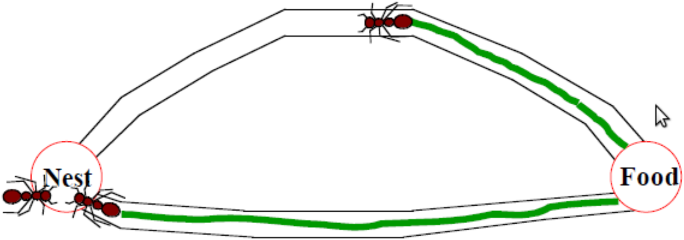
Depositing pheromones in the environment is a classic example of stigmergy. The pheromones are not directed messages from one ant to another, but a modification of the environment that influences the behaviour of other ants. Lets look at ant foraging in a little more detail to understand this.

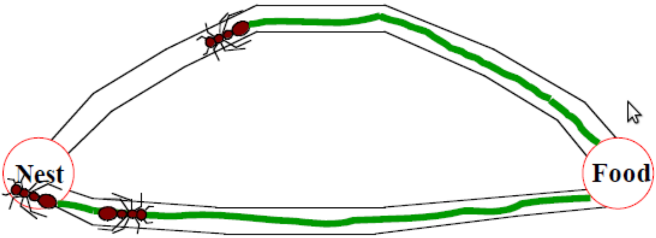
Example: Ant Foraging

- When foraging for food, some ants leave behind pheromone trails on the ground:
  - The pheromone is deposited by ants on their way back to the nest
  - After the food source is exhausted the pheromone trail will dissipate
  - Generally ants find the shortest path between food sources and the nest

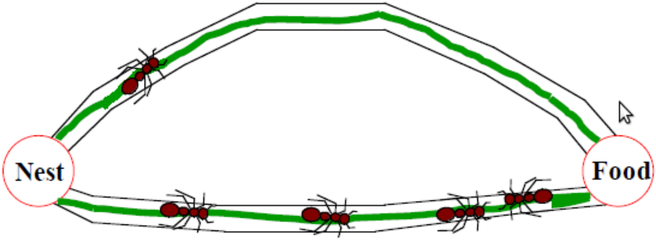

Nest
Food

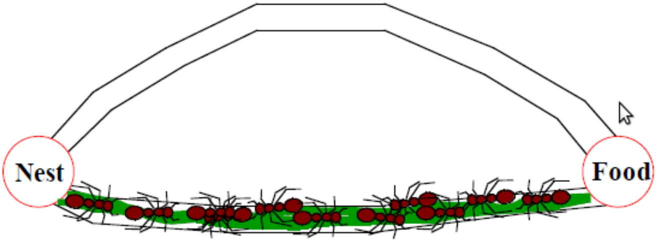

Nest
Food


Nest
Food



This is an example of positive feedback! The shorter branch has more pheromone depositied and therefore attracts the new ant. The new ant will also deposit more pheromone, amplifying the shorter branch even more!


Nest
Food



The pheromone deposited on the longer branch evaporates—an example of implicit negative feedback. If the ants forcibly removed the pheromone from that branch then we would say the negative feedback was *explicit*.

NETLOGO DEMO

It is important to note that the ants will usually reach a state of consensus, with the majority adopting one of the two branches. This is true even if both branches are the same length.

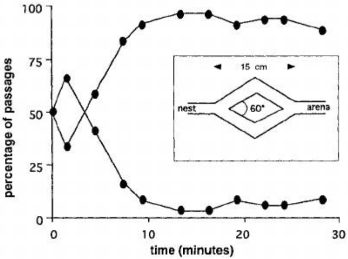
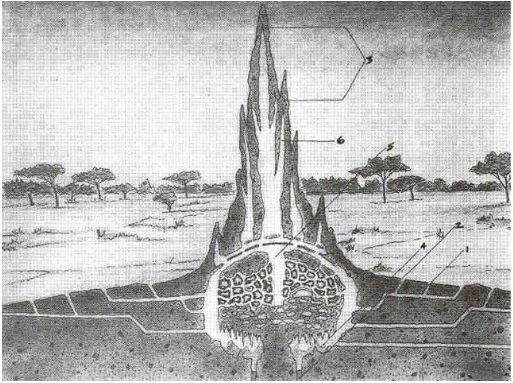


FIGURE 2.1 Percentage of all passages per unit time on each of the two branches as a function of time: one of the branches is eventually used most of the time. Note that the winning branch was not favored by the initial fluctuations, which indicates that these fluctuations were not strong enough to promote exploitation of the other branch. The inset is a schematic representaton of the experimental setup. After Deneubourg et al. [87]. Reprinted by permission © *Plenum Publishing*.

Example: Termite Nest Construction

As we saw in the very first lecture, some termite species build massive nests, which are intricately structured and detailed. It seems unlikely that any one ant can be directed the others and it is also difficult to understand how an individual termite's genetic blueprint can encode such complex structures.



1.night entrance and exit;
2.underground water supply for drinking and cooling nest;
3."lungs" that expel rising hot air;
4.Cool air eventually sinks back to the cellar;
5. Warm air rises via central air duct;
6. Interior oxygen diffuses through the chimneys.

In (Ladley and Bullock, 2005) some of the models proposed for termite mound construction are summarized. In their own model Ladley and Bullock focus on the following features of termite mounds:

- The "royal chamber", an open area surrounding the queen (an immobile termite, many times larger than any other termite)
- Tunnels that connect various chambers of the mound

Three different types of termite (a.k.a. castes) are involved: the queen, builders, trail-followers, and nursing termites. Except the queen, real termites can switch between these roles and others, but they are fixed in the model.

Ladley and Bullock proposed that three different kinds of pheremones are emitted:

- Queen pheremone emitted by the queen's body and detected by the builders and used to set the boundaries of the royal chamber
- Trail pheremone emitted by trail followers
- Cement pheremone emitted by newly placed pellets

The virtual termites in this model have the following behaviours:

Builders

Builders come into the world carrying a pellet of material, looking for a place to put it. Very similar to the cemetary cluster ants, they have a probability of depositing their pellet that is proportional to the amount of cement pheremone sensed. But they also sense queen/trail pheromone and will only place their pellet if the level of these other pheromones is in a certain range.

Once a builder places its pellet, it disappears and is replaced by a new builder. This models the notion of the builder now leaving the scene to obtain a new pellet of material.

Trail Followers

Trail followers represent termites that are engaged in non-building activities (e.g. foraging). They are attracted to trail pheromone and also lay new trail pheromone as they move. They move in a random but consistent direction across the world.

Nursing Termites

The nursing termites are very much like the trail followers except that they just move back and forth, away from the queen, then towards her. This models delivering food to the queen and taking her larvae.

In constructing the royal chamber, only builder ants are required.

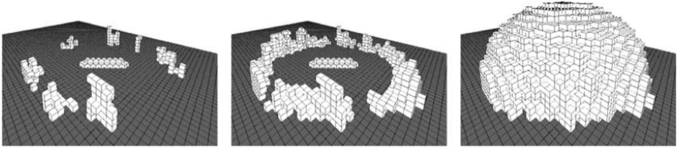


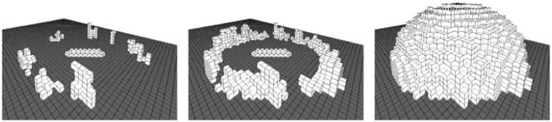
Fig. 3. A royal chamber being constructed. Parameters: $f = 400, r = 0.5, \alpha = \frac{1}{7}, v = 0.1, p = 0.1, n = 300, m = 5, s = 0.0$.

LEFT: The queen pheromone restricts placement only to a certain range of distances away from the queen (blob in centre). Initial random placements seed the formation of clusters.

CENTRE: The clusters join and grow vertically.

RIGHT: A roof is eventually formed.

Wind is modeled as a force that shifts the pheromone. The incorporation of wind simply elongages the structure.



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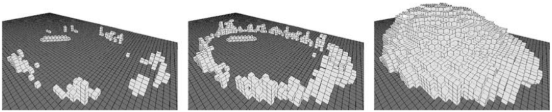

Fig. 4. A royal chamber being constructed under mildly windy conditions (wind emanates from the upper-left lattice edge). Parameters as Fig. 2, except: $s = 0.15$.

The swarm works well when there are many other agents acting on the environment, creating new oppourtunities for placement.

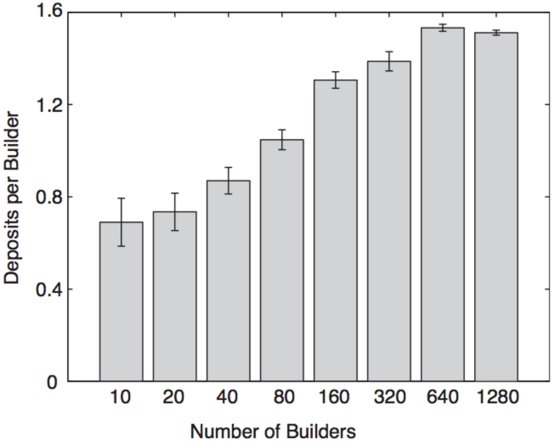

Fig. 5. A graph showing the amount of work done per termite versus the number of termites present in the simulation. Each error bar represents the standard error from the results of 10 replicates. Note the geometric scale on the abscissa. The sinusoidal shape is similar to that observed in real termites (Bruinsma, 1979).

The creation of tunnels is a combined (but uncoordinated) effort by the trail followers who establish the trail and the builders who surround it with material.

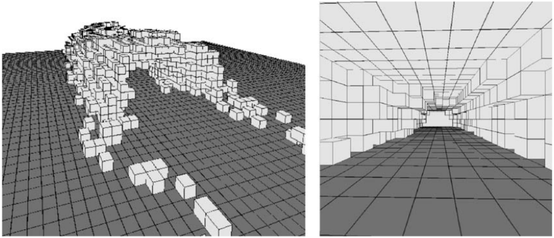

Fig. 6. A covered walkway is constructed. Parameters as Fig. 2, save that a flow of trail termites has been introduced: $t = 10, c = 0.5$. At each time step, between zero and 10 builder termites enter the lattice, with probability 0.5 per termite. The tunnel's interior is clear of obstructions, and the cross-section is quite regular.

Here is the result of combinging the queen, nursing termites, and builders. Multiple tunnels begin to radiate out from the royal chamber, but eventually the nursing termites converge to two tunnels and the others are closed in by the builders.

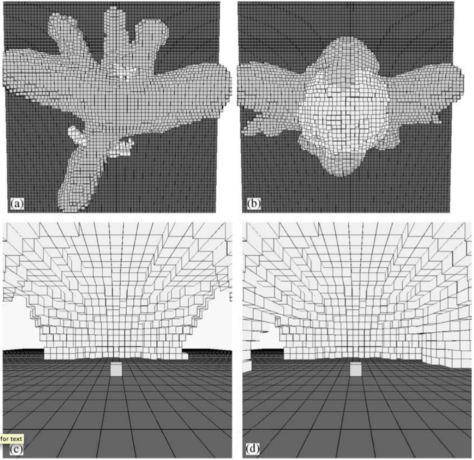

Fig. 10. An example of entrance formation. Parameters as Fig. 2, except $e = 300$ (300 nurse termites are added) (a) 50 time steps: several (medium tone) pheromone trails between a central queen and the lattice periphery have formed (shown from above). (b) 500 time steps: only two trails remain. (c) 500 time steps: A view from inside the dome. (d) 800 time steps: only one entrance remains.

Swarm Robotics

Swarm robotics (SR) is the application of the principles of swarm intelligence (SI) to robotics.

Swarm Robotics

Swarm robotics (SR) is the application of the principles of swarm intelligence (SI) to robotics. Those principles are as follows:

- Self-organization (mechanisms: postive and negative feedback, multiple interactions)
- Stigmergy

The main idea is to exploit self-organization to solve a problem. SR remains an active research area whose promise remains to be demonstrated in an industrial setting. Thus, the problems addressed are usually quite constrained.

In addition to the promise of solving practical problems, SR has been used to test and validate scientific theories about animal behaviour.

A robot swarm is composed of individual robots which can sense and communicate only locally. However, robot swarms can be configured in many different ways:

Simplicity The individual robots are often claimed to be simple, but simplicity is a relative term. Therefore, the individual robots used by researchers vary enormously in their sophistication.

Size How many robots does it take to make swarm. Some claim > 100 but most experiments consist of just a few robots.

Homogeneity The members of the swarm may all be of the same type (homogeneous) or many different types (heterogeneous).

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