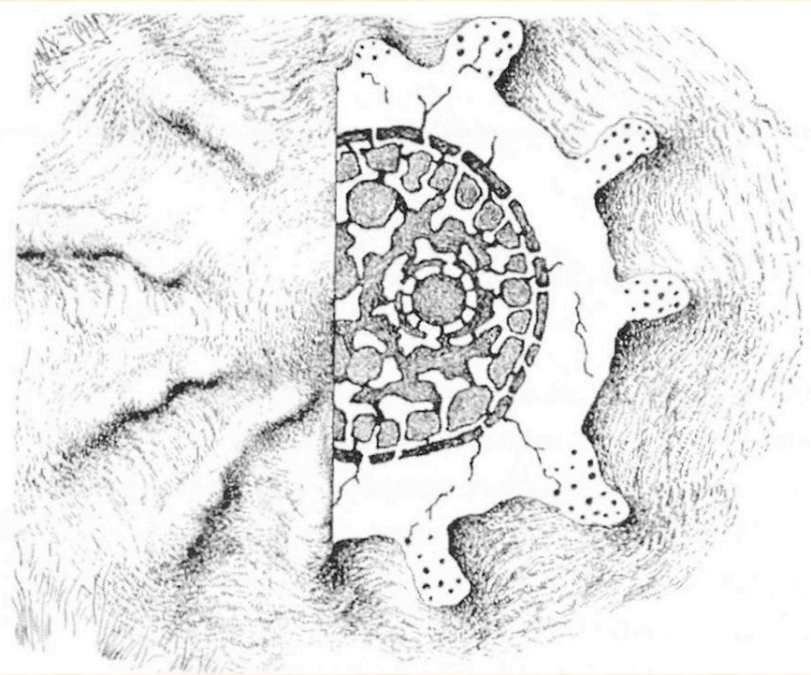
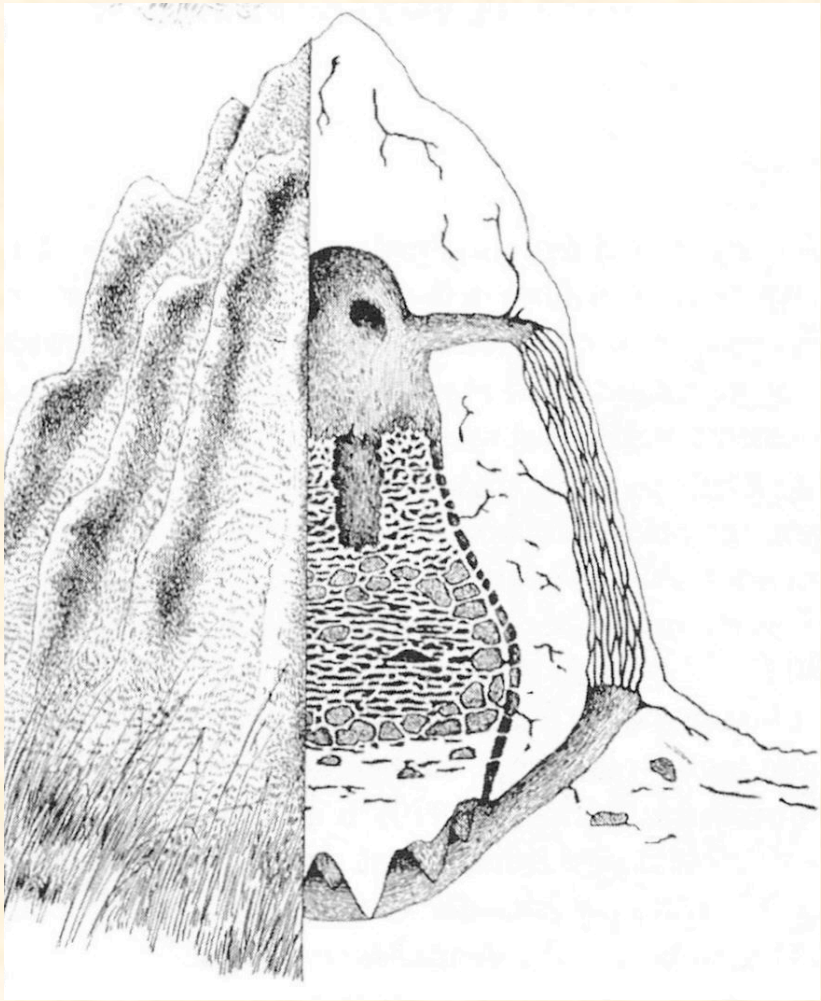
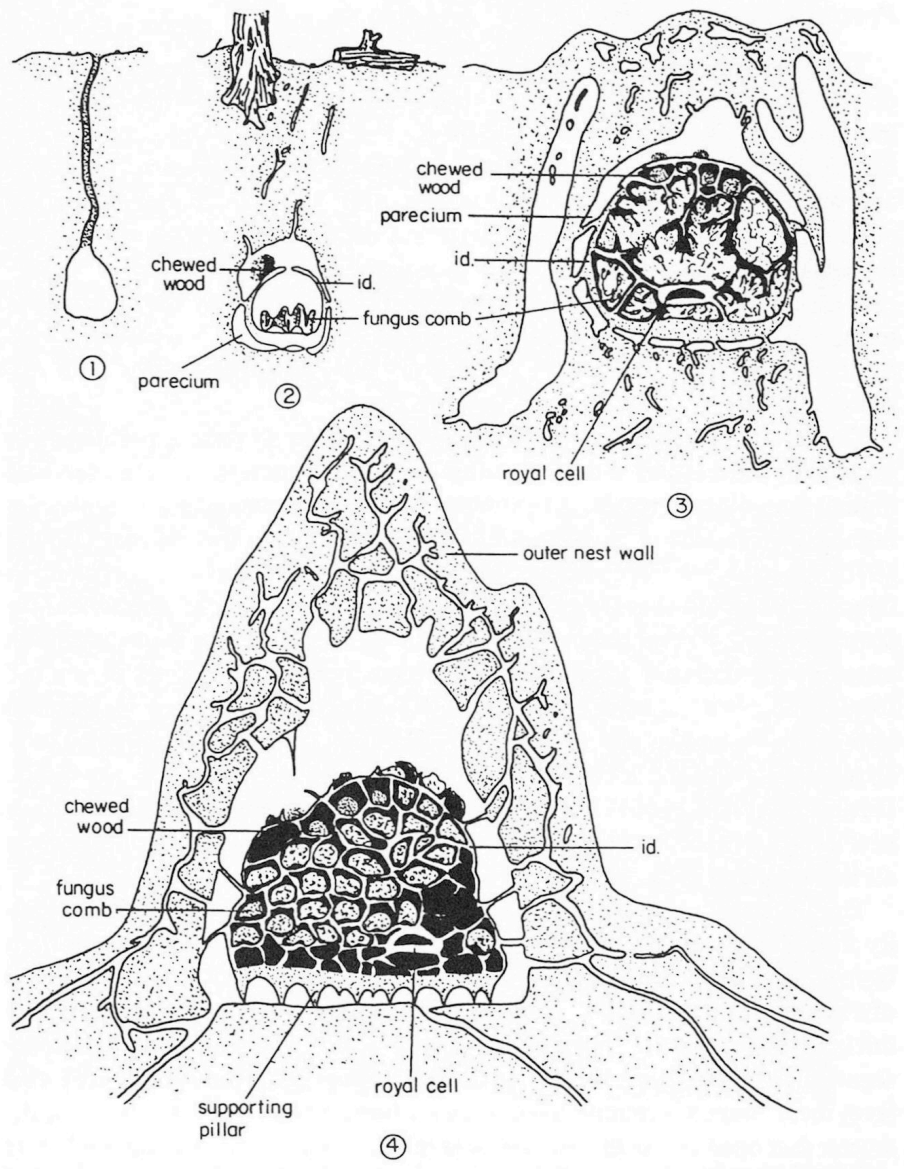
Mound Building by *Macrotermes* Termites

Structure of Mound





figs. from Lüscher (1961)



Construction of Mound

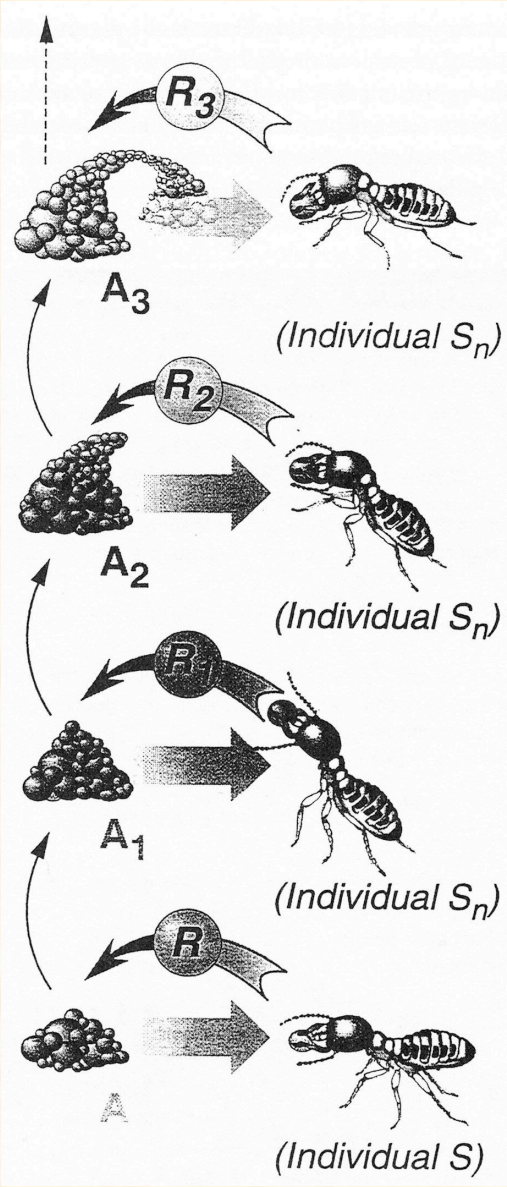
(1) First chamber made by royal couple

(2, 3) Intermediate stages of development

(4) Fully developed nest

Alternatives to Self-Organization

- Leader
  - directs building activity of group
- Blueprint (image of completion)
  - compact representation of spatial/temporal relationships of parts
- Recipe (program)
  - sequential instructions specify spatial/temporal actions of individual
- Template
  - full-sized guide or mold that specifies final pattern



Basic Mechanism of Construction (Stigmergy)

- Worker picks up soil granule
- Mixes saliva to make cement
- Cement contains pheromone
- Other workers attracted by pheromone to bring more granules
- There are also trail and queen pheromones

Construction of Arch (1)

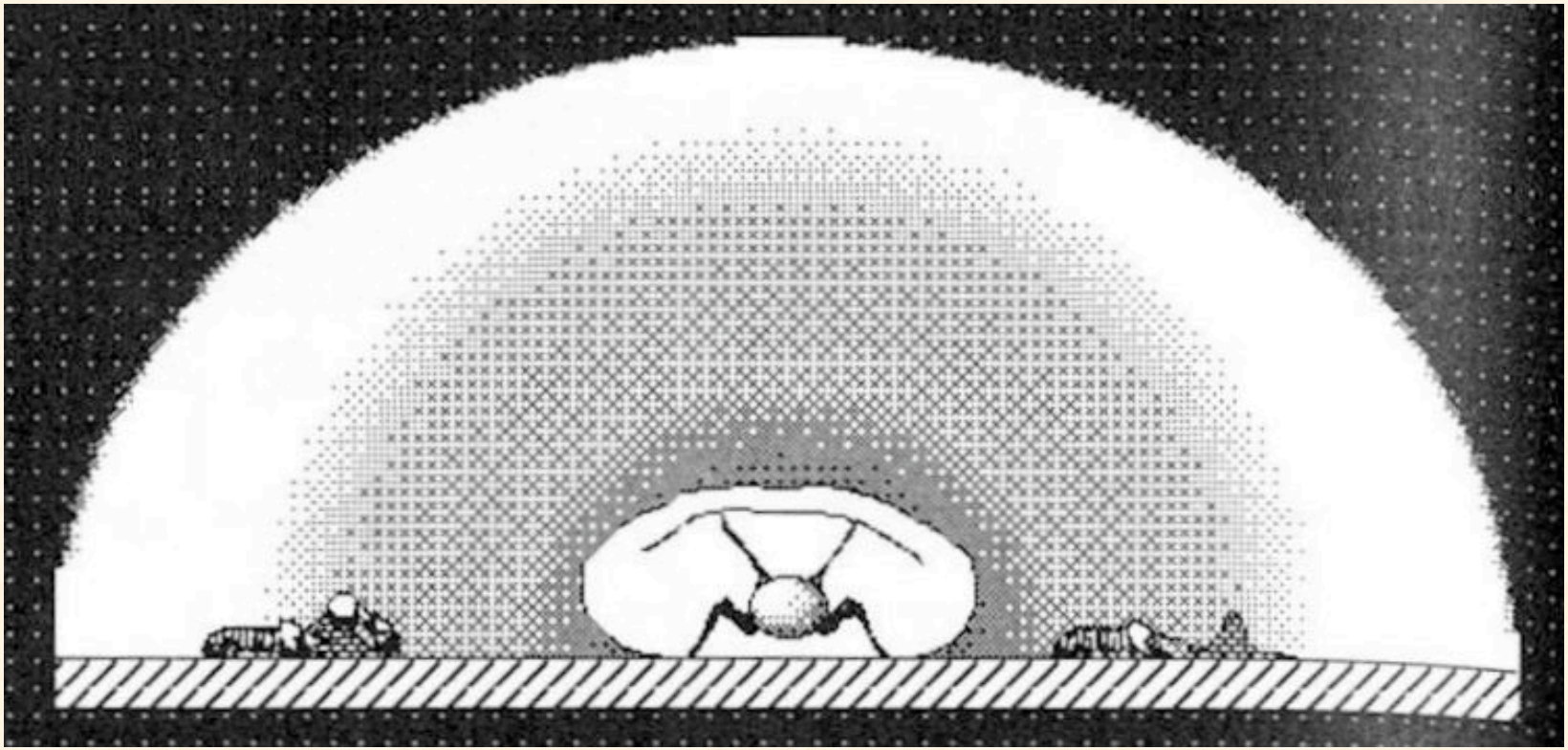


Fig. from Bonabeau, Dorigo & Theraulaz

Construction of Arch (2)

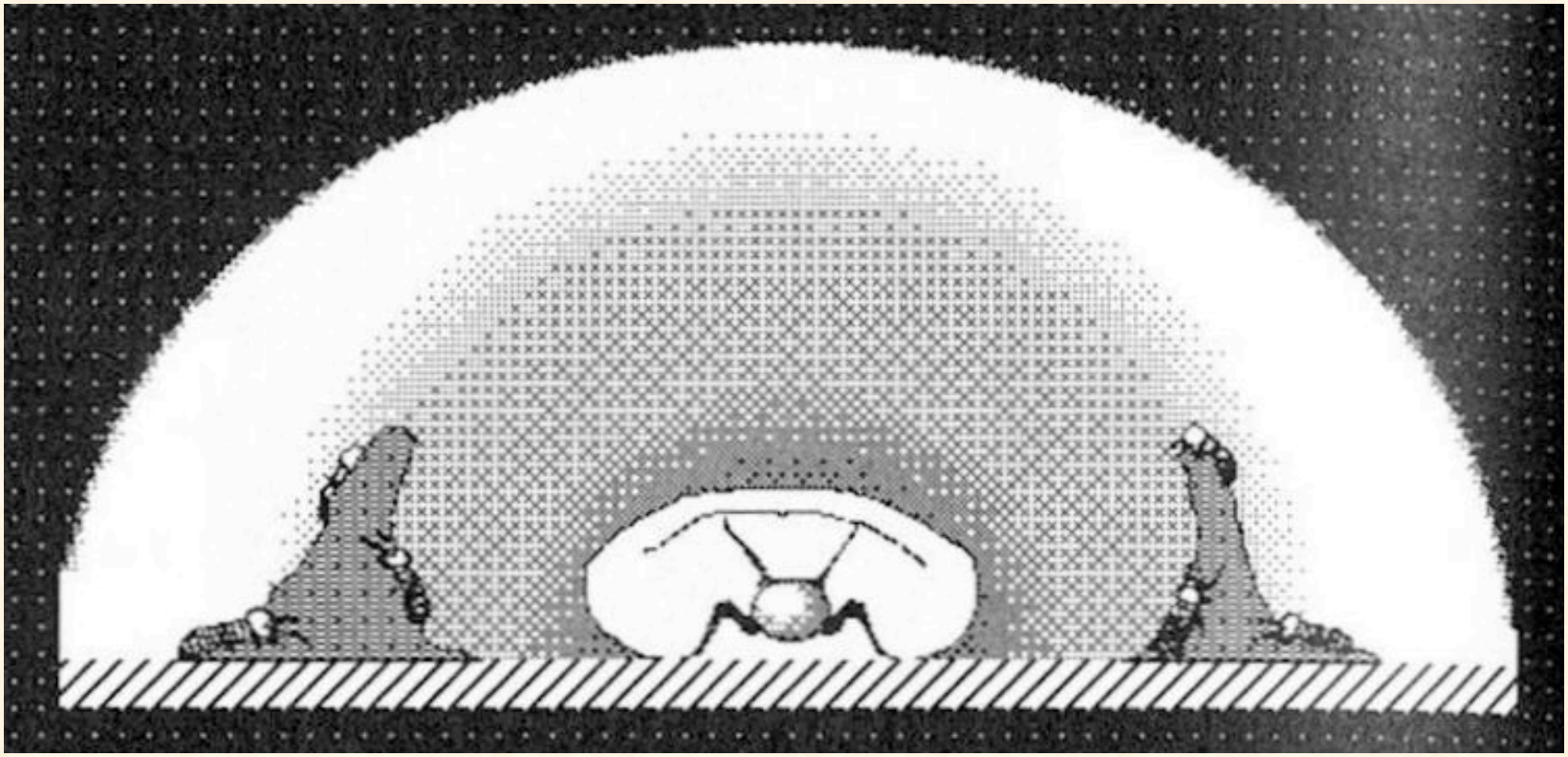


Fig. from Bonabeau, Dorigo & Theraulaz

Construction of Arch (3)

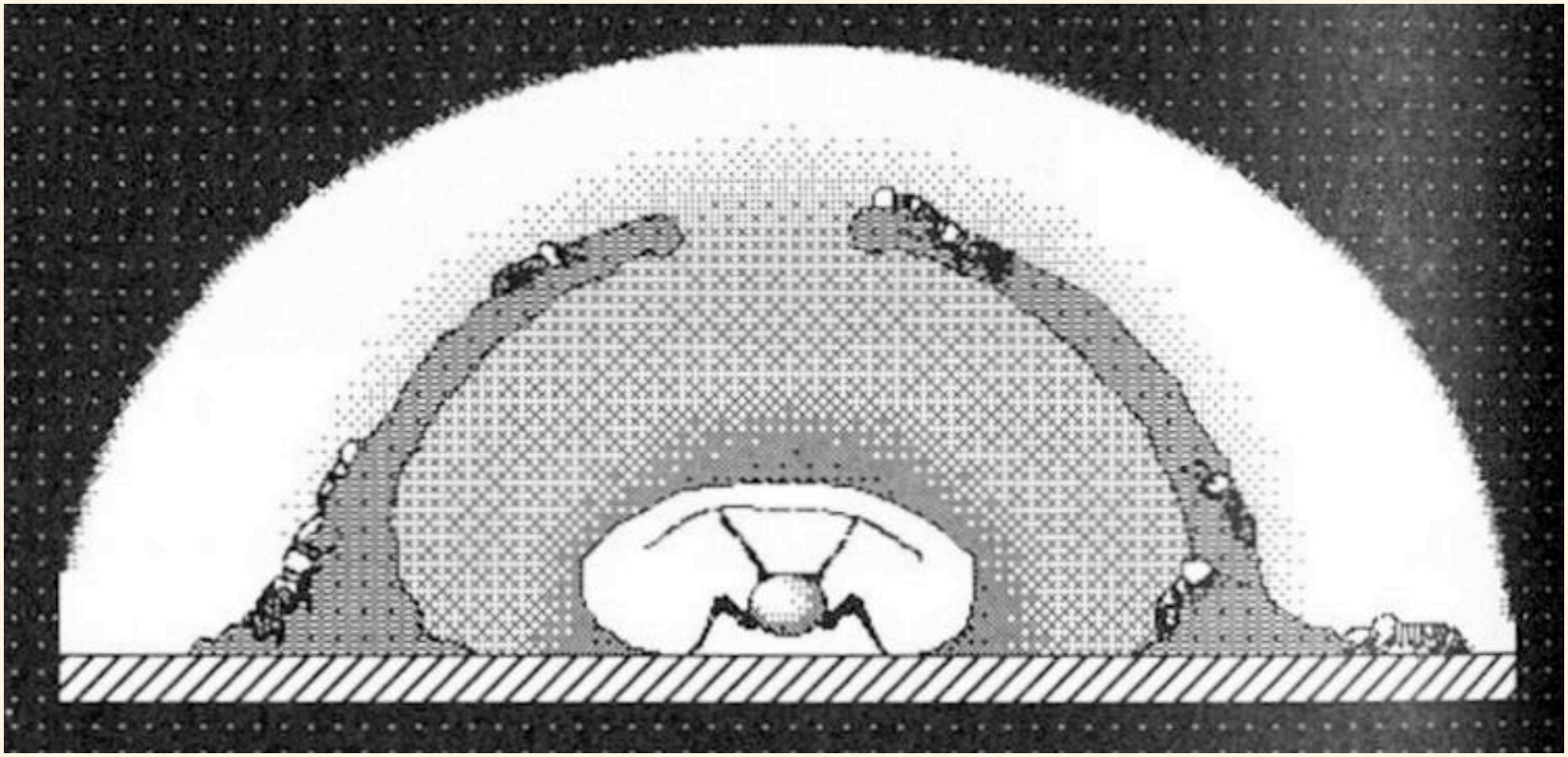


Fig. from Bonabeau, Dorigo & Theraulaz

Basic Principles

- Continuous (quantitative) stigmergy
- Positive feedback:
  via pheromones
- Negative feedback:
  depletion of soil granules and competition between pillars

Deneubourg Model

- $H(r, t)$ = concentration of cement pheromone in air at location r & time t
- $P(r, t)$ = amount of deposited cement with still active pheromone at r, t
- $C(r, t)$ = density of laden termites at r, t
- $\square$ = constant flow of laden termites into system

Equation for P
(Deposited Cement with Pheromone)

$\partial_t P$ (rate of change of active cement) =

$k_1 C$ (rate of cement deposition by termites)

$- k_2 P$ (rate of pheromone loss to air)

$$\partial_t P = k_1 C - k_2 P$$

Equation for H
(Concentration of Pheromone)

$\partial_t H$ (rate of change of concentration) =

$k_2 P$ (pheromone from deposited material)

$- k_4 H$ (pheromone decay)

$+ D_H \nabla^2 H$ (pheromone diffusion)

$$\partial_t H = k_2 P \nabla k_4 H + D_H \nabla^2 H$$

Equation for C
(Density of Laden Termites)

$\partial_t C$ (rate of change of concentration) =

∇ (flux of laden termites)

$- k_1 C$ (unloading of termites)

$+ D_C \nabla^2 C$ (random walk)

$- \nabla \cdot (C \nabla H)$ (chemotaxis: response to pheromone gradient)

$$\partial_t C = \nabla \left(k_1 C + D_C \nabla^2 C \right) - \nabla \cdot \left(C \nabla H \right)$$

Additional Explanation of Chemotaxis Term

- The termite flow into a region is the negative divergence of the flux through it

  $-\nabla \cdot \mathbf{J}$

- The flux is proportional to the pheromone gradient

  $\mathbf{J} \propto \nabla H$

- The flux is proportional to the number of moving termites

  $\mathbf{J} \propto C$

- Hence, $-\nabla \cdot \mathbf{J} = -\nabla \cdot (C \nabla H)$

Simulation ($T = 0$)

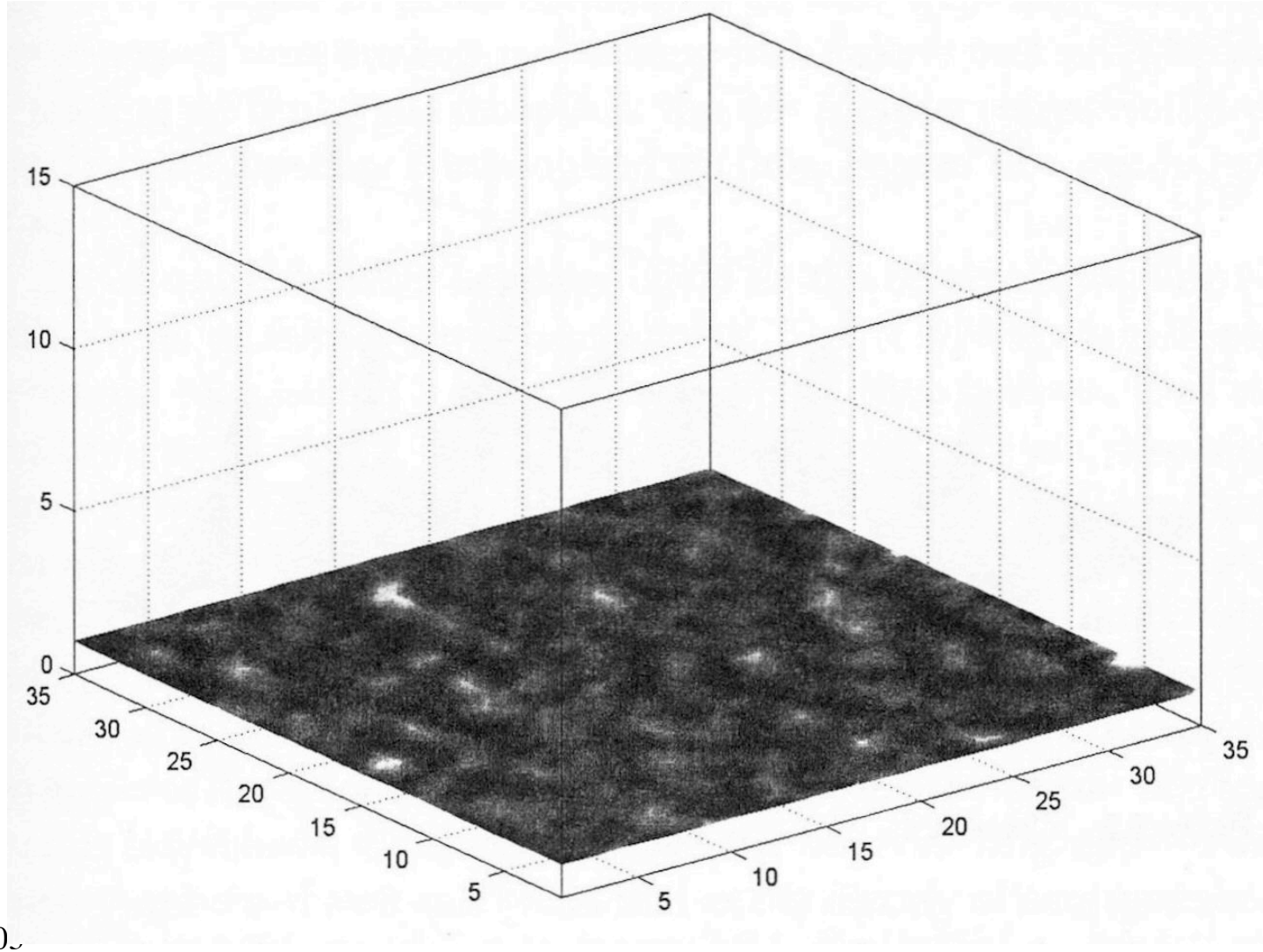


fig. from Solé & Goodwin

Simulation ($T = 100$)

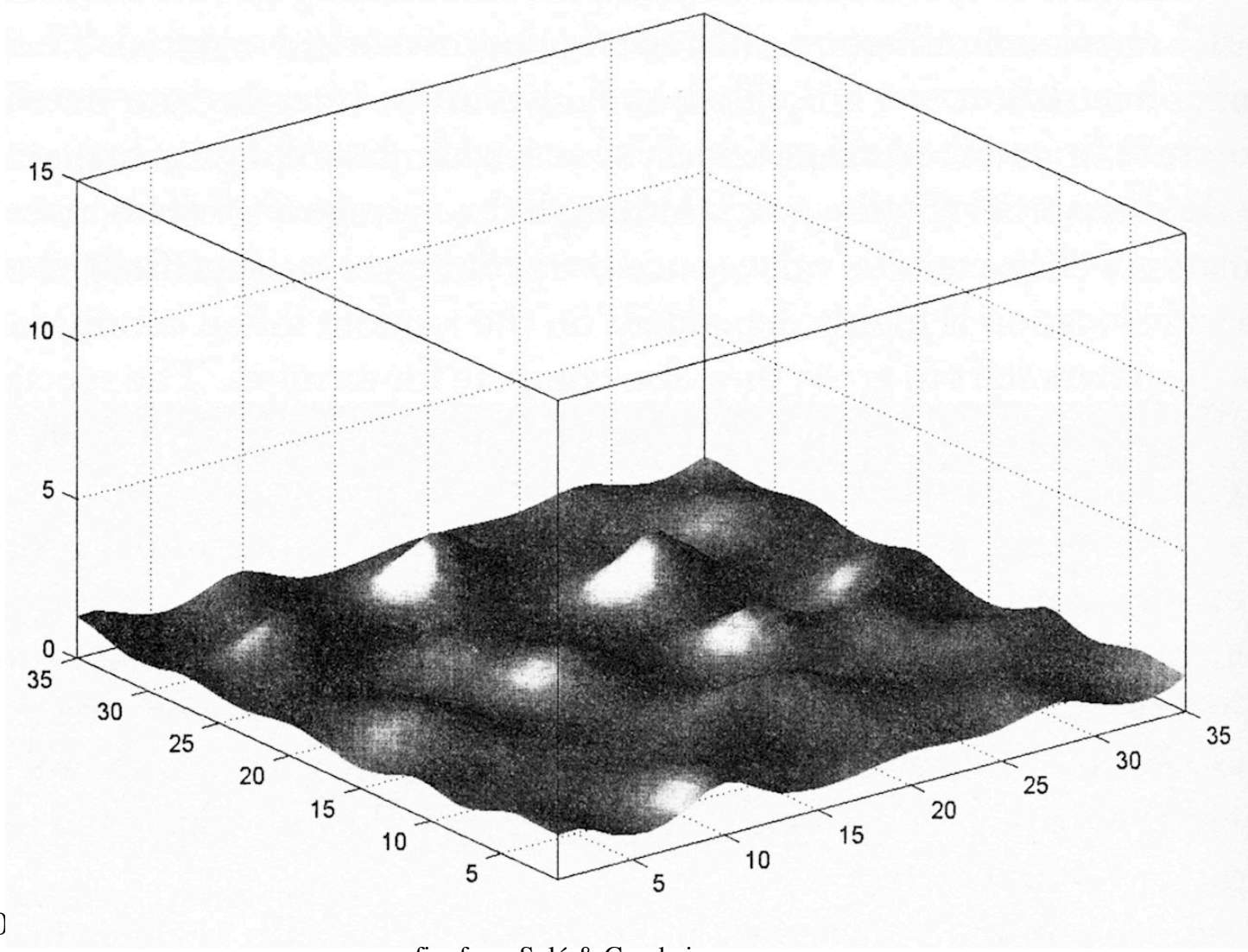


fig. from Solé & Goodwin

Simulation ($T = 1000$)

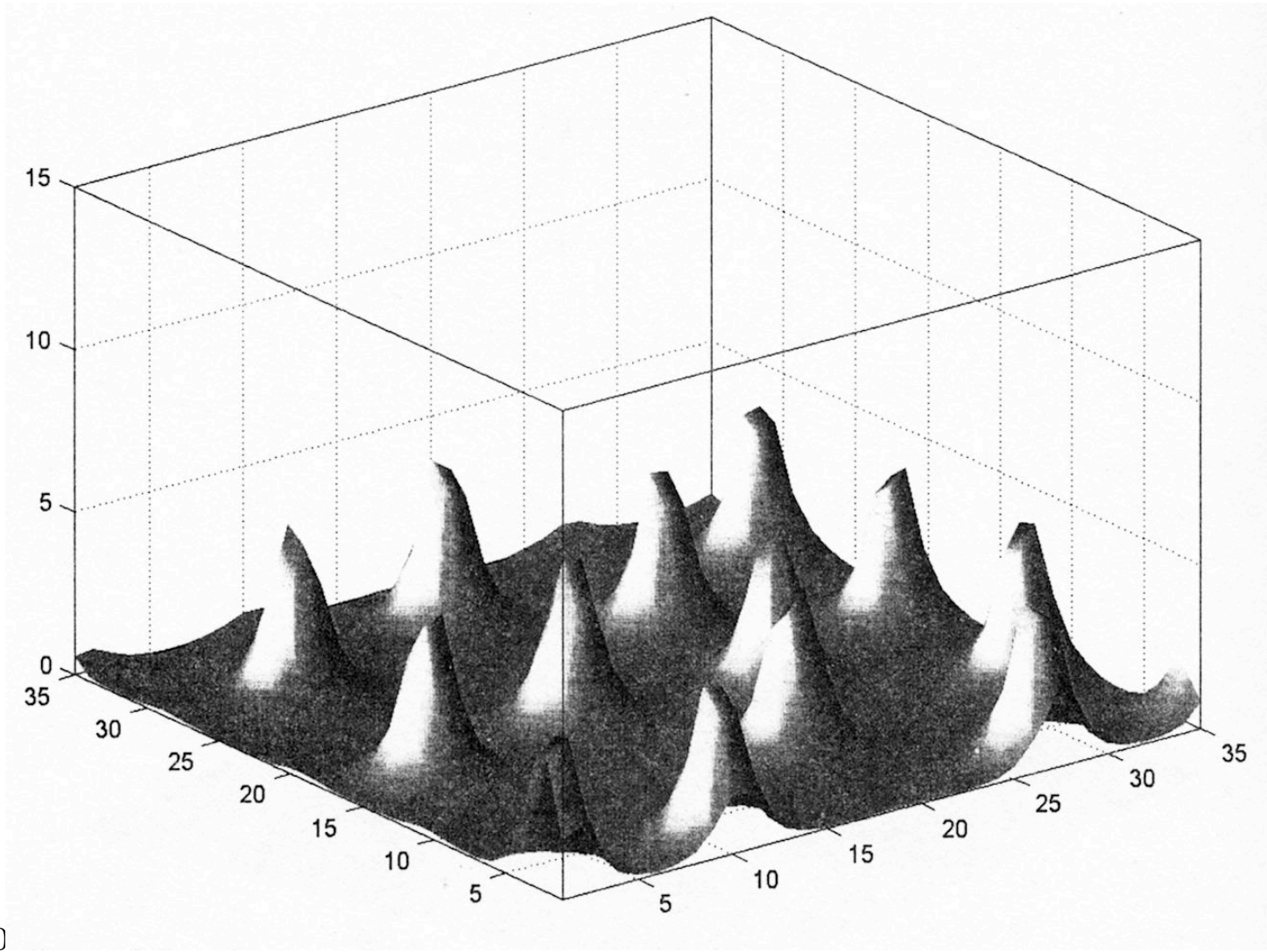
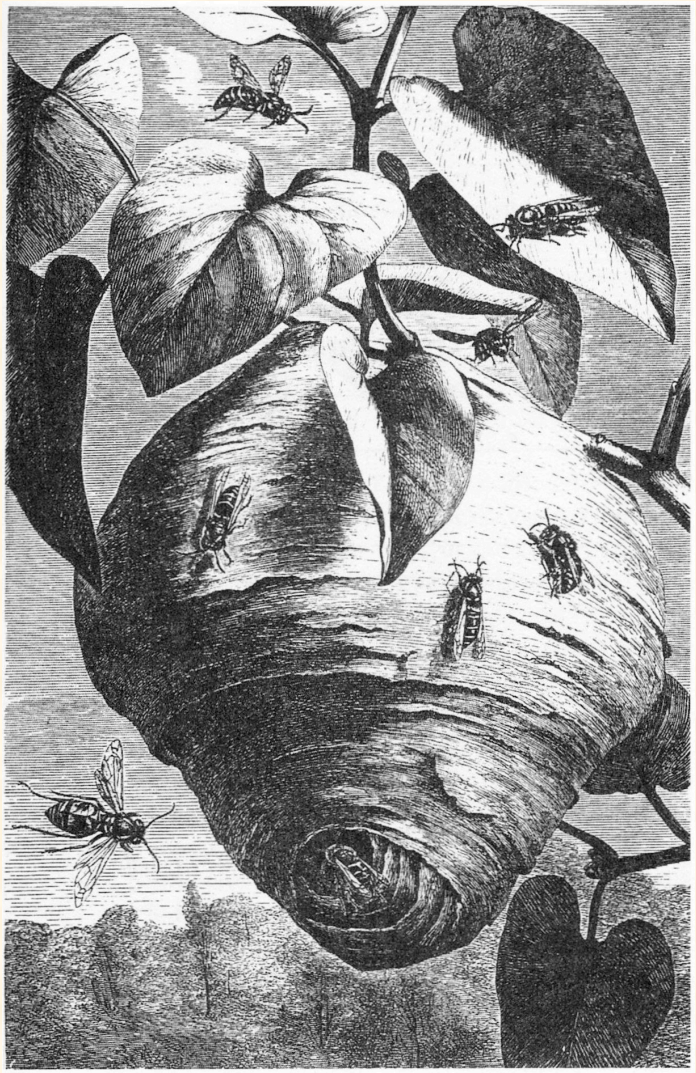


fig. from Solé & Goodwin

Conditions for Self-Organized Pillars

- Will not produce regularly spaced pillars if:
  - density of termites is too low
  - rate of deposition is too low
- A homogeneous stable state results

$$C_0 = \frac{\square}{k_1}, \qquad H_0 = \frac{\square}{k_4}, \qquad P_0 = \frac{\square}{k_2}$$



Wasp Nest Building and Discrete Stigmergy

Structure of Some Wasp Nests

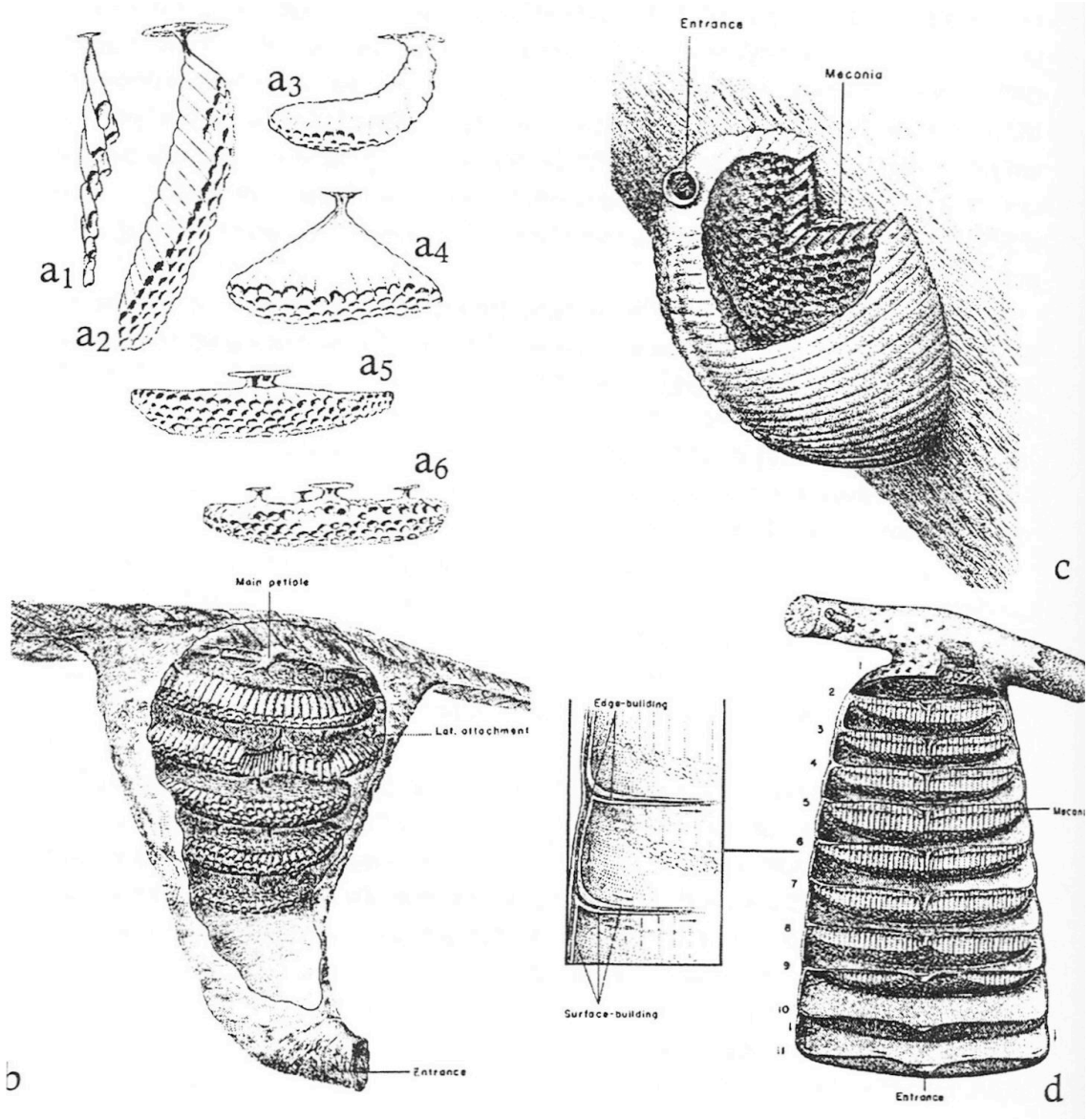
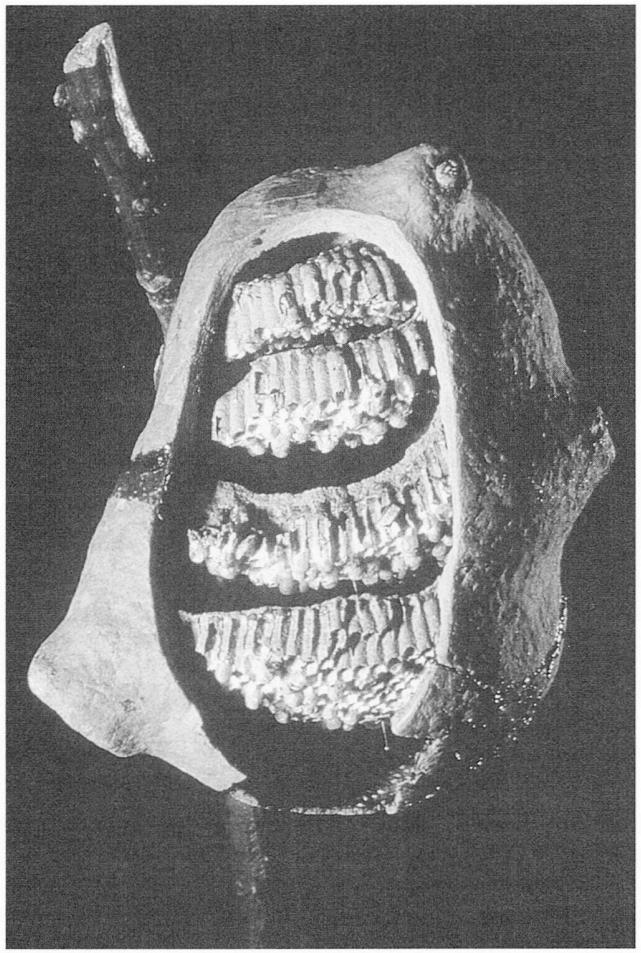
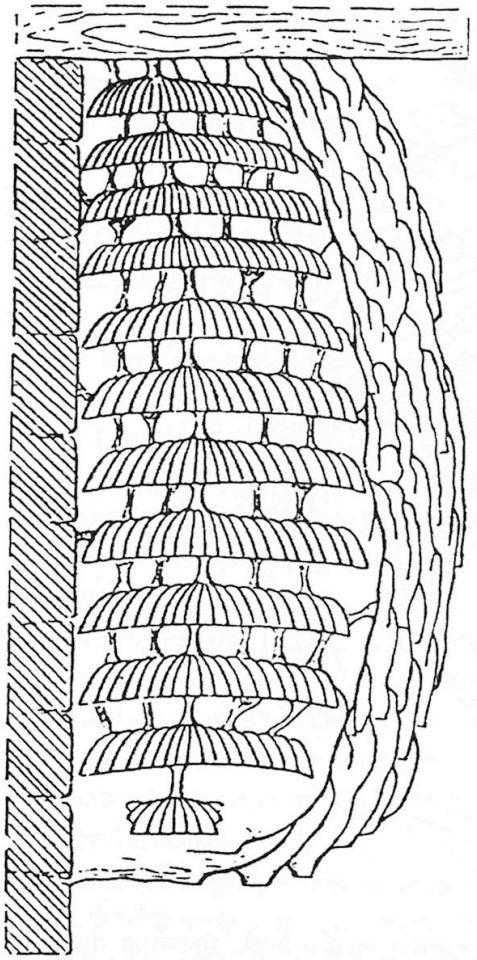


Fig. from *Self-Org. Biol. Sys.*

Adaptive Function of Nests



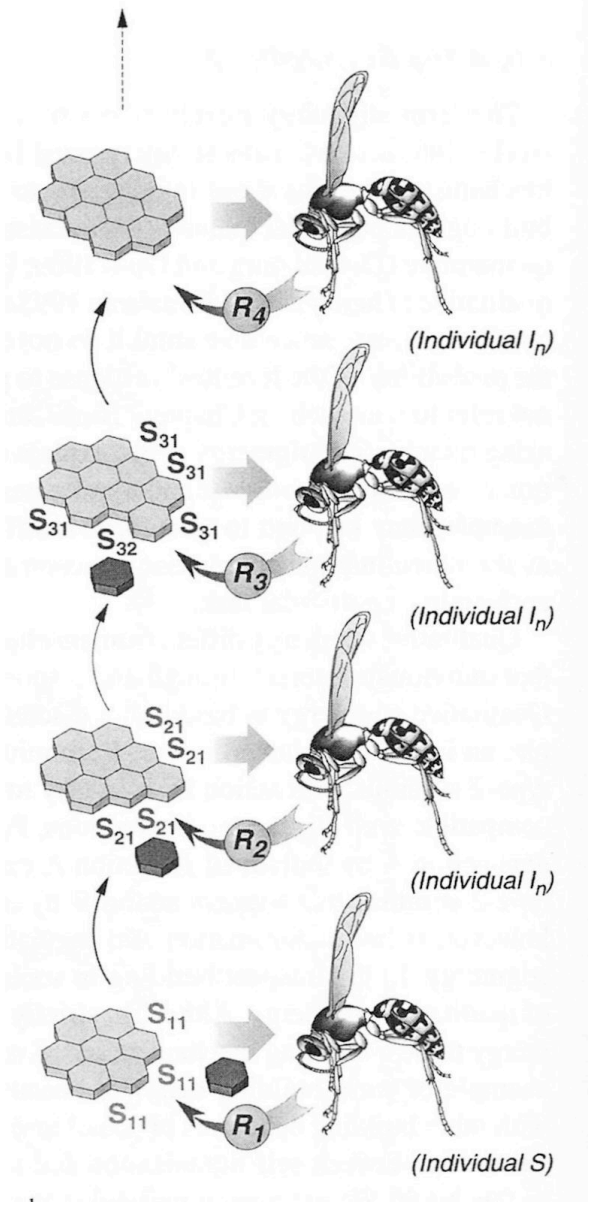


Lattice Swarms

(developed by Theraulaz & Bonabeau)

Discrete vs. Continuous Stigmergy

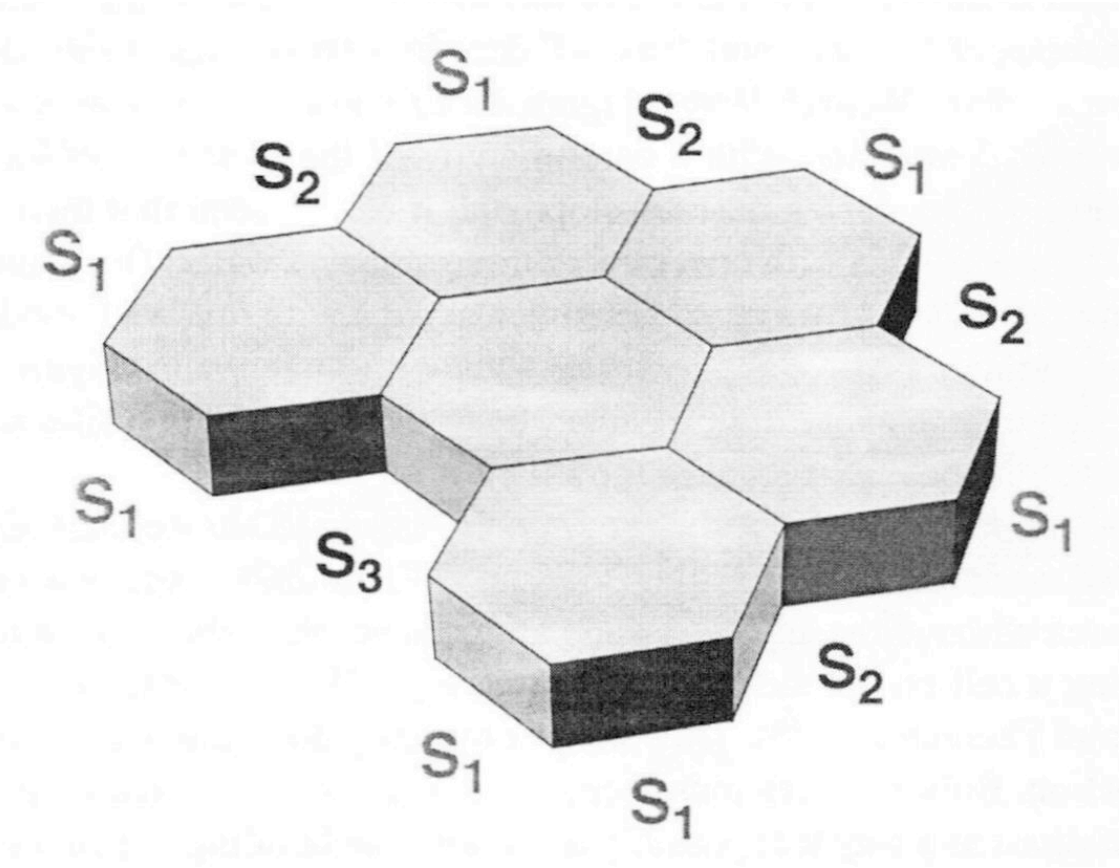
- Recall: *stigmergy* is the coordination of activities through the environment
- *Continuous* or *quantitative* stigmergy
  - quantitatively different stimuli trigger quantitatively different behaviors
- *Discrete* or *qualitative* stigmergy
  - stimuli are classified into distinct classes, which trigger distinct behaviors



Discrete Stigmergy in Comb Construction

- Initially all sites are equivalent
- After addition of cell, qualitatively different sites created

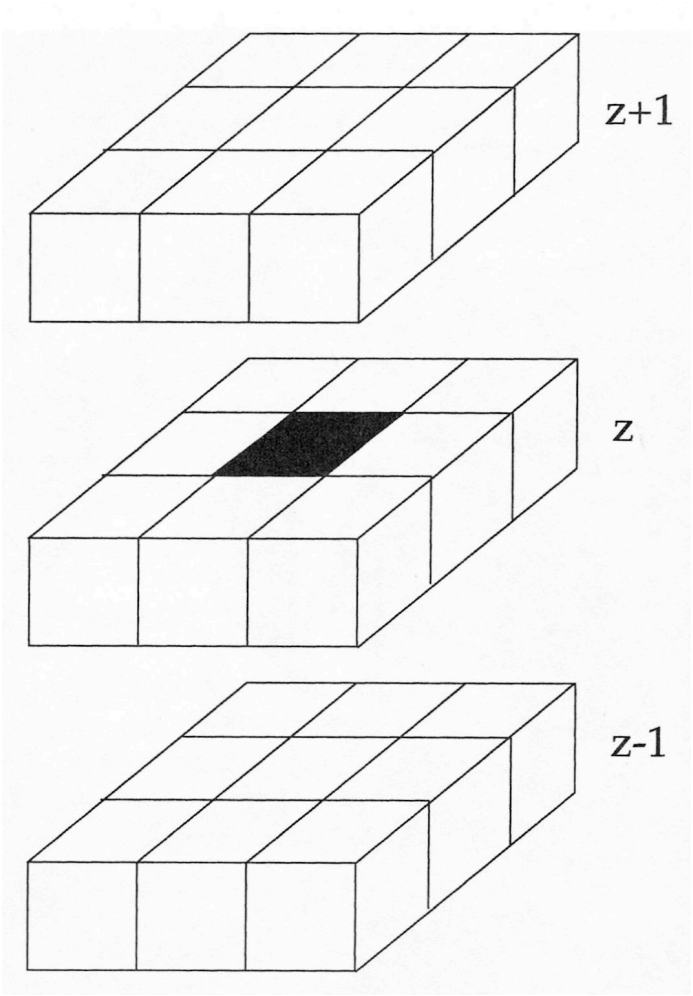
Numbers and Kinds of Building Sites



Lattice Swarm Model

- Random movement by wasps in a 3D lattice
  - cubic or hexagonal
- Wasps obey a 3D CA-like rule set
- Depending on configuration, wasp deposits one of several types of "bricks"
- Once deposited, it cannot be removed
- May be deterministic or probabilistic
- Start with a single brick

Cubic Neighborhood



- Deposited brick depends on states of 26 surrounding cells
- Configuration of sur-rounding cells may be represented by matrices:

$$\begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \bullet \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Hexagonal Neighborhood