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A Simulation of the Construction Process of a Termite Nest

P.-J. COURTOIS† AND F. HEYMANS

Philips Research Laboratory Av. A. Einstein, 4, Louvain-la-Neuve, Belgium

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The paper describes the essential characteristics and the results of a computer simulation program which models the early steps of the construction process of a termite nest. The model is highly parametrized. One shows how small differences in the definition of the interactions programmed in a simulation can induce important changes in the nest structures which are obtained.

1. Introduction

One can find in Nature complex processes which span several scales of length or time, and whose macroscopic behavior emerges from the individual disorderly behaviors of a multitude of microscopic entities. As computer scientists, we have become interested in understanding the basic mechanisms of this sort of processes, in the hope that they will reveal ways of exploiting the massive parallelism of modern and future super-computing machines.

The name "self-organized structure" (Prigogine & Stengers, 1983), has been chosen to coin these processes. Their macroscopic stable behavior results from the amplification and cumulative effect of fluctuations which initially belong to the microscopic level. These structures have certain similarities to dissipative structures for which, dissipation of energy, normally associated with disorder (increase of entropy) can be, when the system is far from equilibrium states, a source of order.

A vivid example is given by the construction of a termite nest. Grassé's first observations (Grassé, 1959) and the models studied in (Deneubourg, 1977) and (Bruinsma & Lenthold, 1977) show that the initial steps consist in the construction of pillars or walls which emerge from a multitude of disorderly movements of termites which transport and drop at random small quantities of earth, mixed with pheromone. Termites are known to be attracted by pheromone. The initial, and critical, fluctuation in this case is simply a small but sufficient accumulation of earth at one point. The amplification of this random event is then caused by the higher density of termites attracted by the stronger concentration of pheromone at that point; the probability of earth being dropped in that region is thus increased. The model predicts the forming of pillars or walls separated by a distance related to the range of attraction of the pheromone. A similar constructive behavior has been described and studied for the construction of combs in beehives (Skarka *et al.*, 1990).

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† Present address: Unité D'Informatique, Université Catholique de Louvain, Place Sainte-Barbe, 2, B-1348 Louvain-la-Neuve, Belgique.

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We have programmed on a computer workstation a cellular automaton which simulates the behavior of termites in a two-dimensional plane. Some details on the implementation of this computer simulation program are given in the Appendix.

The structures of termite nests can be quite diversified in size and in shapes (cf. Hansell, 1984; Grassé, 1982). The purpose of our simulation is not to reproduce the design of a nest in its full detail and reality. Our aim was to reproduce only those early steps of the construction of the pillars and of the chambers that we have just discussed.

2. The Model

The model consists of a square grid [see Fig. 1(a)] of 64×64 cells. Each cell initially contains a certain number (the parameter *pop*) of termites and a certain amount of earth (the parameter *earth*). The initial concentration of pheromone in each cell is taken equal to zero.

Each termite is modeled as an automaton the movement of which in the plane is the resultant of a random component and of the gradient of pheromone concentration in its immediate neighborhood.

At each clock tick, the following operations take place in the order of the sequence below:

For each cell and for each termite:

- —Termites not carrying earth pick up one unit of earth with a certain probability provided that there is earth left in the cell; this probability of picking is proportional to the ratio of mean pheromone concentration across the grid to the pheromone concentration in the cell. No earth is picked up otherwise.
- —Termites carrying earth drop it with a certain probability and raise the pheromone concentration in the cell by *one unit*, provided that earth already in the cell does not exceed a maximum height (*maxearth*); this probability of dropping is proportional to the ratio of pheromone concentration in the cell to the mean concentration across the grid. No earth is dropped if the maximum height has been reached.

For each cell:

- —The x- and the y-components of the vector defining the direction of attraction resulting from the pheromone concentration in each of the eight surrounding cells is determined. For this calculation the x- and the y-components are limited to a maximum specified by the value of the parameter *threshold*.

For each termite in each cell:

- —A random perturbation, i.e. a random value between $(-R)$ and $(+R)$, is added to the x- and y-components of the direction of attraction obtained by the above calculation. The resulting direction (N, NE, E, SE, S, SW, W, NW) of the direction of attraction is then determined. Termites carrying earth move one cell into that direction; termites not carrying earth move *one cell* into the opposite direction, in both cases provided that the termite population in the cell of destination does not exceed a maximum determined by the value of the parameter (*maxpop*); otherwise they do not move.

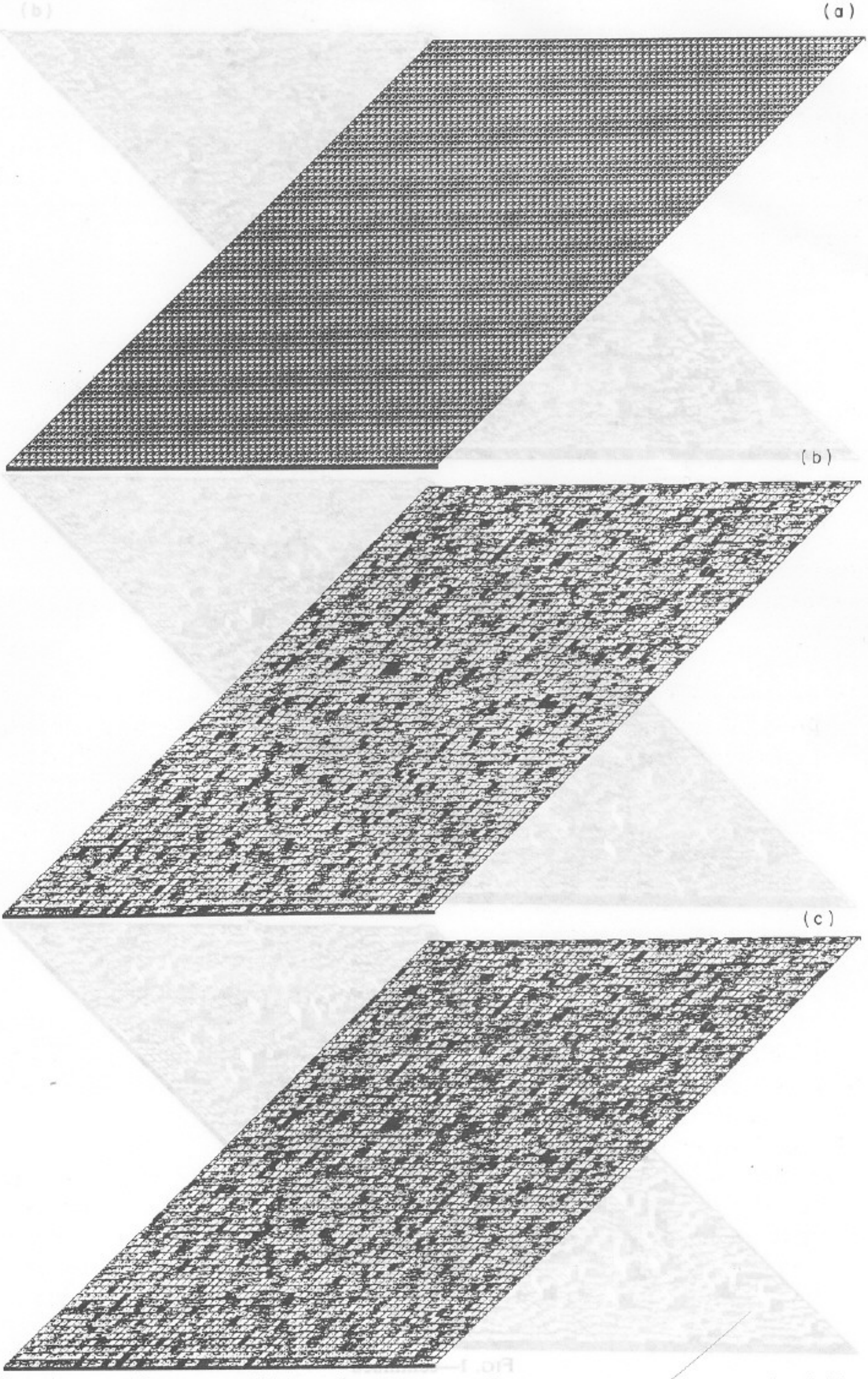

FIG. 1. *pop* = 16, *maxpop* = 4096, *earth* = 256, *maxearth* = 819, *evaporationrate* = 0·5, *threshold* = 10. (a) Time = 0; (b), time = 100; (c) time = 500; (d) time = 1000; (e), time = 2000; (f), time = 10 000.

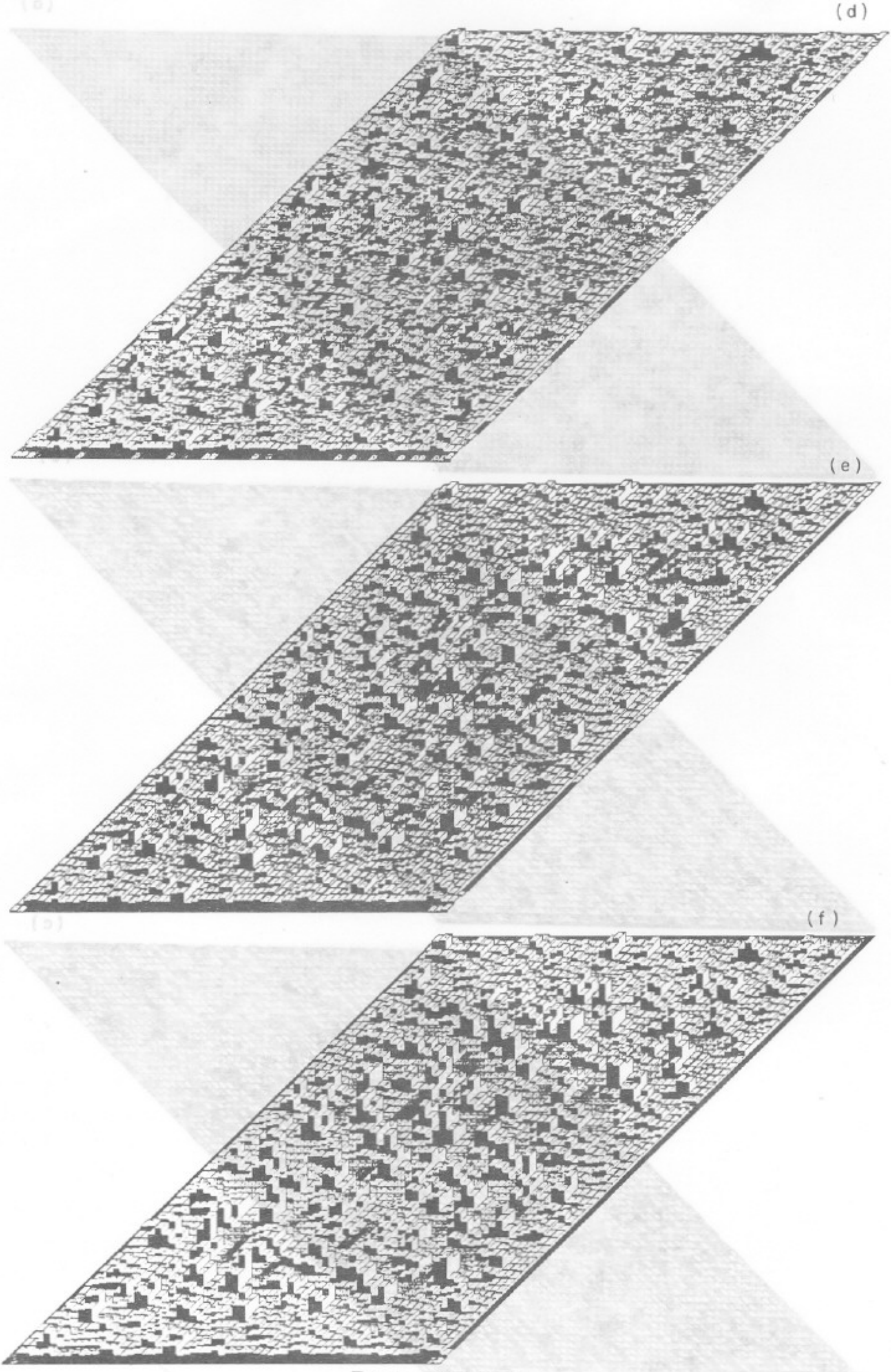

FIG. 1—continued

Finally, for each cell:

- The pheromone concentration is decreased by a constant factor equal to the evaporation rate; i.e. the concentration is multiplied at each clock tick by $(1 - \textit{evaporation rate})$.

Note that the probability of picking is defined as the inverse of the probability of dropping. As explained above, both probabilities are defined in terms of *relative* values of pheromone concentrations, and not of absolute values. Our model therefore assumes that the termite behavior remains independent of these absolute values. We do not claim that this assumption holds in reality; our simple aim is to study the constructive process which can be derived from it. Note also that the inverse proportionality of the picking probability to the pheromone concentration acts as a reinforcement factor in the construction process.

3. Results

Figure 1(b)–(f) gives six snapshots of the termitary construction at different time instants when each termite has iterated 100, 500, 1000, 2000, and 10 000 elementary moves. The height of the shaded block structures in each pixel is proportional to the concentration of earth already dropped at the corresponding point. Dots in each cell correspond to termites present in that cell.

For this simulation run, the following values of the parameters have been somewhat arbitrarily chosen:

$$pop = 16, \; maxpop = 4096,$$

$$earth = 256, \; maxearth = 8192,$$

$$evaporationrate = 0{\cdot}5, \; threshold = 10.$$

The simulation run was not prolonged beyond 10^4 clock ticks as this had already required a substantial amount of computing time (see the Appendix). But the three last snapshots already show that structures, once they have reached some height, do not disappear. Thus, little change can be expected from a longer run.

This model reproduces with some success the early steps of the construction. It should be of some help in the determination of the conditions which should prevail to ensure that the process will start and converge, on the minimum height needed to guarantee that a structure is stable, on the time it takes to reach a certain height, and on other properties of this kind.

Some effort is being made in that direction, by studying the mathematical stochastic properties of a simplistic model of the termite nest consisting of one-dimensional cellular automaton model. These results are the subject of a forthcoming paper (Coffman *et al.*, 1989).

Meanwhile we have obtained other results from the simulation program by modifying some of the steps which are performed at each clock tick. For instance, Fig. 2(a)–(f) shows the structures which can be obtained by nullifying systematically some directions of attraction (in this case S–E and S–W). That is, if S–E or S–W

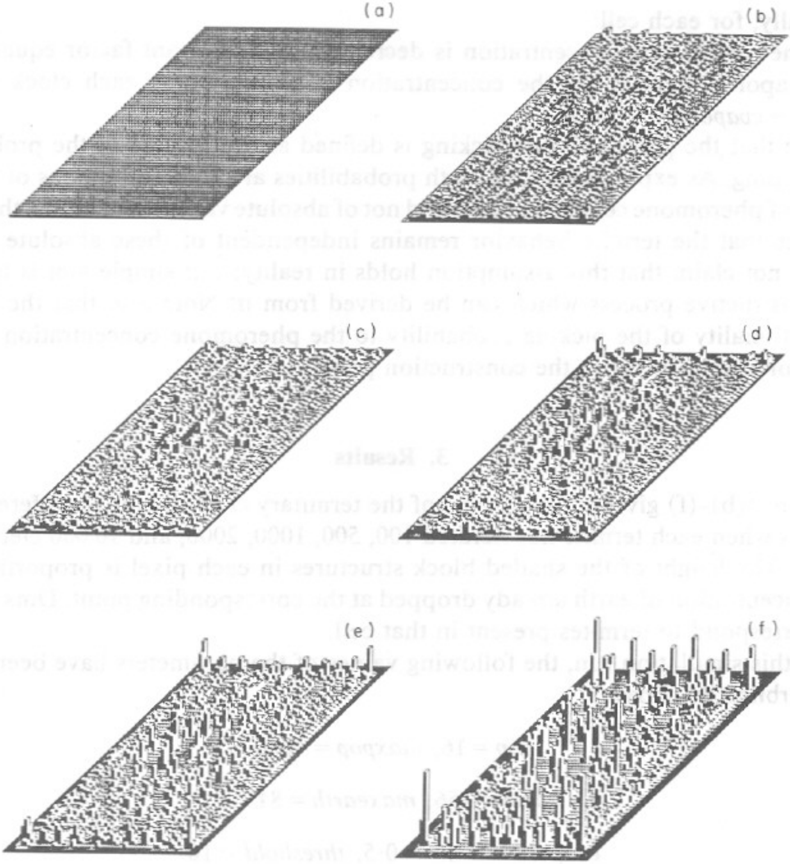

FIG. 2. Same parameters but S–E, S and S–W move to S. (a)–(f) Time is same as for Fig. 1.

is the resulting direction obtained after the random perturbation is made on the x- and y-components, termites which should carry earth in that direction move south. This sort of polarization produces "walls" and "corridors" of the type shown on Fig. 2(f); they are orthogonal to the component of the direction which is nullified.

This may in part explain some of the mechanisms which enable termites to build structures oriented along a given fixed direction of reference, determined for instance by the daily course of the sun.

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APPENDIX

The simulation program consists of 260 lines of Pascal code, embedded in about 2000 lines of support code for graphics and Input/Output operations. It is written as a sequential iterative program. At each clock tick, the move and the action to be performed by each termite are computed in sequence. When they are all computed, they are performed, i.e. the resulting changes in the system state are recorded; then, the next iteration starts with the next clock tick.

The simulation is rather time-consuming: 167 hr of vaxstation processor time were needed for 10^4 iterations, i.e. an average of 57 sec per iteration. A drastic improvement in speed could be expected if a parallel multiprocessor and/or a vectorprocessor machine were used to compute termite moves in parallel. The structure of the program is such that it could fairly easily be rewritten for this type of machine.