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Social insects and self-organization

An ant is quite a simple animal. Its behavioral repertory is limited to ten to forty elementary behaviors. Yet, anthills are very complex. One can find nursery, warehouses or kitchen gardens. Some individuals forage, others take care of the eggs, repair the nest or protect the anthill against miscellaneous threats. What is the secret? How can such mindless animals achieve such complex organization?
Division of labor could be the key. Ants are highly specialized, so specialized that some individuals have to be fed by others; they are unable to get food by themselves. In economics, division of labor leads to efficiency, but, to function properly, some sort of supervision is necessary. The different tasks have to be coordinated. Yet no such supervisors exist in anthills. No ants (and particularly not the queen) are able to manage this exploit. Nevertheless, the coordination necessarily exists; it results from some sort of self-organization process.
Let us examine foraging strategies in ants to illustrate this idea.
At the beginning, a number of ants are walking, more or less randomly, outside the nest. They are looking for food. All along their way, they deposit a light trail of pheromones. When an ant finds some food, it returns home, depositing a stronger trail (the intensity of the trail possibly depends on the richness of the discovered resource). Since ants have trail-following behavior, a growing number of individuals will tend to follow it and to reach the food. When they return, they reinforce the trail. Positive feedback (self-amplification) therefore occurs. More individuals reinforce the trail, attracting new individuals, who in their turn reinforce the trail...
In this example, the ants don't communicate directly. Information is exchanged through modifications of the environment (here local gradients of pheromones). This type of communication is known as stigmergy. This concept was proposed by P.P. Grassé in 1959. Studying nest reconstruction in termites, Grassé showed that it doesn't rely on direct communication between individuals. The nest structure itself coordinates the workers' tasks, essentially through local pheromone concentrations. The state of the nest structure triggers some behaviors, which then modify the nest structure and trigger new behaviors until the construction is over. The process is similar in ant foraging.
The ants tend to follow pheromone trails, but it is only a tendency. There is at any time a positive probability that an ant will abandon the trail and move more or less randomly. It is then possible that the "lost" ant could find a new resource, perhaps far richer than the one that was previously exploited. By constructing a new trail, this ant will attract new individuals and a new positive feedback loop will be set up.
Finally, when satiety occurs, or when the resource is used up, a negative feedback loop occurs. For example, if pheromone decay is quick enough, when the resource is exhausted fewer and fewer ants will tend to follow the trail and it will progressively disappear.

Self-organization in social insects is interpreted through four main mechanisms[1]:

1. The existence of multiple interactions.

[1] Bonabeau E., Dorigo M., Théraulaz G.,Swarm Intelligence. From Natural to Artificial Systems, Oxford University Press, 1999, p. 8-14.

2. Amplification through positive feedback.
3. Negative feedback.
4. Amplification of fluctuations. In the previous example, the fluctuation is when an ant abandons the pheromone trail; it is amplified by the positive feedback loop which then occurs.

Ants foraging process in some species have been analyzed by J.-L. Deneubourg[2] (Université Libre de Bruxelles). He notably showed how ants can find the best (shortest) way to reach a resource. In a nutshell, the accumulation of pheromones is faster on the shortest route, so positive feedback therefore gives it priority.
On this basis, F. Moyson and B. Manderick[3], followed by M. Dorigo[4] proposed the concept of "Ant Colony Optimization" (ACO). Dorigo applied this process to the travelling salesman problem and then extended it to a whole class of optimization problems. Such algorithms can now be found in telecommunications routing, the design of electronic circuits or -- for example -- the organization of industrial processes.

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[2] See for example : Deneubourg J.-L. et al., « Plan d'organisation et population dans les sociétés d'insectes », p. 141-155, dans Prigogine I. (dir.), L'homme devant l'incertain, Paris, Odile Jacob, 2001.
[3] Moyson F. et Manderick B., 1988. « The Collective Behaviour of Ants: an Example of Self-Organisation in Massive Parallelism », Proceedings of the AAAI Spring Symposium on Parallel Models of Intelligence. Stanford, California.
[4] Dorigo M., Gambardella L.M., Ant Colonies for the Traveling Salesman problem, BioSystems, 43, 1997.