The Whole is More than the Sum of its Parts

The title of my project is a fitting one line description of complex systems. After completion of this course, I must admit, I look at normal day to day phenomenon very differently. The things I never bothered giving a second look let alone second thought now interests me because of their complexity as a whole and simplicity of their component parts. I knew the world market, stock exchanges etc were complicated mechanisms but the fact that natural occurrences like the emergence of ant hills, combined work of “insignificant” ants, could be so intriguing were never apparent. Every time I used to see ant trains, more often than not I used to be amused with their “stupidity” as they would crash into each other, never actually looking at the bigger picture-the very elegant result of their simple actions, ant colonies.
On closer inspection and a bit of pondering it was obvious to me that ant colonies, are distributed systems that, in spite of the simplicity of their individuals, present a highly structured social organization. As a result of this organization, ant colonies can accomplish complex tasks that in some cases far exceed the individual capacities of a single ant. Derived from the observation of real ants, role played by stigmergy (a particular form of indirect communication used by social insects to coordinate their activities) as distributed communication paradigm is very prominent.
Introduction

Ant colonies have always fascinated human beings. Books on ants, ranging from pure literature to detailed scientific accounts of all the aspects of their life, have often met extraordinary public success. What particularly strikes the occasional observer as well as the scientist is the high degree of societal organization that these insects can achieve in spite of very limited individual capabilities. Ants appeared on the earth some 100 millions of years ago, and their current population is estimated to be around $10^{16}$ individuals. An approximate computation tells us that their total weight is the same order of magnitude as the total weight of human beings; like human beings, they can be found virtually everywhere on the earth. Ants are undoubtedly one of the most successful species on the earth today, and they have been so for the last 100 million years.
**NATURAL ANTS**

Individual ants are simple insects with limited memory and capable of performing simple actions. However, an ant colony expresses a complex collective behavior providing intelligent solutions to problems such as carrying large items, forming bridges and finding the shortest routes from the nest to a food source.

A single ant has no global knowledge about the task it is performing. The ant's actions are based on local decisions and are usually unpredictable. The intelligent behavior naturally emerges as a consequence of the self-organization and indirect communication between the ants. This is what is usually called *Emergent Behavior*.

The fascinating behavior of ants has been inspiring researches to create new approaches based on some of the abilities of the ants' colonies. Some of the existing applications include the Traveling Salesman Problem, graph coloring, logistics and a lot more.

**Foraging behavior of ants**

Ants can manage to find the shortest path between the nest and a food source using simple local decisions.

Ants use a signaling communication system based on the deposition of pheromone over the path it follows, marking a trail. Pheromone is a hormone produced by ants that establishes a sort of indirect communication among them. Basically, an isolated ant moves at random, but when it finds a pheromone trail there is a high probability that this ant will decide to follow the trail.

An ant foraging for food lay down pheromone over its route. When this ant finds a food source, it returns to the nest reinforcing its trail. Other ants in the proximities are attracted by this substance and have greater probability to start following this trail and thereby laying more pheromone on it. This process works as a positive feedback loop system because the higher the intensity of the pheromone over a trail, the higher the probability of an ant start traveling through it.
Suppose some ants were randomly searching for food when they found two different routes between the nest and the source. Since the route B is shorter, the ants on this path will complete the travel more times and thereby lay more pheromone over it.

As the process continues, the pheromone concentration on trail B will increase at a higher rate than on A. And soon, even those ants on the route A will choose to follow the trail B.

Since most ants are no longer traveling through route A and also due to the volatile characteristic of the pheromone, the trail A will start evaporating and soon just the shortest route will remain.
**Experiment**

An experiment was conducted with ants to investigate the behavior and how it can explain ants finding the shortest path between their nest and a food. The experimental setup is the following. A food source is connected to an ant nest by a bridge with two equally long branches.

*Experimental setup (insert) and percentage of ants that used lower and upper branches as a function of time.*

When the experiment starts the ants select randomly, with equal probability, one of the branches. Because of statistical fluctuations one of the two branches is chosen by a few more ants than the other and therefore is marked by a slightly higher amount of pheromone. The greater amount of pheromone on this branch stimulates more ants to choose it, and so on. This autocatalytic process leads very soon the ant colony to converge towards the use of only one of the two branches.
The experiment can also be run using a bridge with two branches of different length. In this case, the first ants coming back to the nest are those that took the shortest path twice (to go from the nest to the source and to return to the nest), so that more pheromone is present on the short branch than on the long branch immediately after these ants have returned, stimulating nest mates to choose the short branch.

(a) Experimental setup and drawings of the selection of the short branches by a colony of ants, 4 and 8 min after the bridge was placed.

(b) Distribution of the percentage of ants that selected the shorter branch over n experiments. The longer branch is r times longer than the short branch. The second graph (n = 18, r = 2)
corresponds to an experiment in which the short branch is presented to the colony 30 min after the long branch: the short branch is not selected, and the colony remains trapped on the long branch.

This has been called differential length effect and explains how ants in the long run end up choosing the shorter of the two paths without using any global knowledge about their environment. It is also interesting to note that in some ant species the amount of pheromone deposited is proportional to the quality of the food source found: paths that lead to better food sources receive a higher amount of pheromone.

**Division of labor in ant colonies**

Division of labor is an important and widespread feature of life in ant colonies. Social insects like ants are all characterized by one fundamental type of division of labor, reproductive division of labor. Beyond this primary form of division of labor between reproductive and worker castes, there most often exists a further division of labor among workers, who tend to perform specific tasks for some amount of time, rather than to be generalists who perform various tasks all the time. Workers are divided into age or morphological subcastes. Age subcastes correspond to individuals of the same age that tend to perform identical tasks: this phenomenon is called temporal polyethism. In some species, workers can have different morphologies: workers that belong to different morphological castes tend to perform different tasks. But even within an age or morphological caste, there may be differences among individuals in the frequency and sequence of task performance: one may therefore speak of behavioral castes, to describe groups of individuals that perform the same set of tasks in a given period. One of the most striking aspects of division of labor is plasticity, a property achieved through the workers’ behavioral flexibility: the ratios of workers performing the different tasks that maintain the colony’s viability and reproductive success can vary (i.e., workers switch tasks) in response to internal perturbations or external challenges.
Task allocation in ant colonies

Individual ants start to become engaged in task performance when the level of the task-associated stimuli, which plays the role of stigmergic variable, exceeds their threshold. Differences in response thresholds may either reflect actual differences in behavioral responses, or differences in the way task-related stimuli are perceived. When specialized ants performing a given task are withdrawn (they have low response thresholds with respect to stimuli related to this task), the associated task demand increases and so does the intensity of the stimulus, until it eventually reaches the higher characteristic response thresholds of the remaining individuals that are not initially specialized into that task; the increase of stimulus intensity beyond threshold has the effect of stimulating these individuals into performing the task.

Conclusions

In this paper I informally looked at some real ant colony behavior and the inherent stigmergic communication paradigm. Ant colonies exhibit a number of interesting properties like 1. flexibility- colonies responding to internal perturbations and external challenges), 2. robustness-tasks are completed even if some individuals fail, 3. decentralization-there exists no central control and 4. self-organization-solutions to problems faced by colonies are emergent rather than predefined. These make them almost essentially suited for the solution of problems that are distributed in nature, dynamically changing, and require built-in fault-tolerance.
**Stigmergy**
The term *stigmergy* was introduced by Grassé to describe a form of indirect communication mediated by modifications of the environment that he observed in two species of termites: *Bellicositermes Natalensis* and *Cubitermes*. Although Grassé first introduced the term stigmergy to explain the behavior of termite societies, the same term has later been used to indicate indirect communication mediated by modifications of the environment that can be observed also in other social insects.

Nest building in termites is the typical example of stigmergy, and is also the original example used by Grassé to introduce the concept. Termite workers use soil pellets, which they impregnate with pheromone (i.e., a diffusing chemical substance) to build pillars. Two successive phases take place during nest reconstruction. First, a non-coordinated phase occurs which is characterized by a random deposition of pellets. This phase lasts until one of the deposits reaches a critical size (Figure shown next page). Then, a coordination phase starts if the group of builders is sufficiently large and pillars emerge. The existence of an initial deposit of soil pellets stimulates workers to accumulate more material through a positive feedback mechanism, since the accumulation of material reinforces the attractivity of deposits through the diffusing pheromone emitted by the pellets. This autocatalytic snowball effect leads to the coordinated phase. If the density of builders is too small, the pheromone disappears between two successive passages by the workers, and the amplification mechanism cannot work, which leads to a non-coordinated behavior. The system undergoes a bifurcation at this critical density: no pillar emerges below it, but pillars can emerge above it. This example therefore illustrates positive feedback (the snowball effect), negative feedback (pheromone decay), the amplification of fluctuations (pillars could emerge anywhere), multiple interactions (through the environment), the emergence of structure (i.e., pillars) out of an initially homogenous medium (i.e., a random spatial distribution of soil pellets), multistability (again, pillars may emerge anywhere) and bifurcation which make up the signatures of self-organized phenomena.

*Assume that the architecture reaches state So, which triggers response Ro from worker I. So is modified by the action of I (e.g., I may drop a soil pellet), and transformed into a new stimulating configuration S1 that may in turn trigger a new response R1 from I or any other worker In 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 on any other worker in the colony.*
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