# Programming with Stigmergy: Using Swarms for Construction

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**Abstract**

Social insects build extremely complex structures despite their limited perception and the absence of a global control system. Many of the structures built by termites can be construed as emergent phenomena driven by each worker's reaction to local pheremone levels. This work extrapolates from termite building to a system for specifying swarm activity. In the system, swarms are homogeneous and composed of simple, memory-less that perceive only their immediate environment. The swarm's activity is coordinated by virtual pheremone concentrations. The rules governing the agents' reactions can be designed to produce swarms that build complex, composable structures.

## Introduction

Termite nests are large and complex. A nest may be as much as $10^4$ or $10^5$ times as large as an individual termite (Boneabeau *et al.* 1997) — a ratio unparalleled in the animal kingdom. The nests of the African termite sub-family Macrotermitinae are composed of many substructures, such as protective bulwarks, pillared brood chambers, spiral cooling vents, galleries of fungus gardens and royal chambers. For all the architectural sophistication of termite nests, termites themselves are blind, weak and apparently not responsive to a coordinating authority. This work attempts to borrow and generalize the termite construction-algorithm, permitting artificial, decentralized swarms to be programmed to build complex, composable structures.

How do small, blind termites manage to build (relatively) huge, intricate nests? Work on this question includes a simple, decentralized building model (Grasse 1959) (Grasse 1984), an empirical study of termite building behavior (Bruinsma 1979), a mathematical model of the synthesis of pillars in termite nests (Deneubourg 1977), and a model explaining how modest environmental variation can cause the same termite behaviors to generate qualitatively different structures (Boneabeau *et al.* 1997). Most relevant to this work is (Bruinsma 1979), which records three feedback mechanisms governing termite behavior. In the first, a termite picks up a soil pellet, masticates it into a paste and injects a termite-attracting pheremone into it. When the pellet is deposited, the pheremone stimulates nearby termites to pellet-gathering behavior and makes them more likely to deposit their pellets nearby. Second, small obstacles in the terrain stimulate pellet deposits and can seed pillars. Finally, a trail pheremone allows more workers to be drawn to a construction site.

Termites and many social insects interact stigmergically — that is, communication is mediated through changes in the environment rather than direct signal transmission. Computer simulations have used stigmergy to reproduce termite's pillar-making behavior and ant's foraging and the spontaneous cemetery building. These applications rely of qualitative stigmergy — individual agents react to a continuous variations in the environment. An example of quantitative stigmergy is (G. Theraulaz 1995), a simulation of wasp nest building. Wasps build nests by depositing cells on a lattice. Whether an empty cell is filled depends on the adjacent cells. Because all wasps have the same deposit-triggers, multiple wasps are able to simultaneously work on a single nest without without ruining each others work. A set of deposit-triggers is coherent if each no stage in the building process can be confused with an earlier stage by making only local observations, thus obviating the need for centralized control.

The goal of this work is to generalize the construction methodologies of the social insects and create a language for stigmergically assembling complex structures. Such a language permit swarms of agents to erect interesting architectures without benefit of a central controller or explicit inter-agent communication. The primary advantage of this approach is that stigmergically controlled swarms have minimal communication and no coordination overhead. Also, very little processing is demanded of agents, and the swarm can tolerate a degree of agent error. On a more abstract plane, this work is an example of *designing emergent behavior*.

There has been some work on using biomimetic robots inspired by social insects for construction — (Bowyer 2000) describes preliminary work. In the projected

work, small mobile robots build structures by exuding polymerized diphenylmethane 4,4'-diisocyanate foam, a harmless, stable substance widely used as a commercial filler. The foam can be stored in a compressed liquid form which expands, hardens and sets when sprayed out. The solidified foam is strong (a small arch made of it can support a person), but easy to puncture, which makes it a good climbing surface for sharp-clawed robots.

## Stigmergic programming

In this work, swarms are composed of agents moving randomly over a two dimensional lattice. The agents are identical and stateless. They build structures by moving (initially randomly scattered) bricks, coordinating their activities through pheremone plumes, which, unphysically, do not attenuate over time.

Agents' reactions are determined by rules — if an agent detects levels of certain pheremones within certain ranges, it takes a given action. Since these agents can only perceive pheremone concentrations at the point they occupy in the lattice, they are incapable of behaviors like chemotaxis and trail following. The precondition of a rule consists of a conjunction of acceptable bands of pheremone intensity. Pheremones can be enablers or suppressors of a rule. A rule's action is one or both of releasing a pheremone and, if a brick is carried, dropping it.

Deposited pheremones symmetrically through the grid according to an inverse power law. A rule triggered by a band of intensity of a particular pheremone will, given a single deposit of that pheremone, will be triggered in a ring centered on that deposit. Adding a second deposit breaks radial symmetry and creates an ellipse-shaped activation potential. By stringing together ellipses, directed chains of deposits can be formed. It is possible to build two pheremone chains parallel and at a fixed distance from each other — this produces pheremone gradients which can be used to distinguish left from right.

Rules that use local pheremone intensities to estimate the distance to the nearest deposit are inherently vulnerable to interference from other, unexpected deposits. Since interference diminishes with distance, this problem can be worked around by building rule-sets that keep deposits of each pheremone widely separated. An exception is "stabilizer pheremone", which tells passing agents that a brick has been dropped purposefully, and that they should therefore not pick it up. Pheremone-driven rules implement a kind of continuous cellular automaton, defined by changing reaction potentials, on top of a discrete one, defined by the motions of the agent swarm.

The mechanics of pheremone reactions lend themselves to composable actions. The most elementary kind of action is a two-point rule, in which an activation potential is defined by relative position to two precursor points, as shown in figure 1. This kind of rule can be used to add elements to a chain or to cap two converging chains.

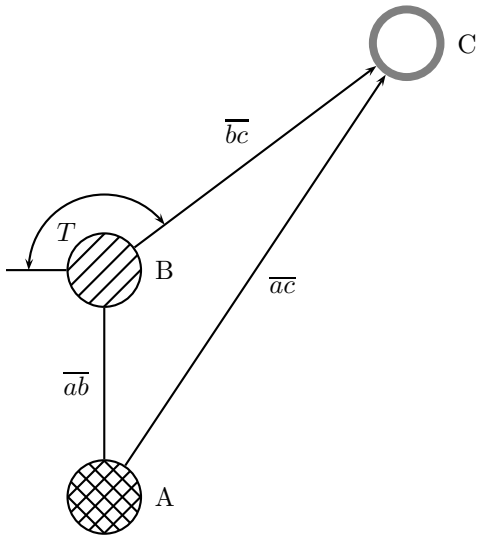


Figure 1: Schematic for a specifying the site of a potential $C$ on the basis of two pheremone deposits $A$ and $B$. When coding for a chain of pheremones it is convenient to specify the distances $\overline{ab}$ and $\overline{bc}$ and the angle $T$, but only $\overline{ac}$ and $\overline{bc}$ are perceptible, so solve for $\overline{ab}$ using $\overline{ac}^2 = \overline{bc}^2 + \overline{ab}^2 + 2\overline{bc} \times \overline{ba} \times \sin T$

Table 1 gives the rules used by a swarm that generates a left-curving arc of bricks. The swarm builds two parallel, left-curving chains. The left-hand chain is composed of links between A and B deposits, and the right-hand of links between deposits of C and D. Each rule will deposit a pheremone at a point *new* that is an estimated distance *near_new_distance*from the deposit *near_source*, where *near_source*is a distance *far_near_source*from the deposit of *far_source*. The angle between the first vector and the perpendicular of the second must make an angle *angle_from_perpendicular* , as illustrated in Figure 1.

Rules can code for the construction of invisible pheremone super-structures or for actually building structure by placing bricks. Structural rules generally create small activation potentials in order to precisely place future pheremone deposits. Brick-placement rules on which no other components of the intended architecture depend may have broader, less precise activation potentials.

The arc-building swarm is seeded with two with two pheremone deposits at a fixed distance. Figure shows an intermediate stage of arc formation. The super-structure of the arc has extended four links from the seeds, but the walls connecting pheremone deposits have not been built. In Figure the arc super-structure has been completed and almost every brick on the lattice has

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| far_source | C | A | D | B | |
| near_source | A | C | B | D | |
| far_near_distance | 7 | 7 | 7 | 7 | |
| near_new_distance | 17.1 | 15 | 17.1 | 15 | |
| angle_from_perpendicular | $-20^o$ | $20^o$ | $-20^o$ | $20^o$ | |
| suppressors | B | D | A | C | |
| suppressor_radii | 26 | 26 | 26 | 26 | |
| deposit | B | D | A | C | |
| drop triggers | | | | | A, B |
| total radii | | | | | 15 |

Table 1: Arc Builder Rules

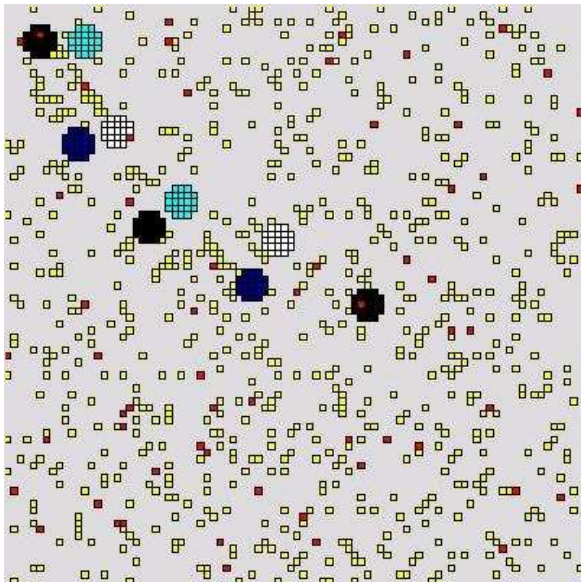

Figure 2: intermediate state of the arc builder. The circles are regions of high pheremone concentration.

been incorporated into walls.

The swarm (partially) defined in 2 illustrates the composition of rule-sets by building a chain along which star shapes are regularly distributed. The rules for this swarm are composed of two subsets — the first encodes the stars, the second the chains along which the stars are positioned. The latter is encoded by means of four pheremones which are deposited in alternation to form a line. The former is encoded by positioning five deposits at angles of 18°, 90°, 162°, 234° and 306° from the line between two of the pheremones used to build the chain. shows the potential activations in an incomplete star-chain and shows the final product. Notice that there are few bricks (yellow pixels) left near the stars that have not been incorporated into them.

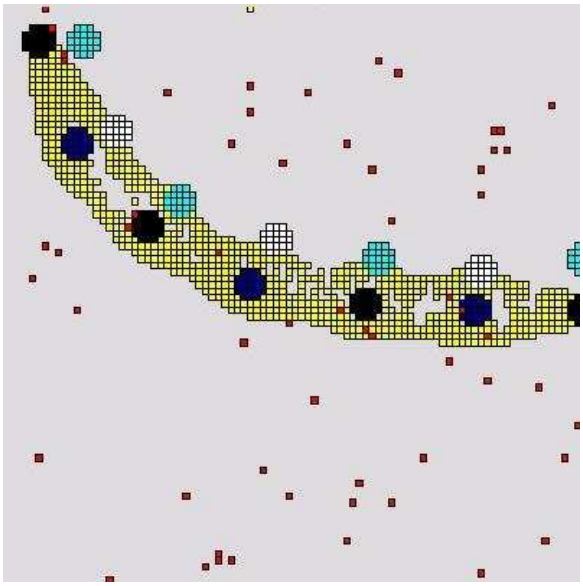

Figure 3: final state of the arc builder. Regions of intense pheremone activity are also shown.

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| far_source | A | A | A | A | A |
| near_source | B | B | B | B | B |
| far_near_distance | 15 | 15 | 15 | 15 | 15 |
| near_new_distance | 15 | 15 | 15 | 15 | 15 |
| angle_from_perpendicular | 18 | 90 | 162 | 234 | 306 |
| suppressors | C | C | C | C | C |
| suppressor_radii | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 |
| deposit | C | C | C | C | C |

Table 2: Star-chain Builder Rules. Rules 1-5 encode the star shapes while rules 6-10 encode the chain on which the stars are built.

## Conclusion

A decentralized, stigmergic control system can be used to program swarms. The swarms achieve fine-grained control by implementing a semi-deterministic cellular automata in which communication is mediated through virtual pheremone plumes. The swarms consist of identical agents which, based on only the pheremone concentrations in their immediate environment, follow a simple set of rules that can interact to allow the creation of complex structures. Thematically, this is a generalization of the building algorithms of termites. This kind of decentralized control is useful in cases where it is more practical to have many simple agents than a few complex ones and where direct communication and coordination are difficult.

In future work the system system will be extended to three dimensions. This will require modeling the stability of structures in gravity and refining the control

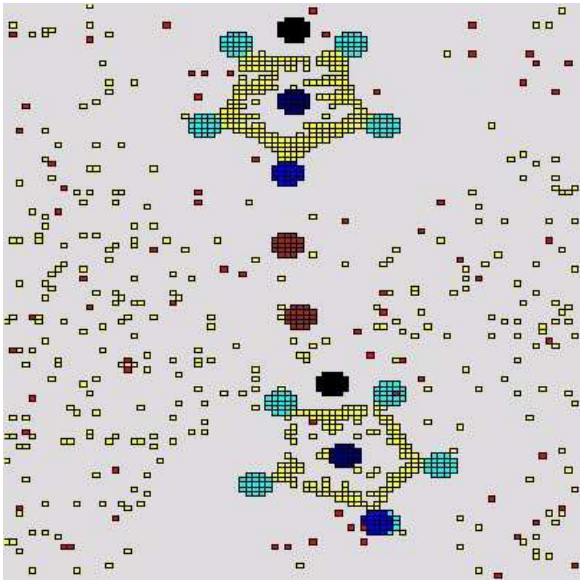

Figure 4: final state of the star-chain builder.

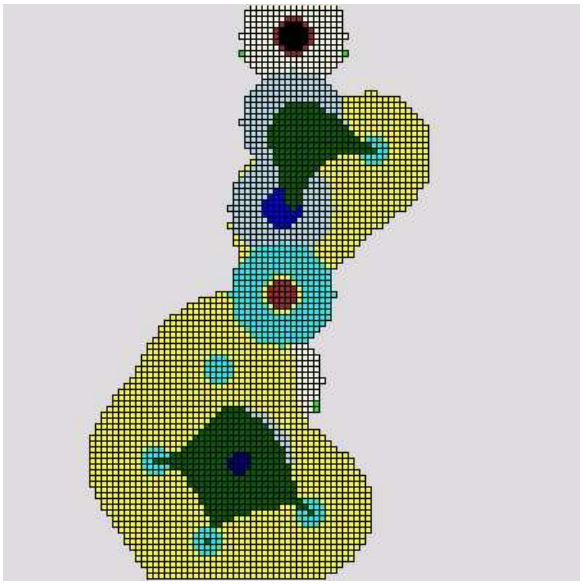

Figure 5: pheremone distribution in an intermediate state of the star-chain builder.

of agent motion so that agents only walk where they are adequately supported. Other future work includes programming construction swarms by specifying the target structure directly, letting a compiler infer the corresponding rule-set (if one exists.) On the theory that simpler agents are better, it would be useful to be find the minimal set of pheremones capable of generating a particular target object, and of quantifying the trade-offs between pheremone number and various building metrics, such as accuracy and probability of failure. Also, the simulator could be more physically realistic — for instance, by introducing pheremone attenuation or variations in pheremone diffusion due to changes in the air or surrounding structures. The software for this system is available at

`http://www.cs.brandeis.edu/~zmason/stigmergy.html`

## References

Boneabeau; Theraulaz; Deneubourg; Franks; Rafelsberger; Joly; and Blaco. 1997. A model for the emergence of pillars, walls and royal chambers in termite nests. *Phil. Trans. R. Soc. London* 353:1561–1576.

Bowyer, A. 2000. Automated construction using cooperating biomimetic robots. Technical Report 11/00, University of Bath Department of Mechanical Engineering.

Bruinsma, O. H. 1979. *An analysis of building behaviour of the termite Macrotermes subhyalinus* . Ph.D. Dissertation, Landbouwhogeschool.

Deneubourg, J. L. 1977. Applications de l'ordre par fluctuations a la description de certaines etapes de la construction du nid chez les termites. *Insectes Soc.* 25:117–130.

G. Theraulaz, E. Bonabeau, J. 1995. Modeling the collective building of complex architectures in social insects with lattice swarm. *J. Theor. Biol.* 177:381.

Grasse, P. 1959. La reconstruction du nid et les coordinations inter-individuelles chez *bellicostitermes natalensis* et *cubitermes* . sp. la theorie de la stigmergie: essai d'interpretation du comportement des termites constructeurs. *Insectes Soc.* 61:41–81.

Grasse, P. 1984. *Termitologia, Tome II - Fondation des societies construction.* Paris: Masson.

## References

Boneabeau; Theraulaz; Deneubourg; Franks; Rafelsberger; Joly; and Blaco. 1997. A model for the emergence of pillars, walls and royal chambers in termite nests. *Phil. Trans. R. Soc. London* 353:1561–1576.

Bowyer, A. 2000. Automated construction using cooperating biomimetic robots. Technical Report 11/00, University of Bath Department of Mechanical Engineering.

Bruinsma, O. H. 1979. *An analysis of building behaviour of the termite Macrotermes subhyalinus* . Ph.D. Dissertation, Landbouwhogeschool.

Deneubourg, J. L. 1977. Applications de l'ordre par fluctuations a la description de certaines etapes de la construction du nid chez les termites. *Insectes Soc.* 25:117–130.

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Grasse, P. 1959. La reconstruction du nid et les coordinations inter-individuelles chez *bellicostitermes natalensis* et *cubitermes* . sp. la theorie de la stigmergie:

essai d'interpretation du comportement des termites constructeurs. *Insectes Soc.* 61:41–81.

Grasse, P. 1984. *Termitologia, Tome II - Fondation des societies construction.* Paris: Masson.