Coordination in Distributed Building

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A formal model of distributed building is presented that was inspired by the observation of wasp colonies. Algorithms have been obtained that allow a swarm of simple agents, moving randomly on a three-dimensional cubic lattice, to build coherent structures.

Individual insects generally possess a limited behavioral repertoire, but social insects are collectively capable of performing complex tasks, such as nest building (*1*), through the direct or indirect interactions taking place between individuals. In many cases, the structuration of the environment caused by the colony's activities structures in turn individual behaviors, in a process that Grassé coined stigmergy (*2*). He showed that task coordination and regulation of the building activity in termites do not depend on interactions between the workers themselves but are mainly achieved by the nest structure: Individual behaviors are controlled and guided by previous work. Every time a worker takes a building action, it modifies the shape of the local configuration that triggered its building action. The new configuration then automatically stimulates new actions from any worker in the colony.

The focus of this report is stigmergic building algorithms (*3–6*), that is, distributed building algorithms in which individuals communicate only through the local environment they perceive: the workers' actions are directed by the dynamically evolving shape in construction. One important problem is to understand how stimulations organize themselves in space and time so as to ensure coherent building. In a swarm, many activities can be performed at the same time, and individual building acts do not follow a priori a well-defined sequence. The ability of a swarm to build at more than one location on a growing nest is certainly an important evolutionary step for the development of complex nest architectures (*7*). However, the local cues regulating the building behavior have to be organized in an appropriate way to allow for a coherent construction. If the agents determine their building behavior on the sole basis of local configurations of matter, there must be general characteristics of the individual building behavior in order for the group to produce a coherent architecture. The problem of identifying these characteristics has a counterpart in the theory of parallel computing, where it is known that concurrent operations, if they do not satisfy particular constraints, can yield inconsistent results.

In order to study this question, we have developed a simple computer model of artificial agents randomly moving on a lattice and capable only of depositing elementary bricks depending on the local configuration of matter. The numerical experiments reported below show that the organization of individual activities can in principle be totally directed by the material patterns encountered on the nest. In order to avoid conflicting cues during the building process, configurations that trigger a building action have to satisfy a nonoverlapping property: Coherent architectures that can be built with such a model are all generated by specific building algorithms in which the shape to be built is naturally decomposed into modular subshapes, as are observed in wasp nest architectures, whose corresponding stimulating configurations do not overlap (a stimulating configuration is a local configuration of matter that triggers the deposit of a brick). This is our main result, together with the fact that algorithms with overlapping configurations yield structureless shapes, never found in nature.

Our simulated agents move randomly on a three-dimensional cubic lattice and can drop elementary bricks of two types, according to their local neighborhoods, that is, the 26 surrounding cells. The size of the neighborhood corresponds to the radius of perception of the agents. Actions to be taken are prewired under the form of a look-up table with as many entries as there are stimulating configurations; nonstimulating configurations do not trigger any building action. The bricks are the atomic building material. All agents are able to put down the right brick whenever they meet a stimulating configuration. We present in Fig. 1 a few architectures that have been obtained through computer simulations using these simple deterministic rules. Space limitation does not allow us to reproduce in extenso all the rules used to grow the architectures presented in Fig. 1, but as an example, the rule table used to generate architecture b (Fig. 1) is presented in Fig. 2. More rule tables will be published elsewhere (*8*).

The qualitative difference between architecture g and all other architectures is striking: g looks structureless, whereas all other architectures look coherent. We believe that some of the structured architectures of Fig. 1 resemble natural wasp nests [see, for example, (*9*) for a classification of wasp nests]. Similar to what is found in these nests, plateaus are observed in architectures b, d, e, f, h, and k, and the different levels of the nests are linked together with either a straight axis (b, f) or with a set of pedicels (d, e). The qualitative difference between g and all other shapes corresponds, at a more fundamental level, to a difference in the natures of the algorithms. Our empirical conclusion, drawn on the basis of many simulations, is the following: In order

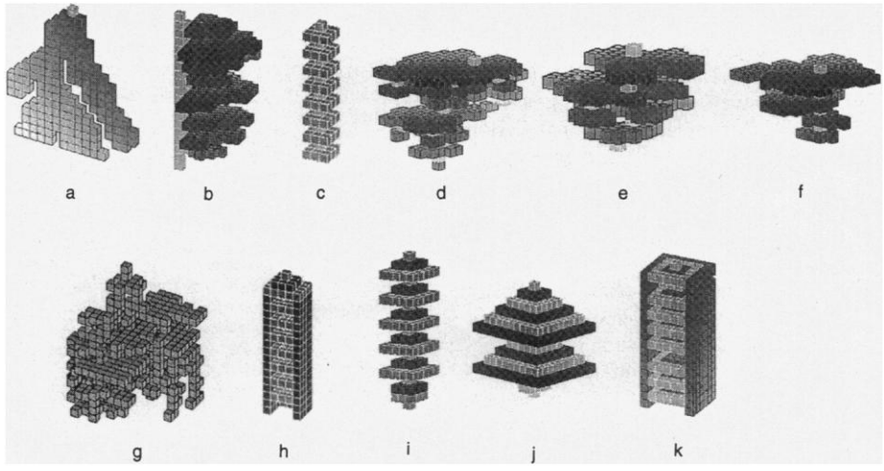

Fig. 1. Architectures obtained from simulations of collective building with a three-dimensional lattice swarm (simulations on a 20 × 20 × 20 lattice with 10 agents). All architectures but g have been produced with coordinated algorithms. Some of these architectures resemble wasp nests (a: *Parapolybia*; b: *Parachartergus*; d and e: *Stelopolybia*; f: *Vespa*; h and k: *Chartergus*).

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for a swarm to build a coherent shape, it is necessary that all agents respond in a uniform manner to the whole set of local configurations they encounter on the architecture. Therefore, at any given time, there must exist an active set of local configurations that all trigger the same qualitative type of brick deposit.

Let $C = \{C_1, C_2, \ldots, C_n\}$ be the set of all local stimulating configurations, that is, the configurations that trigger the building behavior (put down a brick) if they are encountered. In order for the construction to proceed in a coherent way, there has to be a succession of a certain number of qualitatively distinct building stages. Let $(S_1, S_2, \ldots, S_n)$ be the set of these building stages. Each of these stages is characterized by a subset of C, $C(S_p)$. Each subset is unique $[\cup_p C(S_p) = C]$, and together they fully define C $[\forall p_1 \neq p_2, C(S_{p1}) \cap C(S_{p2}) = \varnothing]$. Let us consider a building stage S_p. Each brick put down gives rise to one or more configurations belonging to $C(S_p)$. The completion of S_p corresponds to the appearance of new configurations belonging to $C(S_{p+1})$ and not to $C(S_p)$: if a swarm of agents is to build a given architecture, the shape has to be decomposed into a finite number of building steps, with the necessary condition that the local configurations that are created by a given stage and trigger building actions differ from those created by a previous or a forthcoming building stage so as to avoid the deorganization of the building activity. We call such a building algorithm, whose time evolution obeys this nonoverlapping condition, a coordinated algorithm, because all individuals within a given region of space cooperate in the current building stage at any time.

All architectures but g have been generated with such coordinated algorithms. Although we present almost exclusively structured architectures in Fig. 1 (with the exception of g), structureless architectures are much more likely to be generated if an arbitrary rule table is used: structured architectures are rather rare and, as can be shown by a factorial correspondence analysis (FCA), occupy a very restricted region of rule space (8). The notion of coherent architecture is obviously difficult to formalize, but the FCA further showed us that rule tables that lie close in rule space produce close architectures, indicating the existence of features common to all coherent architectures at the algorithmic level. Finally, a given coordinated rule table always converges toward architectures that possess similar global features; sometimes, the result is even deterministic, that is, all simulations lead to exactly the same architecture despite the random component in individual behavior. This results from the implicit handshakes and interlocks that are set up at every stage in a coordinated algorithm. On the contrary, architectures resulting from successive simulations using the same noncoordinated algorithm are very dissimilar.

Figure 3 illustrates the notion of building stage: it represents the successive steps of the construction of a nest resembling the nest of the neotropical wasp *Epipona* (9). The transition between two successive building steps depends on a given number of local configurations stimulating brick deposits. Once all the bricks in the current step have been deposited, the

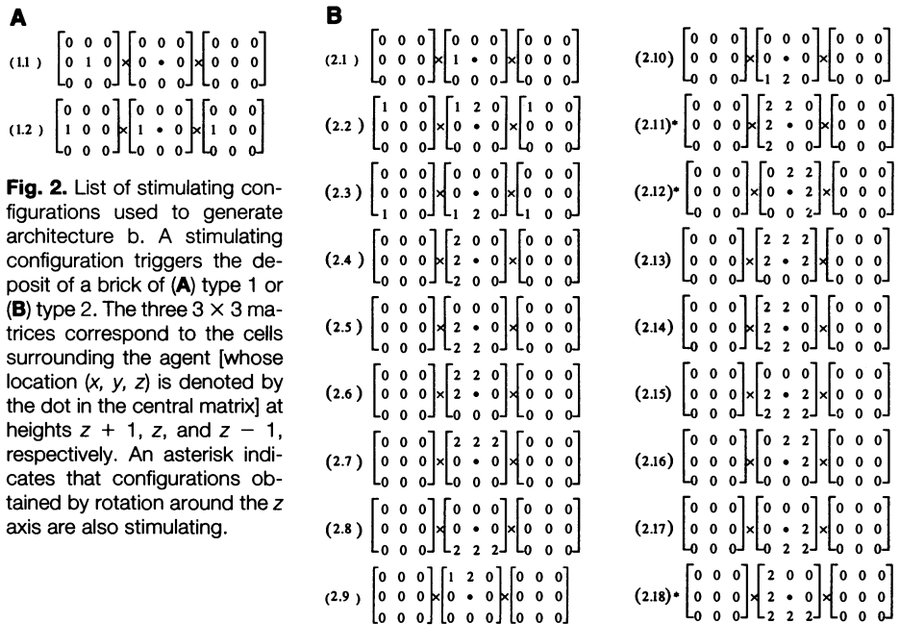

Fig. 2. List of stimulating configurations used to generate architecture b. A stimulating configuration triggers the deposit of a brick of (**A**) type 1 or (**B**) type 2. The three 3 × 3 matrices correspond to the cells surrounding the agent [whose location (*x*, *y*, *z*) is denoted by the dot in the central matrix] at heights $z + 1$, z, and $z - 1$, respectively. An asterisk indicates that configurations obtained by rotation around the *z* axis are also stimulating.

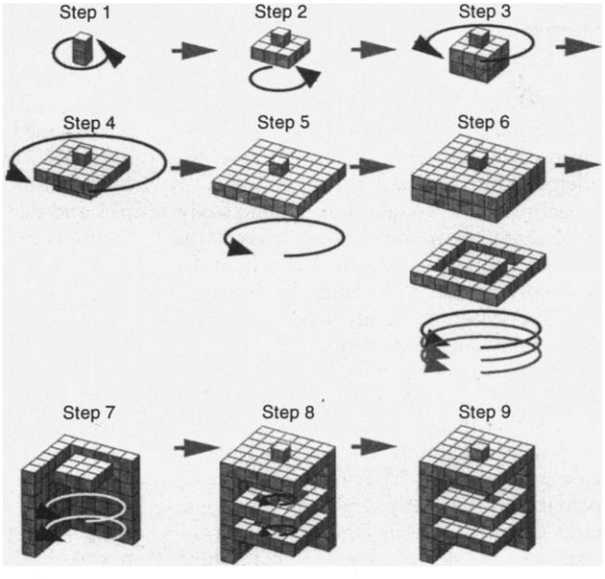

Fig. 3. Successive steps in the construction of a structured lattice architecture including a pedicel, an external envelope, regularly spaced internal layers or combs, and an "entrance hole." This architecture resembles that of the *Epipona* nest. The completion of each step gives rise to stimulating configurations that belong to the next one. All of the stimulating configurations are organized so as to ensure a regular building process. In particular, within a given step, the stimulating configurations do not have to be spatially joined and can occur simultaneously at different locations. In steps 7 to 9, front and right portions of the external envelope have been cut away.

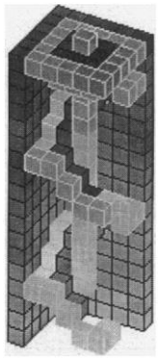

Fig. 4. Lattice architecture including a pedicel, an external envelope, and a long-range internal helix similar to what is observed in an *Apicotermes* termite nest.

building process goes on to the next step. Steps 1 to 5 correspond to the enlargement of the top of the nest, including the first sessile comb of cells (step 3). Steps 6 and 7 represent the construction of the external envelope, from which parallel floors are built (steps 8 and 9). The final step 9 determines the location of the entrance and access holes at the different levels (in the periphery of the architecture). Highly structured architectures with a complex long-range order can be generated with our simple model (Fig. 4). We suggest that the pattern in Fig. 4 is reminiscent of helicoidal ramps that make wide communication structures between the successive floors observed in the nest of the termite *Apicotermes arquieri* (*10*).

In summary, we have shown, within the framework of a simple computer model, that distributed algorithms have to belong to a particular class of algorithms, which we named "coordinated algorithms," to generate coherent structures in a strictly stigmergic mode. In such algorithms, local patterns of matter that result from past construction provide the exclusive cues necessary to direct and coordinate the building activities of the swarm. Therefore, any coherent architecture naturally induces coordination, which may then be seen as a by-product of the architecture; moreover, coordination severely constrains in turn the space of possible coherent architectures. In view of these results, ethologists may be able to take advantage of our approach "despite" its formal nature.

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Molecular Identification of an IgE-Dependent Histamine-Releasing Factor

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An immunoglobulin E (IgE)–dependent histamine-releasing factor (HRF) produced by lymphocytes of atopic children and present in biological fluids of allergic patients has been identified and purified. Amino-terminal sequencing revealed extensive homology to a mouse protein, p21, and its human homolog, p23. Both recombinant proteins caused histamine release from the human basophils of a subpopulation of donors, and this release was dependent on IgE. Polyclonal antibodies recognized and removed the biological activity of recombinant and native HRF. HRF identifies a heterogeneity of IgE and is believed to play a prominent role in chronic allergic disease processes.

Several in vivo systems are used to study human allergic disease. The model currently favored is the late response in humans that occurs hours after the immediate reaction to allergen challenge (*1*). The pathophysiological events, such as decreased airway function, are characterized by infiltration of inflammatory cells and by the presence of mediators such as histamine, which are findings similar to those observed in people with chronic allergic diseases such as asthma. The histamine released in this late-phase reaction (LPR) results from activation of basophils that, along with eosinophils and lymphocytes, infiltrate tissues during this response (*1*, *2*). Because the allergen that initiated the response is no longer present, two questions require study: the nature of the agent that triggers the release of inflammatory mediators from the basophils in the LPR, and the basis for the observation that only about half of allergic individuals experience an LPR.

Many laboratories have been attempting to answer these questions by identifying cytokines with histamine-releasing activity on human basophils. The first such molecule was described 15 years ago in the supernatants from peripheral blood mononuclear cell (PBMC) preparations (*3*). A decade ago we described an HRF in fluids derived from the LPR in the skin (*4*). This HRF was dependent on IgE bound to basophils, and it defined an IgE heterogeneity: Only half of atopic individuals had basophils that responded to HRF. Responders had serum IgE—which we designated as IgE^+—which could passively sensitize normally unresponsive basophils to release histamine in response to the HRF (*5*). A variety of cytokines with histamine-releasing activity have recently been discovered, including several C-C chemokines—MCP-3, MCP-1, and RANTES—as well as interleukins such as interleukin-3 (IL-3) (*6*–*9*). None of these molecules cause basophils to release histamine by a mechanism that involves cell surface IgE. This report describes the subcloning, sequencing, and expression of a unique IgE-dependent HRF.

Although an IgE dependent HRF can be detected in nasal lavages (*5*), PBMC culture supernatants (*10*), and fluids from human LPR (*11*), we used supernatants from overnight cultures of U937 cells, a human macrophage cell line (*12*), for the isolation and sequencing of the HRF. Fifty liters of these supernatants were concentrated and the proteins contained therein purified by Sephadex G75 gel filtration, MONO Q anion exchange, and repetitive Superdex chromatography. The basophil-releasing activity was concentrated, subjected to SDS–polyacrylamide gel electrophoresis (PAGE), blotted onto a polyvinylidene difluoride membrane, and stained with Coomassie blue, revealing four major protein bands (at 60 kD and 29 kD and a doublet at 23 kD). The NH_2-terminal sequences of each of these four bands were determined by protein sequencing. The 18 NH_2-terminal amino acids of one of the 23-kD components are shown in Fig. 1. A GenBank search revealed 94% homology to p21, a predicted 21-kD murine peptide whose complementary DNA (cDNA) was isolated from mouse tumor cells (*13*), as well as identity to p23, the human homolog, described by Böhm *et al.* (*14*). The complete protein sequences of p21 and p23 are also shown in Fig. 1. Both were cloned on the basis of their abundant expression in tumor cells, and no function has been ascribed to either molecule. The p21 and p23 proteins do not have obvious hydrophobic residues at the NH_2-termini, which suggests that they are not secreted. However, because HRF is found in in vivo fluids, it may use a secretory pathway such as that described for IL-1β; or, again like IL-1, it may be released during apoptosis (*15*). Because there is a stop codon upstream from the initial methionine, it appears that p21 and p23 are not posttranslationally processed at their NH_2-termini. p21 cDNA was subcloned into the pGEX-2T plasmid (*16*), expressed as a fusion protein with glutathione-S-transferase (GST),

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