Fairy Circles

Fairy Circles

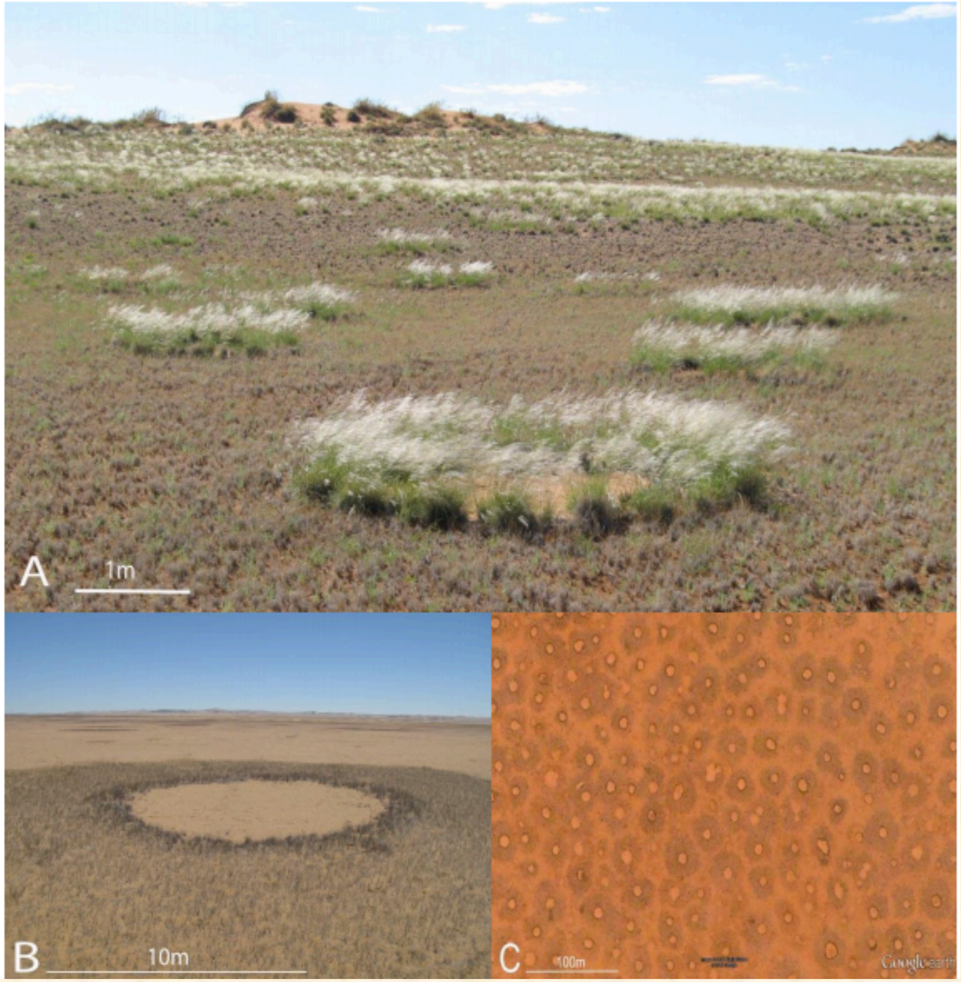
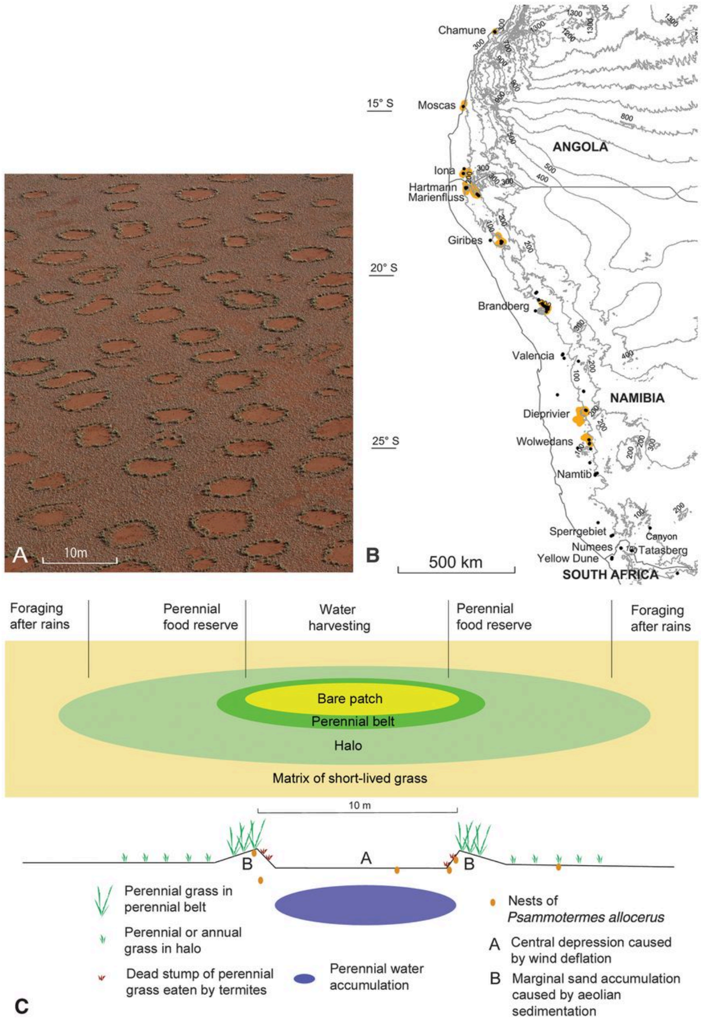


Fig. 1 (A) Spatial pattern of FCs. (B) Geographical distribution of FCs (black dots) and hotspots of FC occurrences at wider landscape scale (yellow clusters).



N Juergens Science 2013;339:1618-1621

Published by AAAS

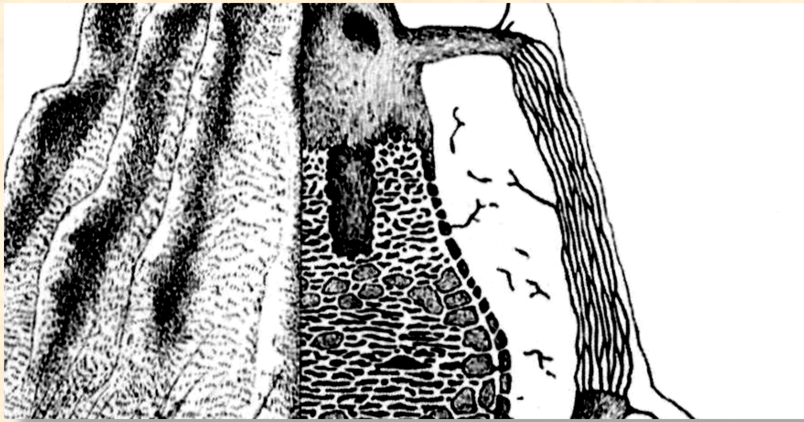
Part C

Nest Building

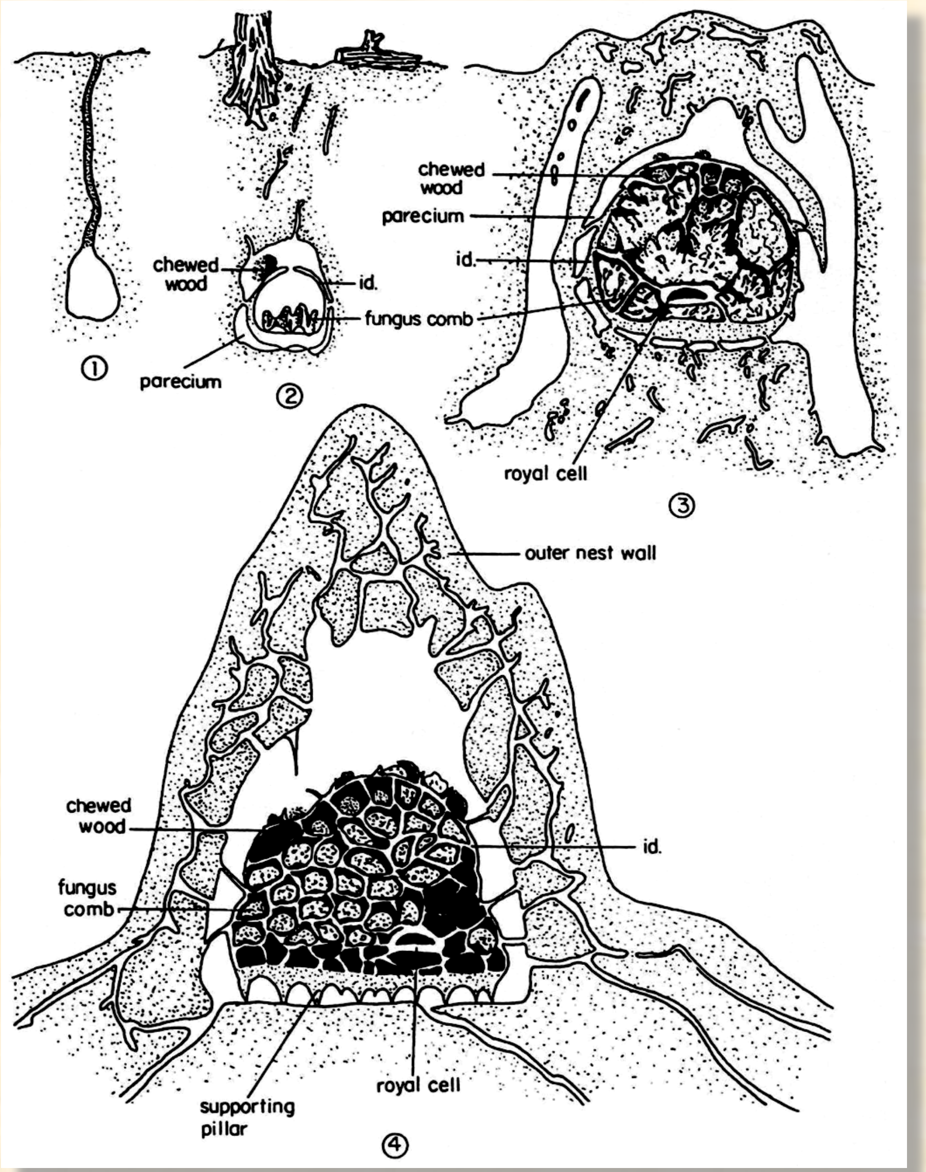
Nest Building by Termites (Natural and Artificial)

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

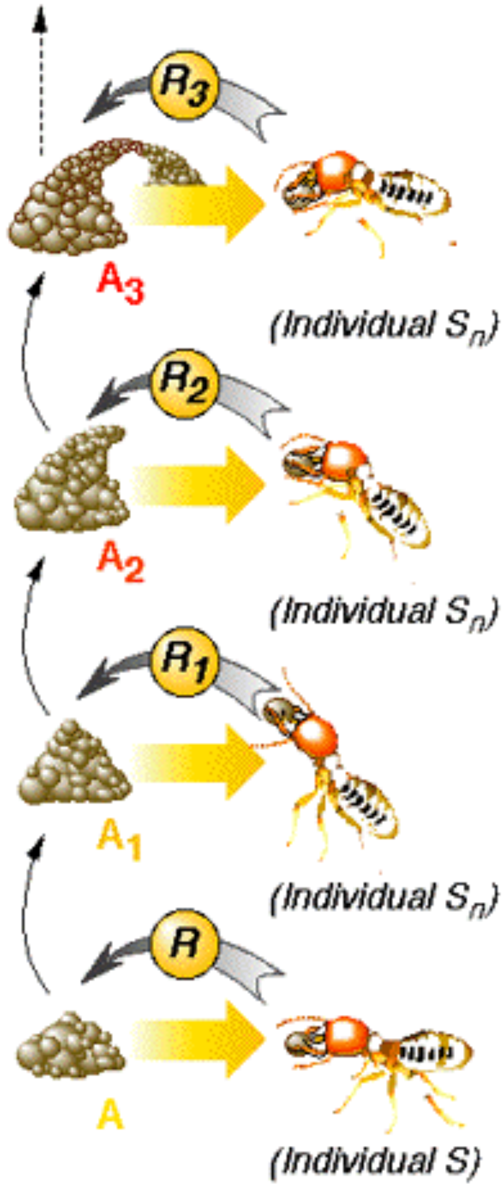
(4) Fully developed nest

Fig. from Wilson (1971)

Termite Nests

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

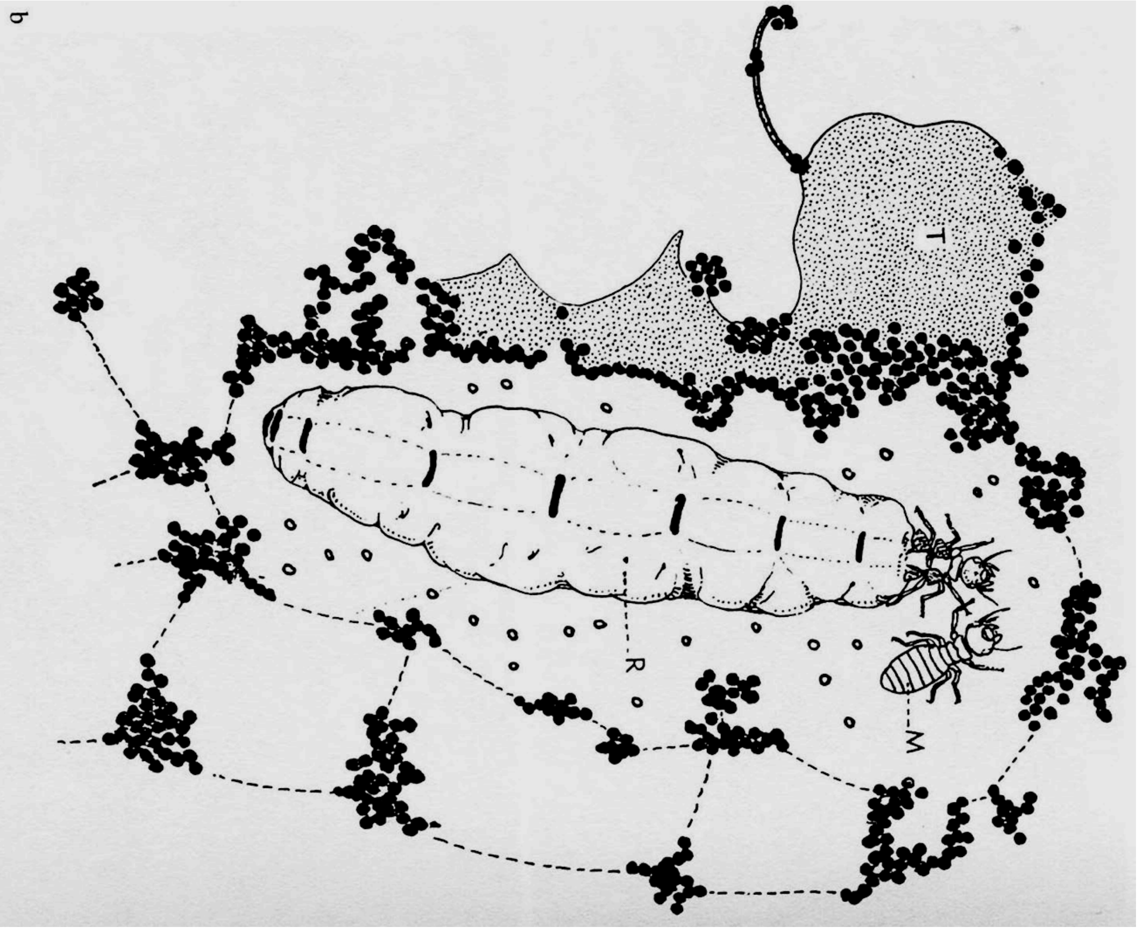


Basic Mechanism of Construction (Stigmergy)

- 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

Fig. from Solé & Goodwin

Construction of Royal Chamber



Construction of Arch (1)

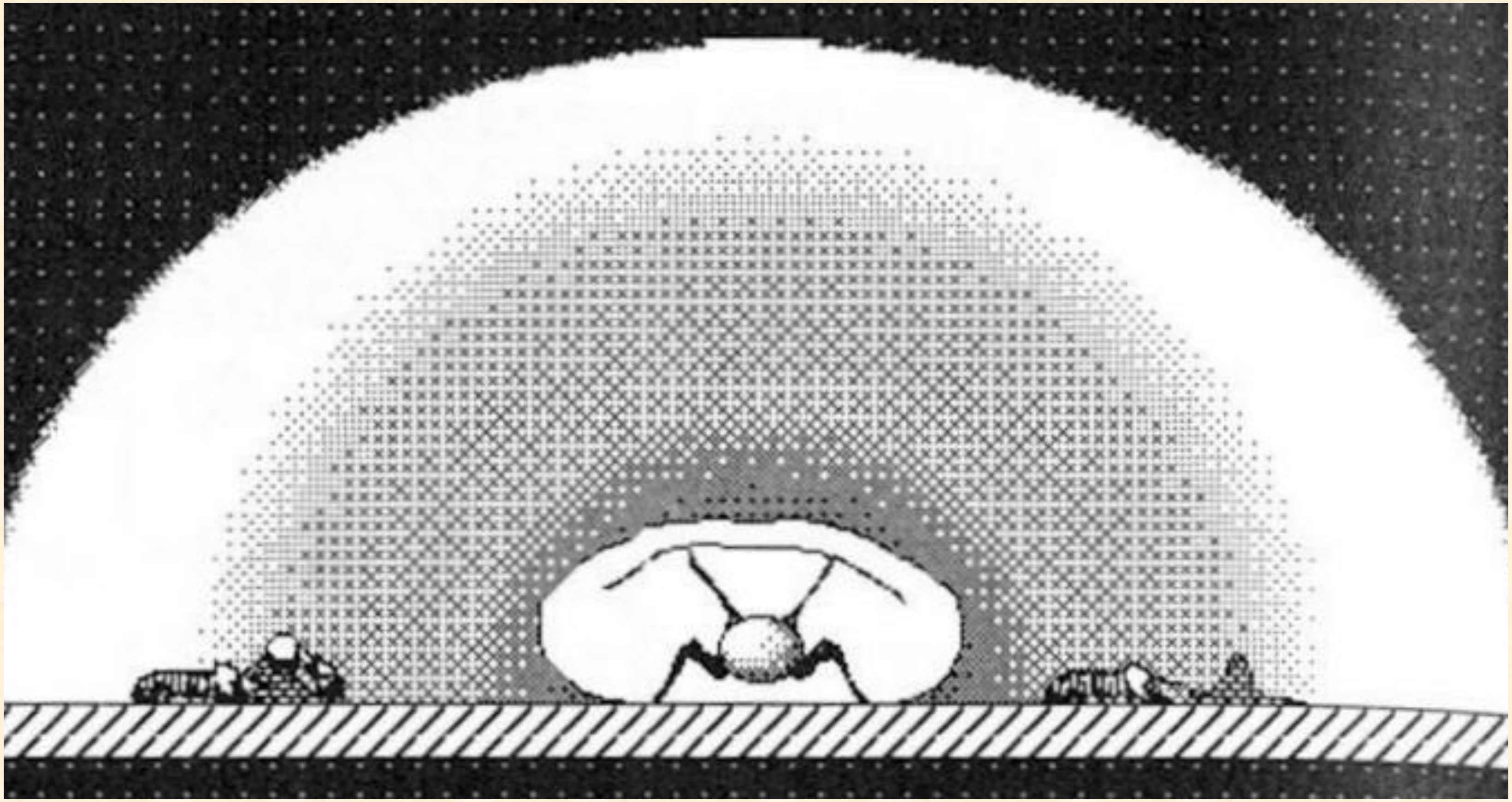


Fig. from Bonabeau, Dorigo & Theraulaz

Construction of Arch (2)

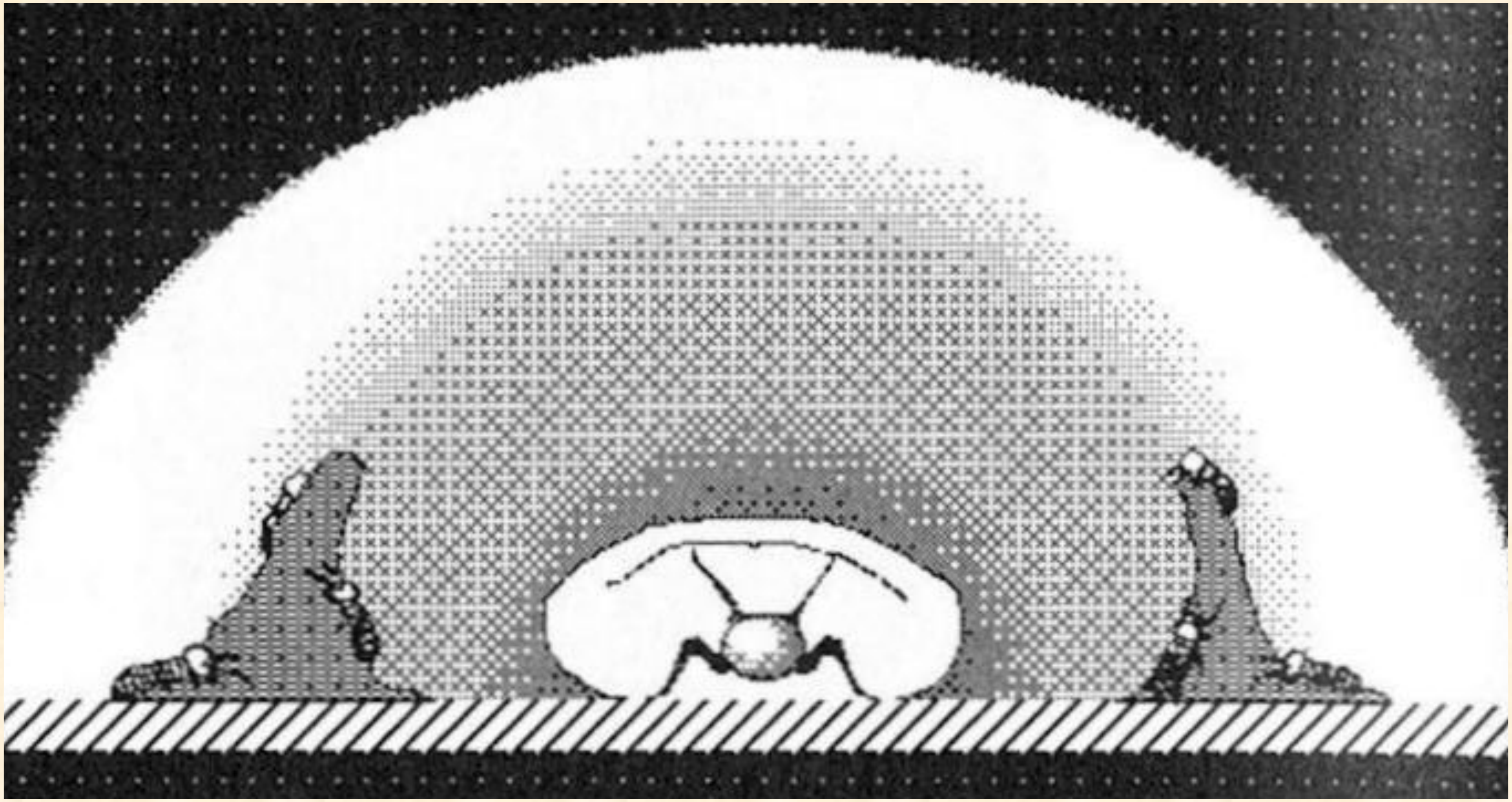


Fig. from Bonabeau, Dorigo & Theraulaz

Construction of Arch (3)

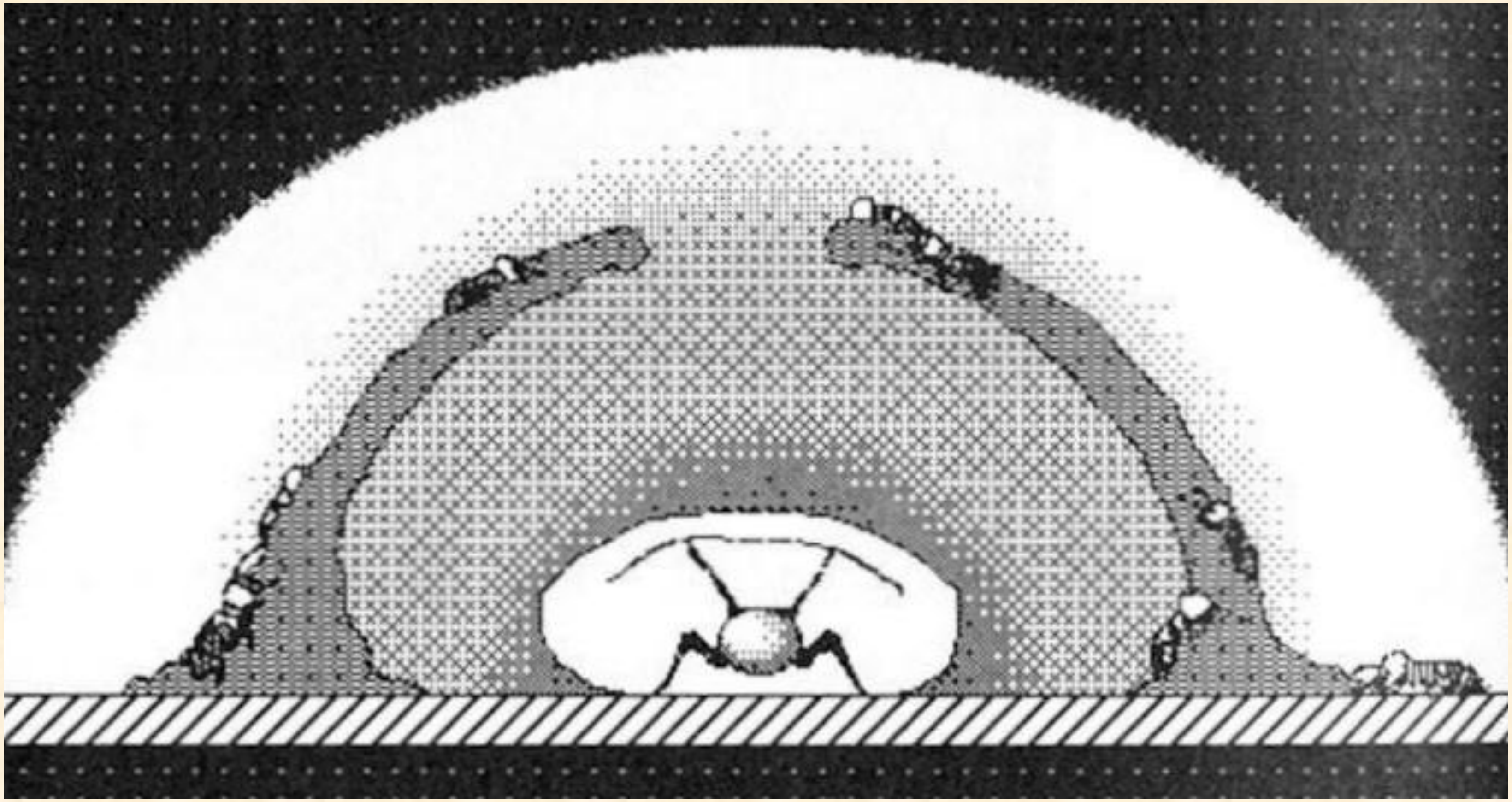


Fig. from Bonabeau, Dorigo & Theraulaz

Basic Principles

- Continuous (quantitative) stigmergy
- Positive feedback:
  - via pheromone deposition
- Negative feedback:
  - depletion of soil granules & competition between pillars
  - pheromone decay

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
- Φ = 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)

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

Equation for C
(Density of Laden Termites)

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

Φ (flux of laden termites)

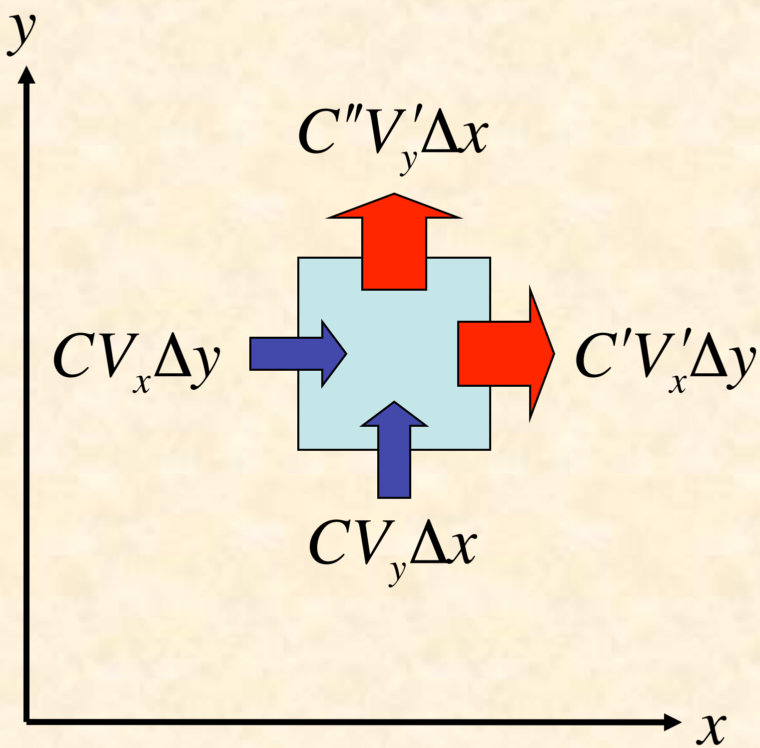
$- k_1 C$ (unloading of termites)

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

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

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

Explanation of Divergence



- velocity field = $\mathbf{V}(x,y)$ $= \mathbf{i}V_x(x,y) + \mathbf{j}V_y(x,y)$
- $C(x,y)$ = density
- outflow rate = $\Delta_x(CV_x)\,\Delta y + \Delta_y(CV_y)\,\Delta x$
- outflow rate / unit area

$$= \frac{\Delta_x\left(CV_x\right)}{\Delta x} + \frac{\Delta_y\left(CV_y\right)}{\Delta y}$$

$$\rightarrow \frac{\partial\left(CV_x\right)}{\partial x} + \frac{\partial\left(CV_y\right)}{\partial y} = \nabla \cdot C\mathbf{V}$$

Explanation of Chemotaxis Term

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

  $-\nabla \cdot \mathbf{J} = -(\partial J_x / \partial x + \partial J_y / \partial y)$
- The flux velocity is proportional to the pheromone gradient

  $\mathbf{J} \propto \nabla H$
- The flux density is proportional to the number of moving termites

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

Simulation ($T = 0$)

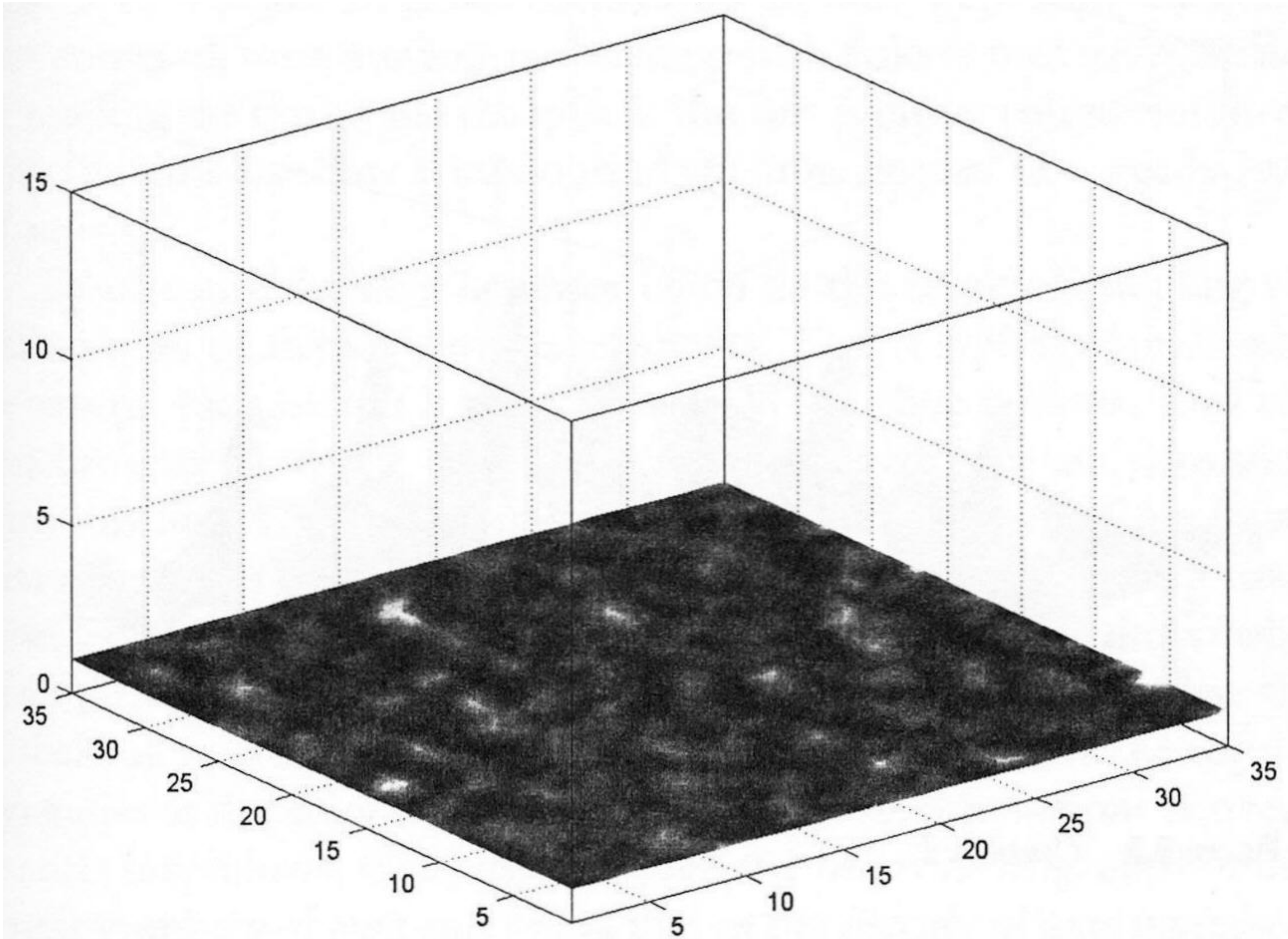


fig. from Solé & Goodwin

Simulation (T = 100)

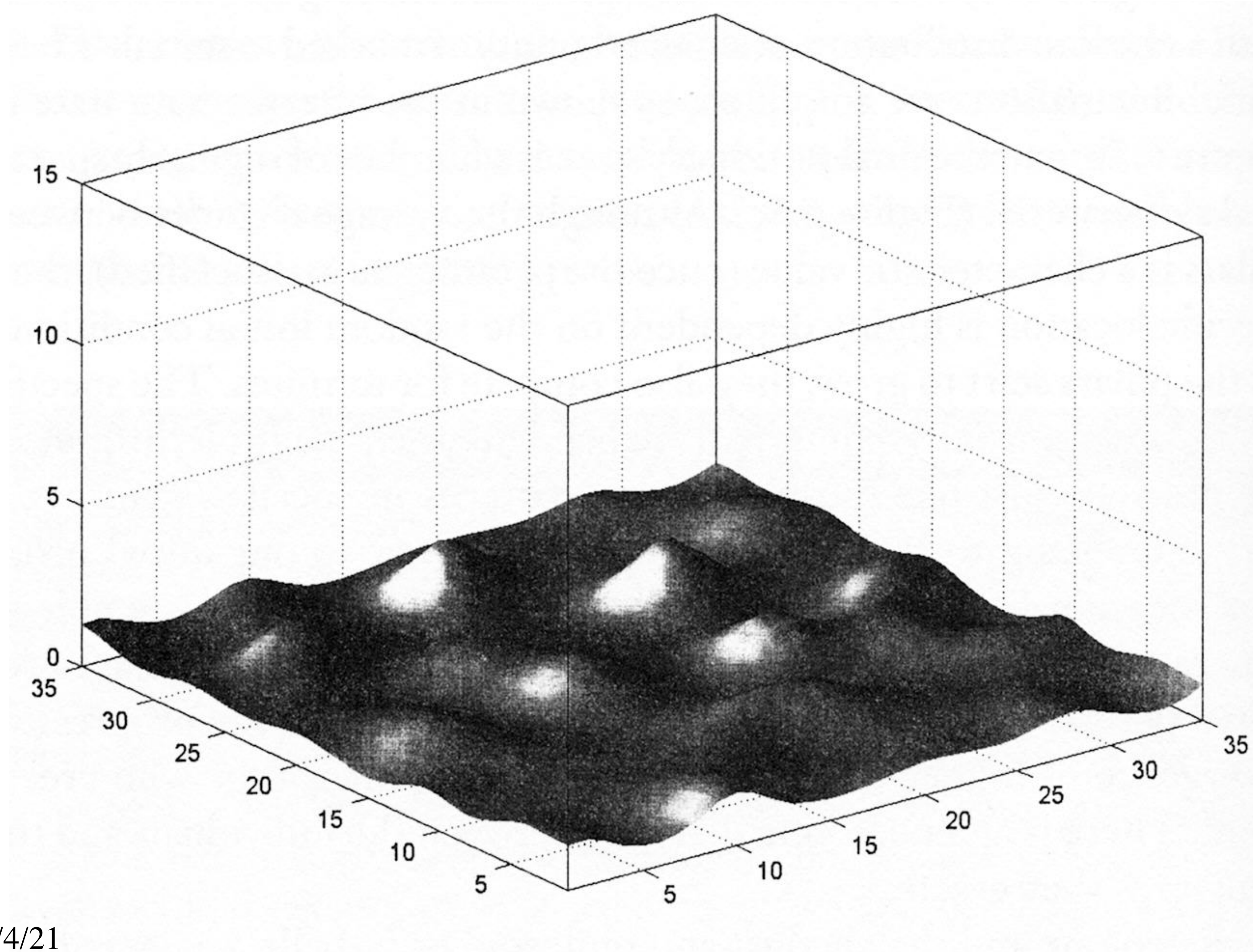


fig. from Solé & Goodwin

Simulation (T = 1000)

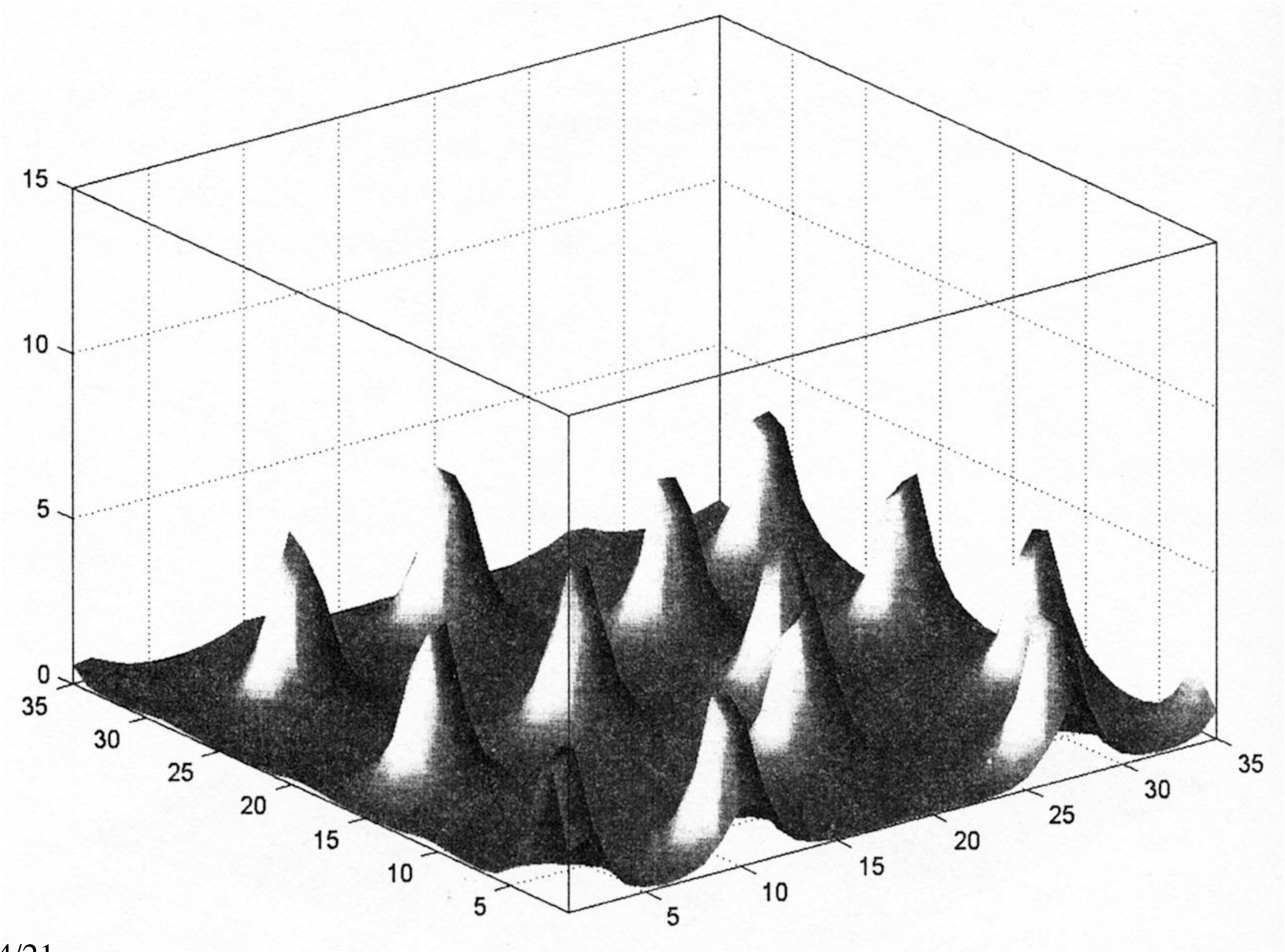


fig. from Solé & Goodwin

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

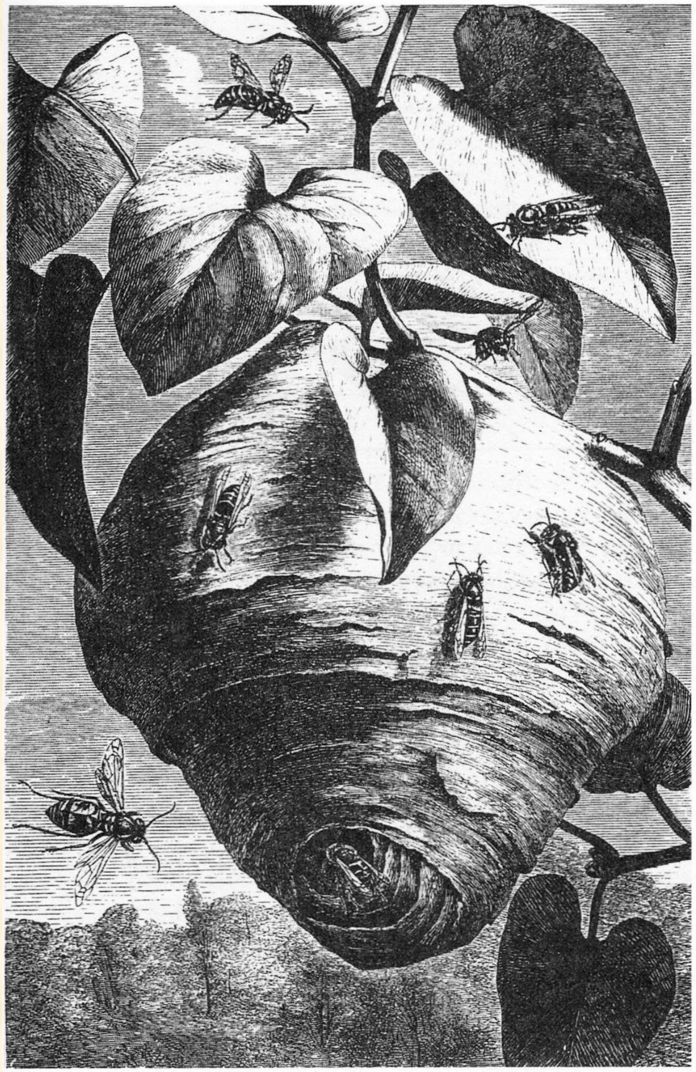
$$C_0 = \frac{\Phi}{k_1}, \qquad H_0 = \frac{\Phi}{k_4}, \qquad P_0 = \frac{\Phi}{k_2}$$

NetLogo Simulation of Deneubourg Model

Run Pillars3D.nlogo

Interaction of Three Pheromones

- Queen pheromone governs size and shape of queen chamber (template)
- Cement pheromone governs construction and spacing of pillars & arches (stigmergy)
- Trail pheromone:
  - attracts workers to construction sites (stigmergy)
  - encourages soil pickup (stigmergy)
  - governs sizes of galleries (template)



Wasp Nest Building and Discrete Stigmergy

Fig. from Solé & Goodwin

Structure of Some Wasp Nests

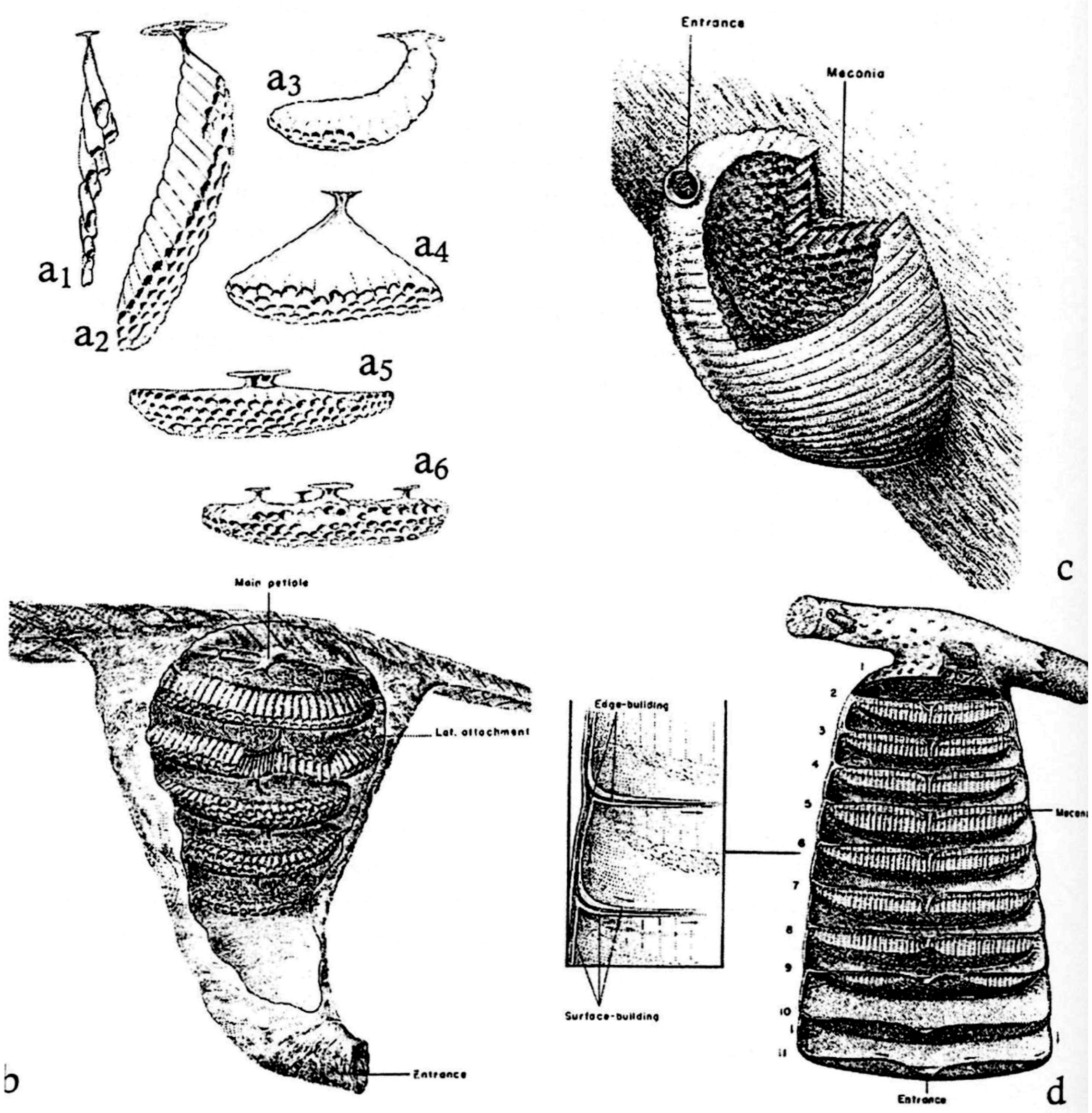
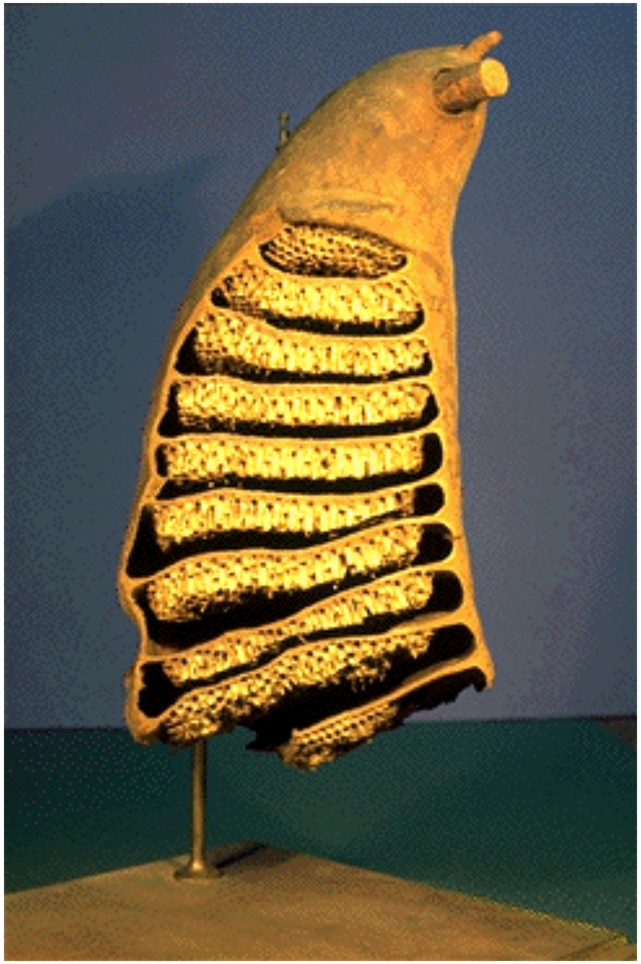
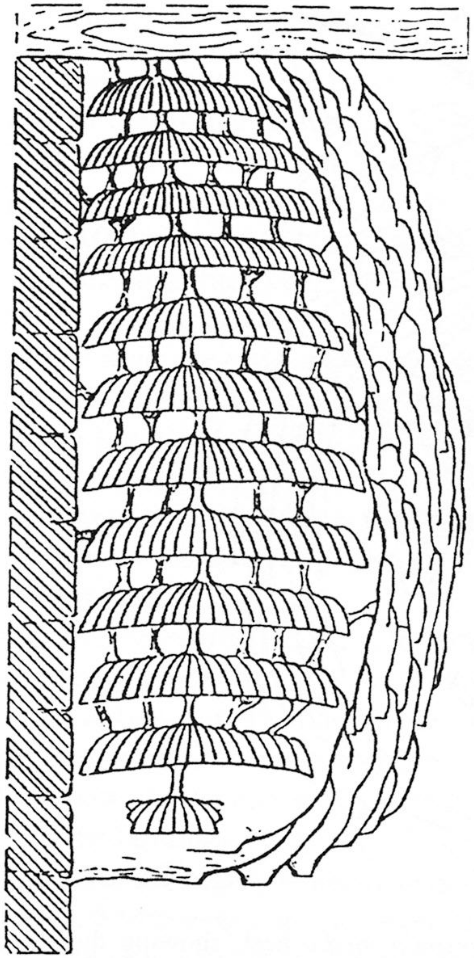


Fig. from *Self-Org. Biol. Sys.*

Adaptive Function of Nests





Figs. from Self-Org. Biol. Sys,

How Do They Do It?

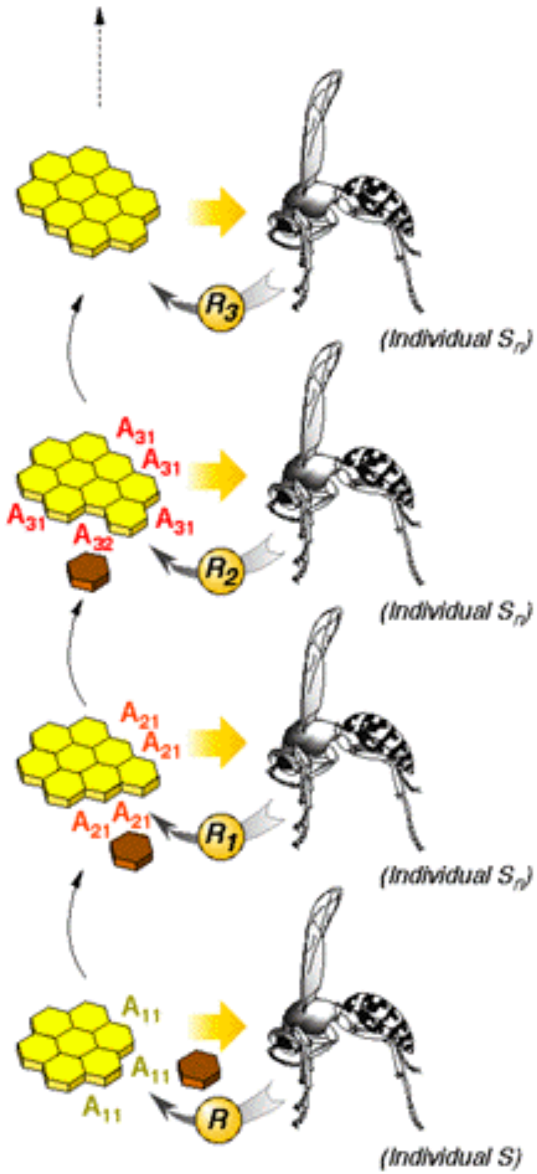
Lattice Swarms

(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

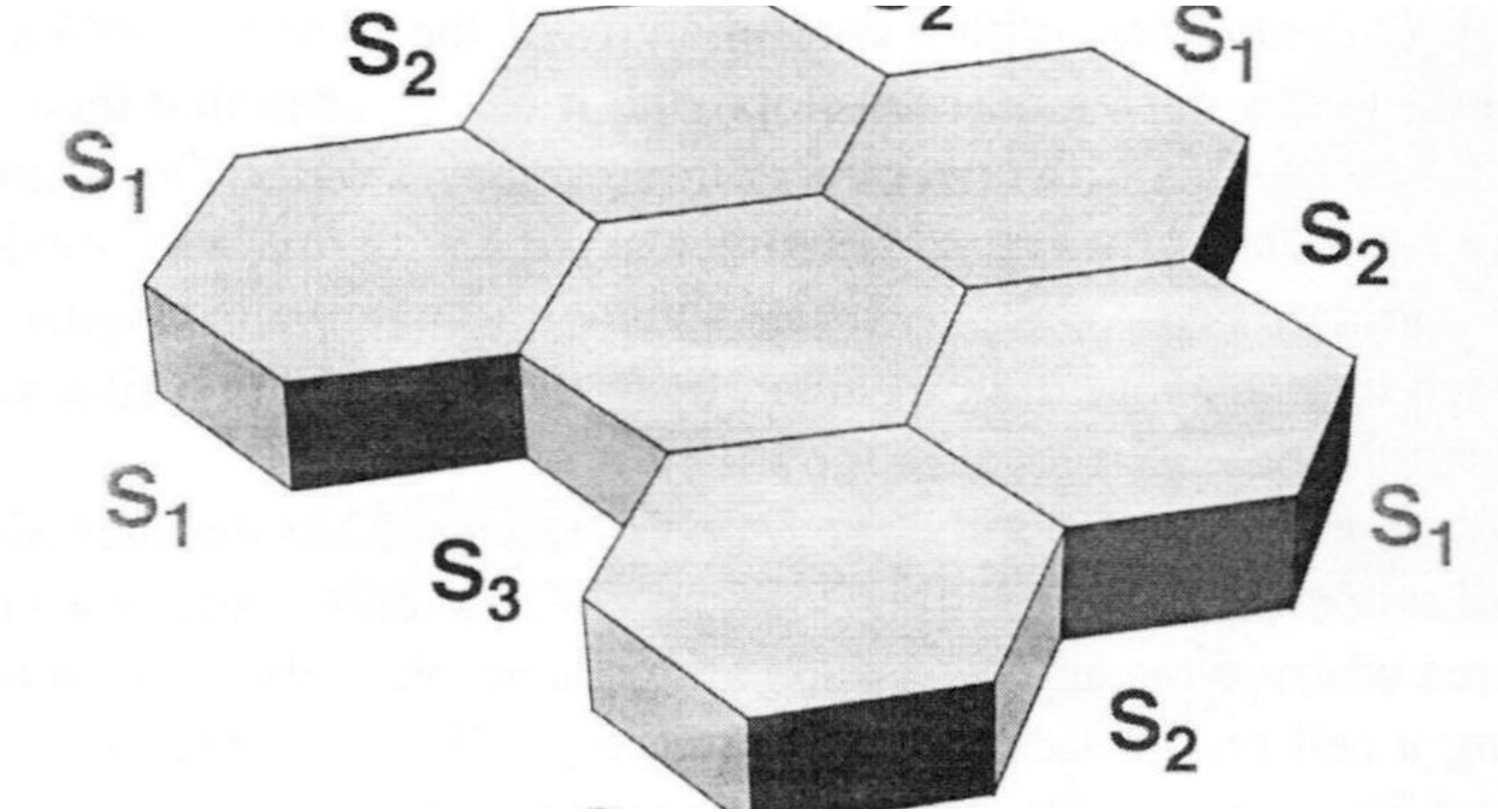
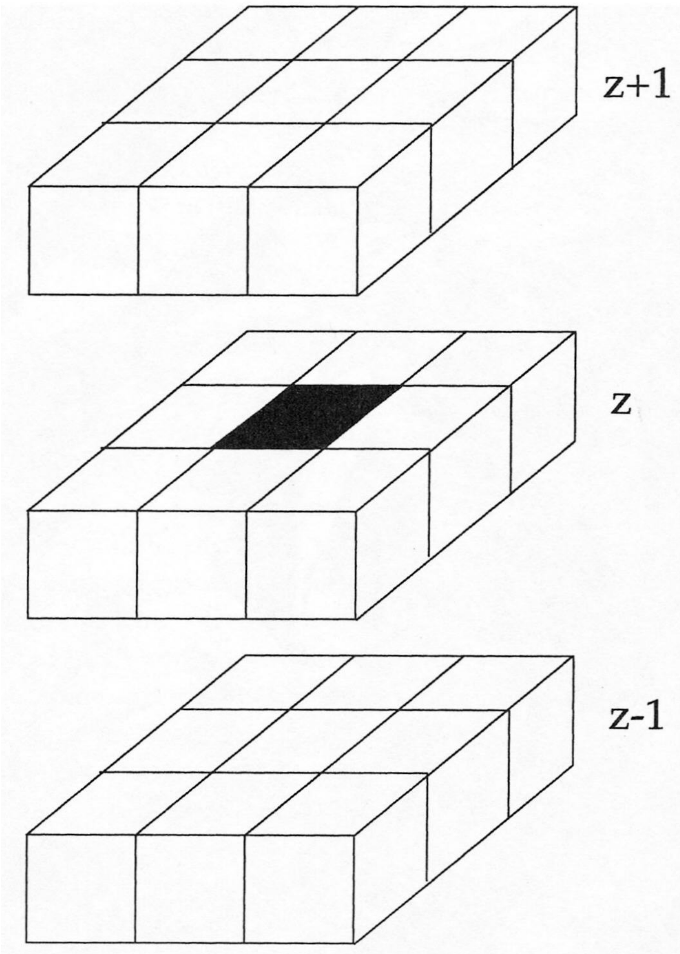


Fig. from *Self-Org. Biol. Sys.*

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 surrounding cells may be represented by matrices:

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

Hexagonal Neighborhood

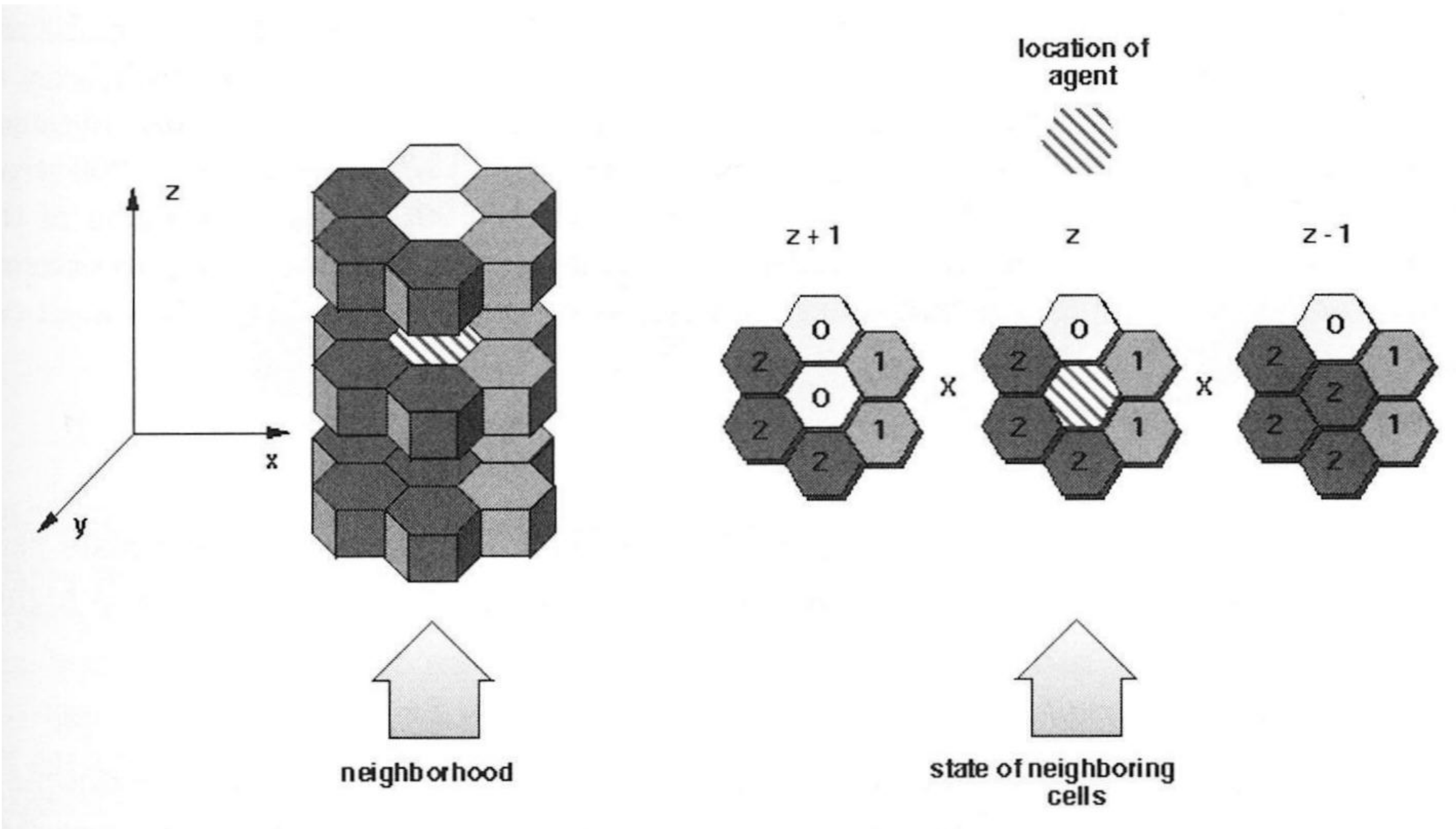


Fig. from Bonabeau, Dorigo & Theraulaz

Example Construction

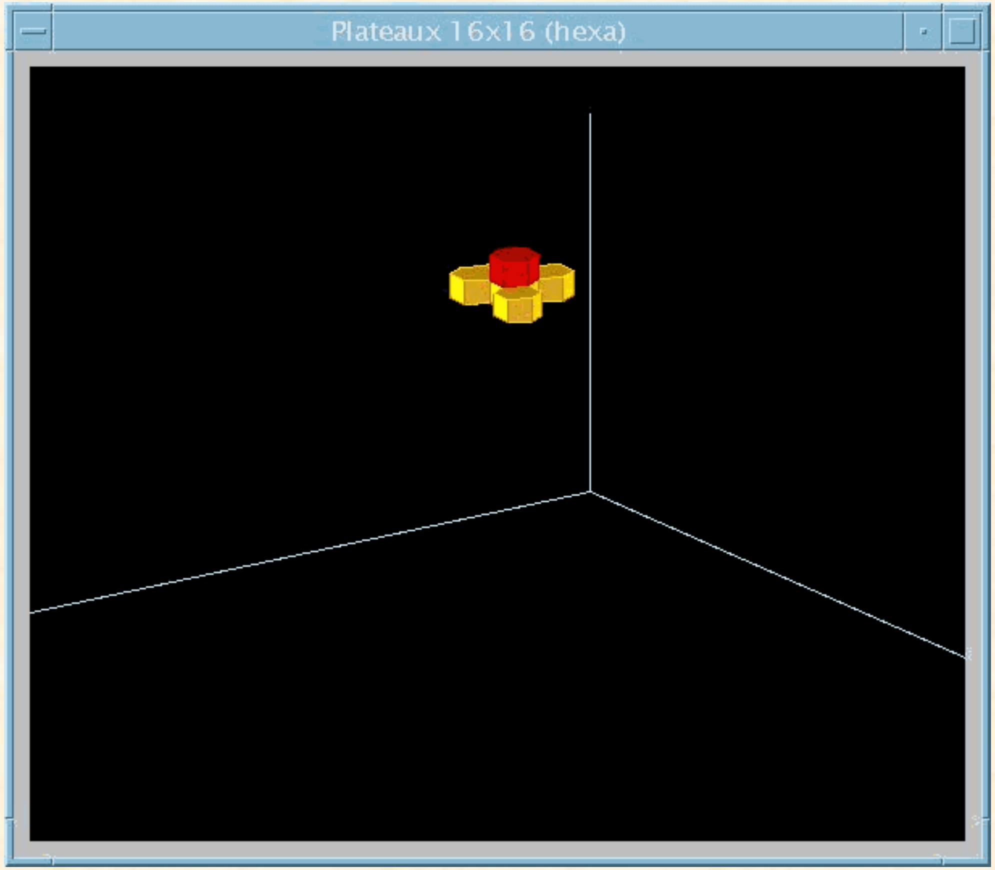


Fig. from IASC Dept., ENST de Bretagne.

Another Example

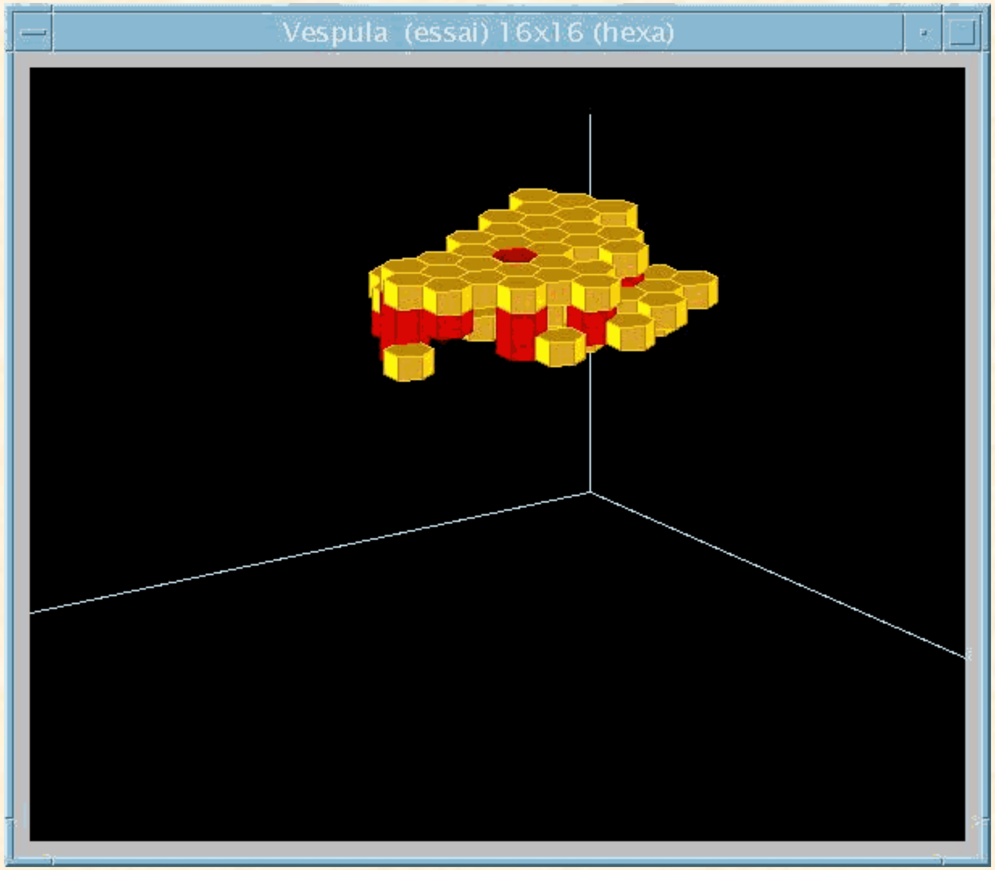


fig. from IASC Dept., ENST de Bretagne.

A Simple Pair of Rules

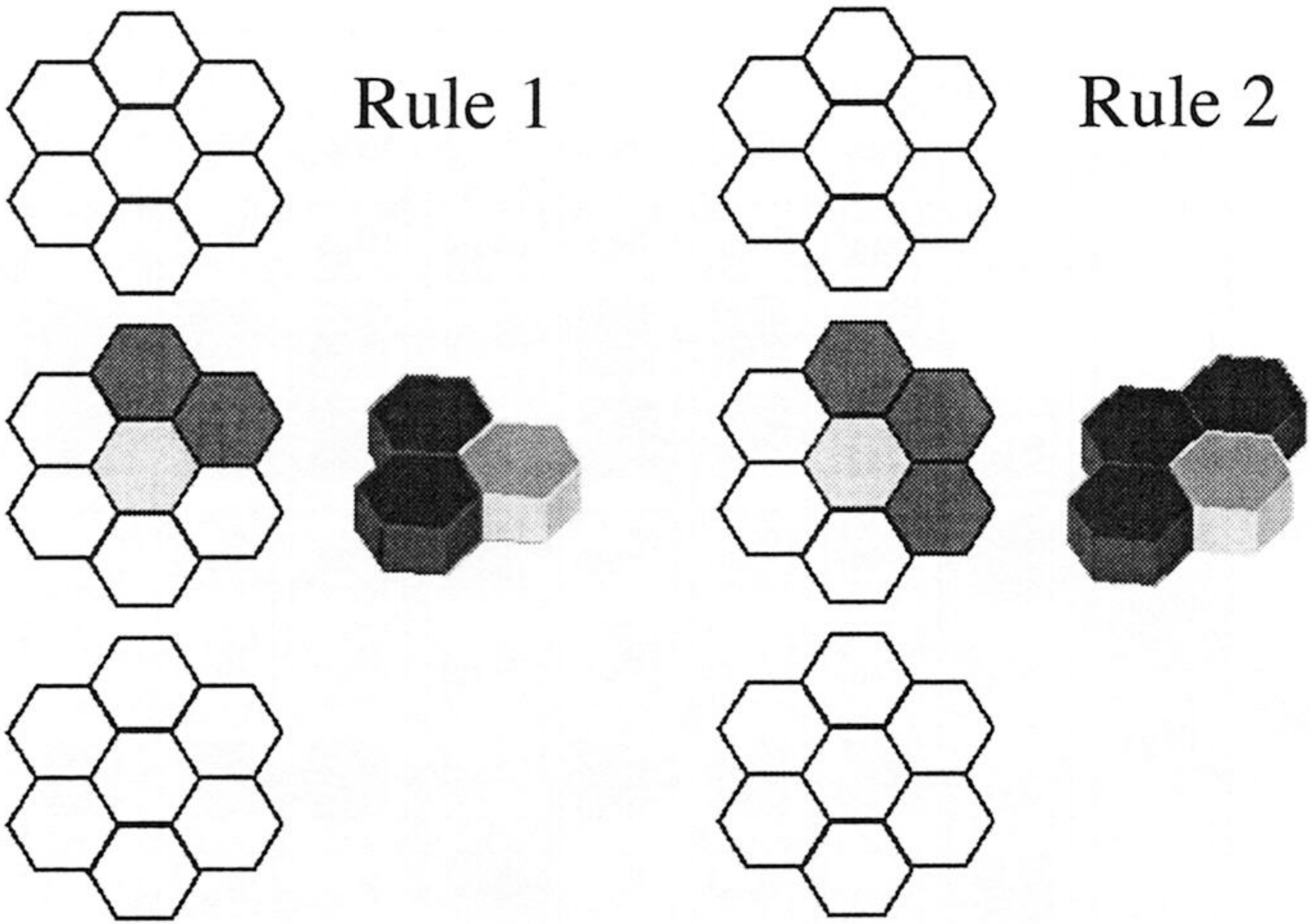


Fig. from *Self-Org. in Biol. Sys.*

Result from Deterministic Rules

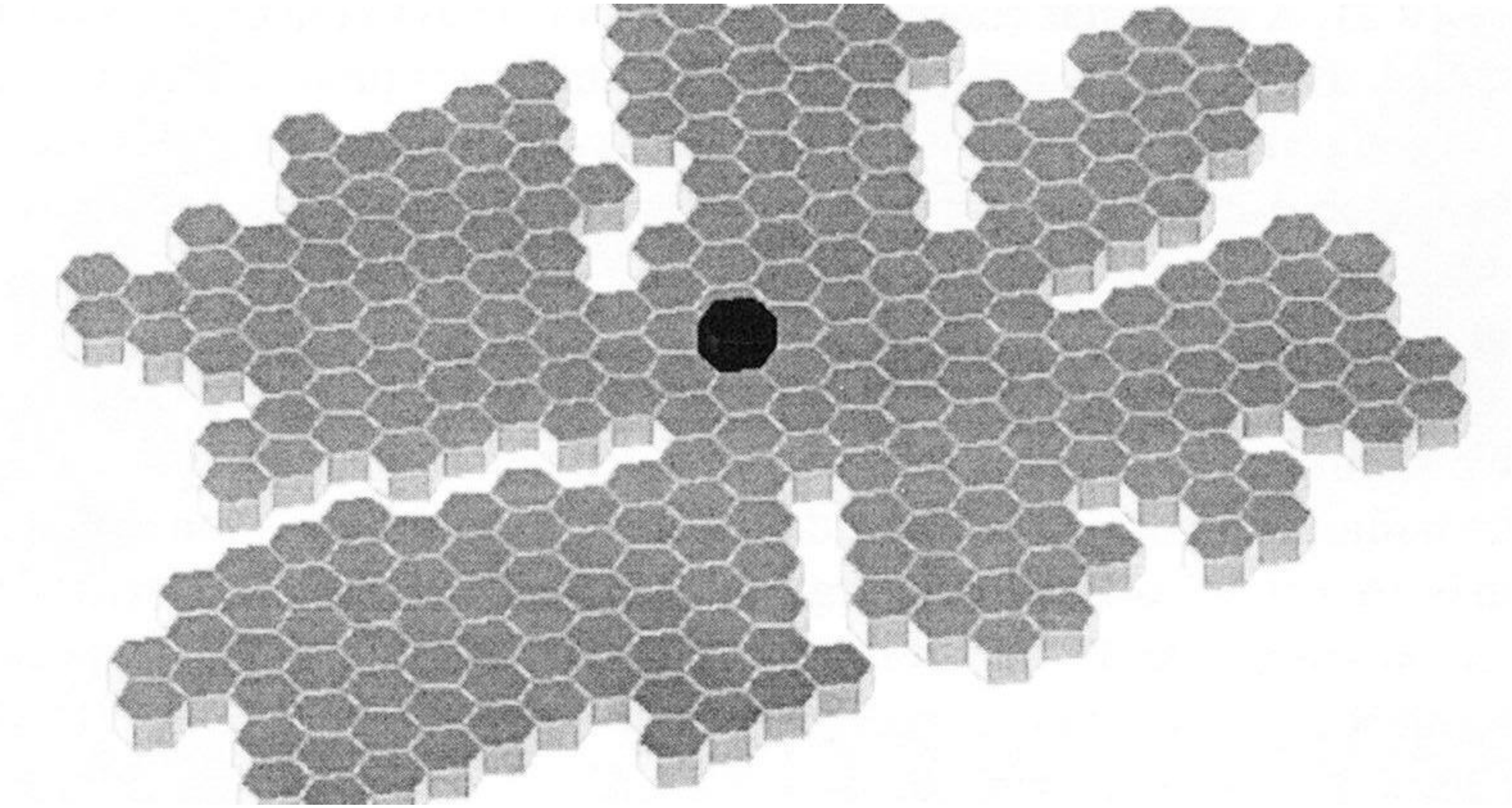


Fig. from *Self-Org. in Biol. Sys.*

Result from Probabilistic Rules

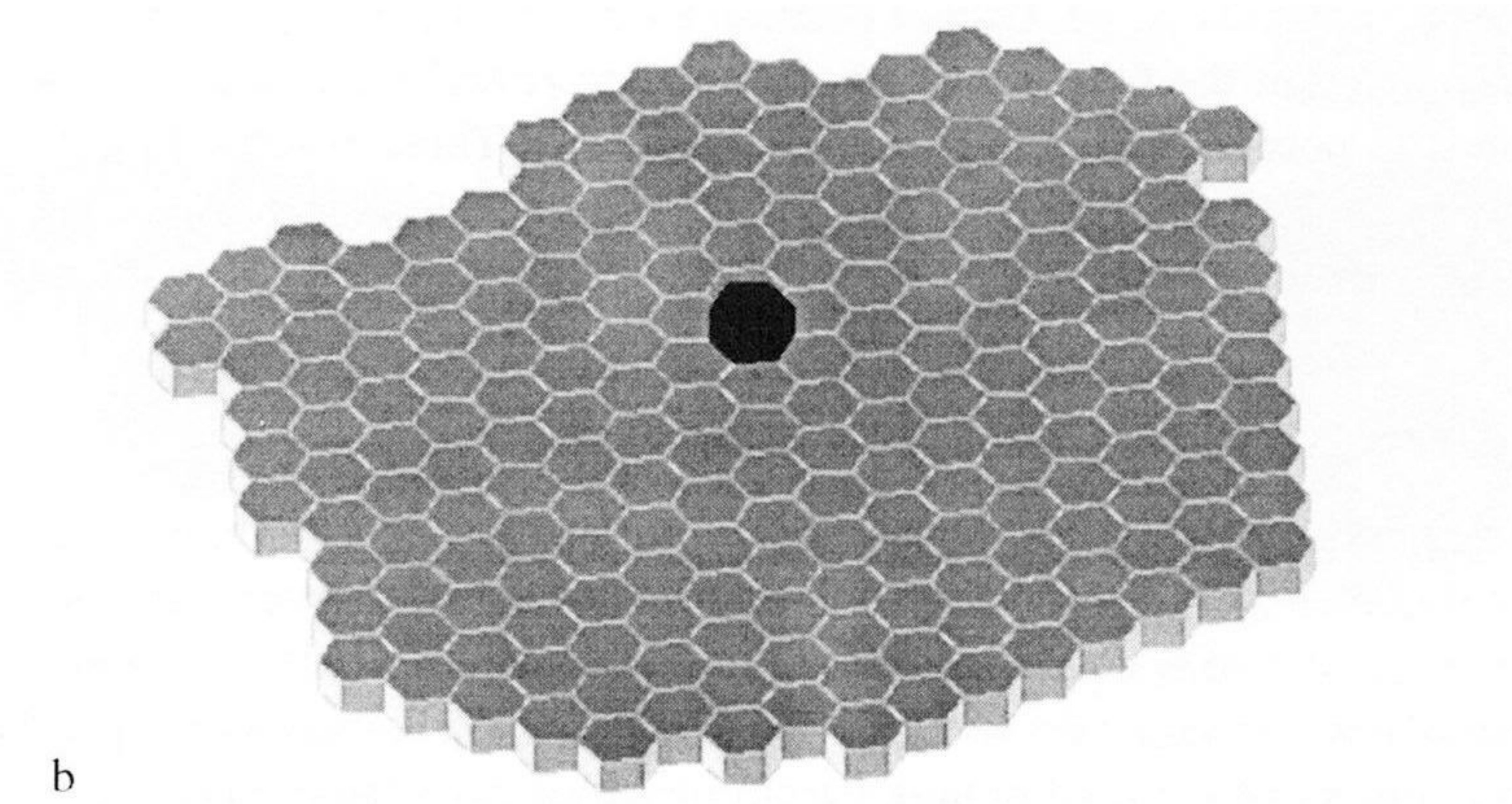


Fig. from *Self-Org. in Biol. Sys.*

Example Rules for a More Complex Architecture

The following stimulus configurations cause the agent to deposit a type-1 brick:

$$(1.1)\quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 0 & \bullet & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$(1.2)\quad \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 1 & \bullet & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Second Group of Rules

B

$$(2.1)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\1&\bullet&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.2)\ \begin{bmatrix}1&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}1&2&0\\0&\bullet&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}1&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.3)\ \begin{bmatrix}0&0&0\\0&0&0\\1&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&\bullet&0\\1&2&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\1&0&0\end{bmatrix}$$

$$(2.4)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}2&0&0\\2&\bullet&0\\2&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.5)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\2&\bullet&0\\2&2&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.6)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}2&2&0\\2&\bullet&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.7)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}2&2&2\\0&\bullet&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.8)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&\bullet&0\\2&2&2\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.9)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}1&2&0\\0&\bullet&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.10)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&\bullet&0\\1&2&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.11)^*\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}2&2&0\\2&\bullet&0\\2&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.12)^*\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&2&2\\0&\bullet&2\\0&0&2\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.13)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}2&2&2\\2&\bullet&2\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.14)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}2&2&0\\2&\bullet&0\\2&2&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.15)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\2&\bullet&2\\2&2&2\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.16)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&2&2\\0&\bullet&2\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.17)\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&\bullet&2\\0&2&2\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$(2.18)^*\ \begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}\times\begin{bmatrix}2&0&0\\2&\bullet&0\\2&2&2\end{bmatrix}\times\begin{bmatrix}0&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

For these configurations, deposit a type-2 brick

Result

- 20×20×20 lattice
- 10 wasps
- After 20 000 simulation steps
- Axis and plateaus
- Resembles nest of *Parachartergus*

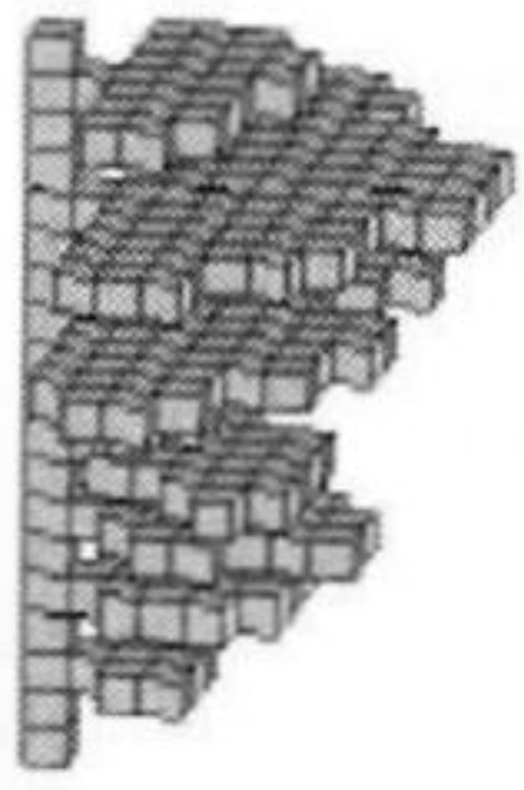


Fig. from Bonabeau & al., *Swarm Intell*.

Architectures Generated from Other Rule Sets

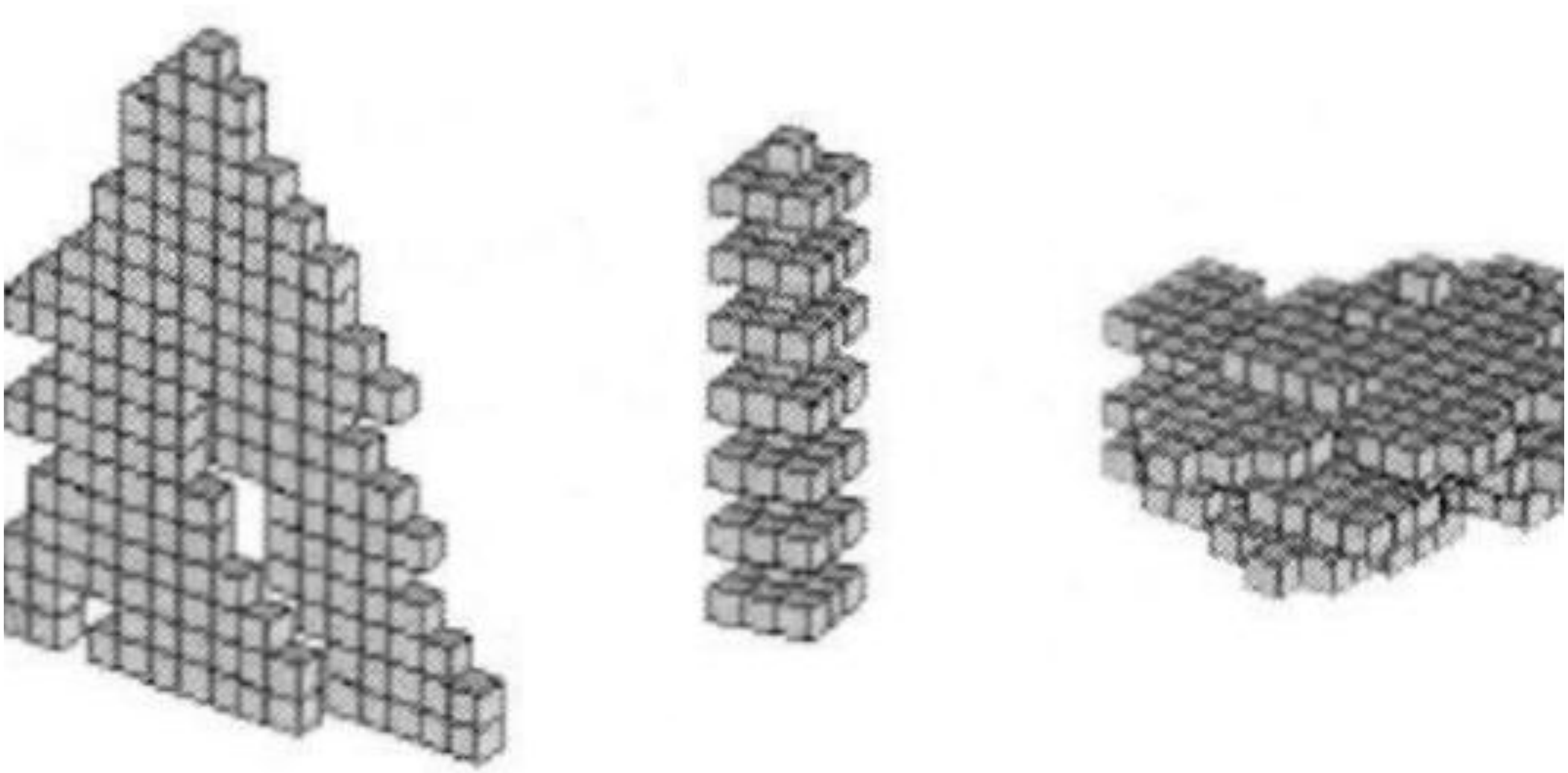


Fig. from Bonabeau & al., *Swarm Intell*.

More Cubic Examples

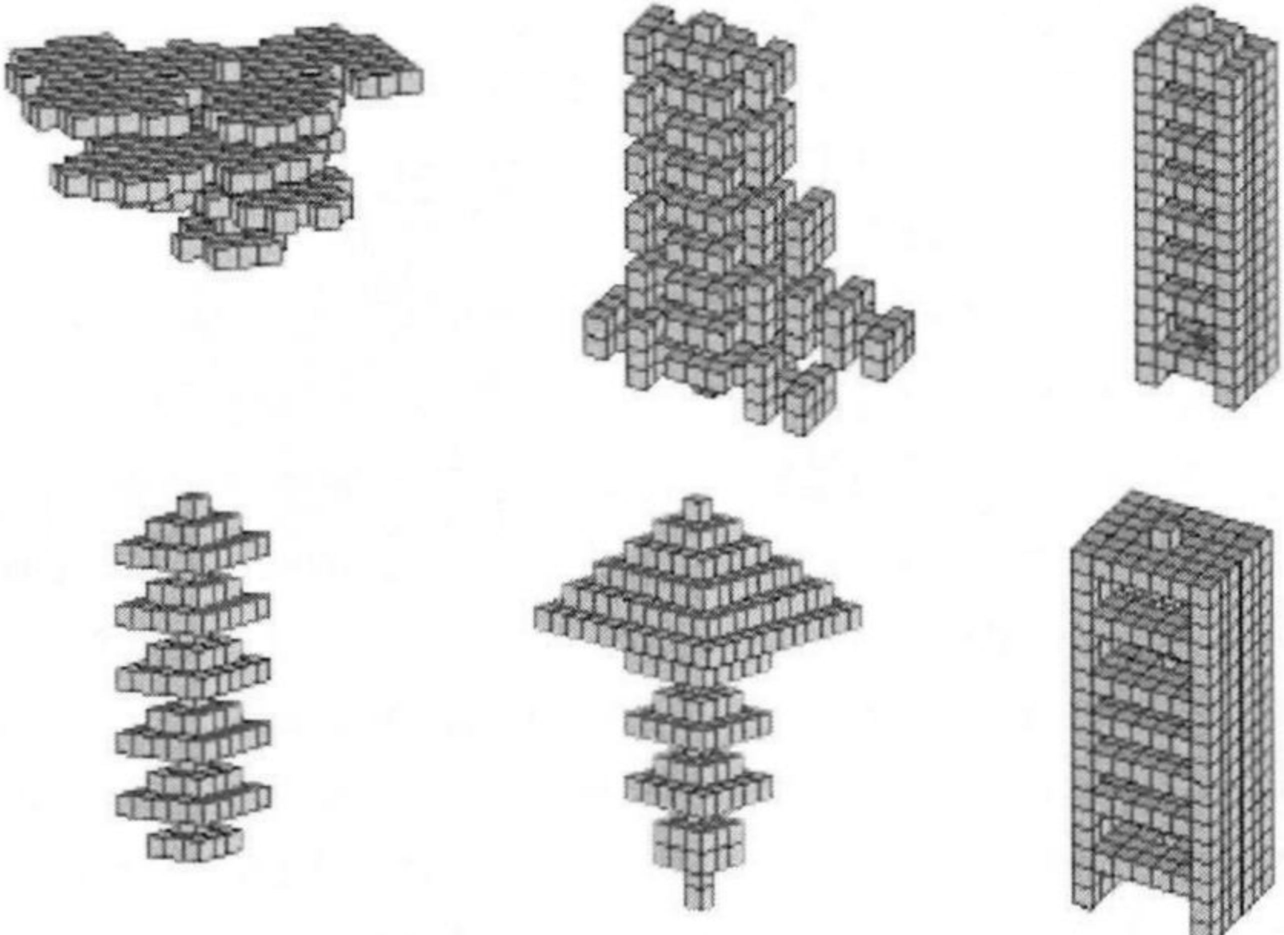
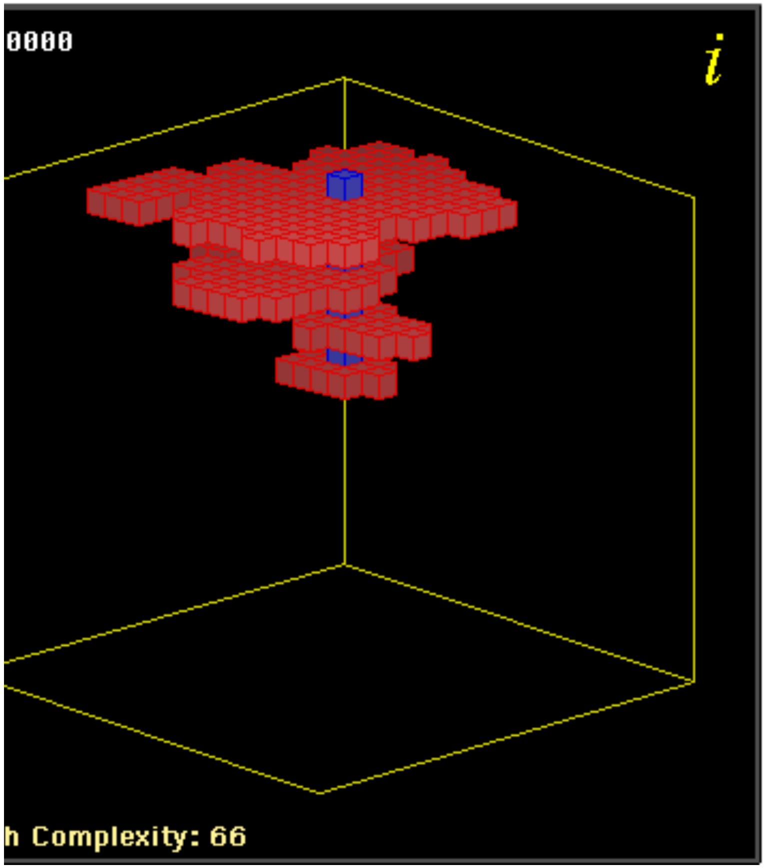
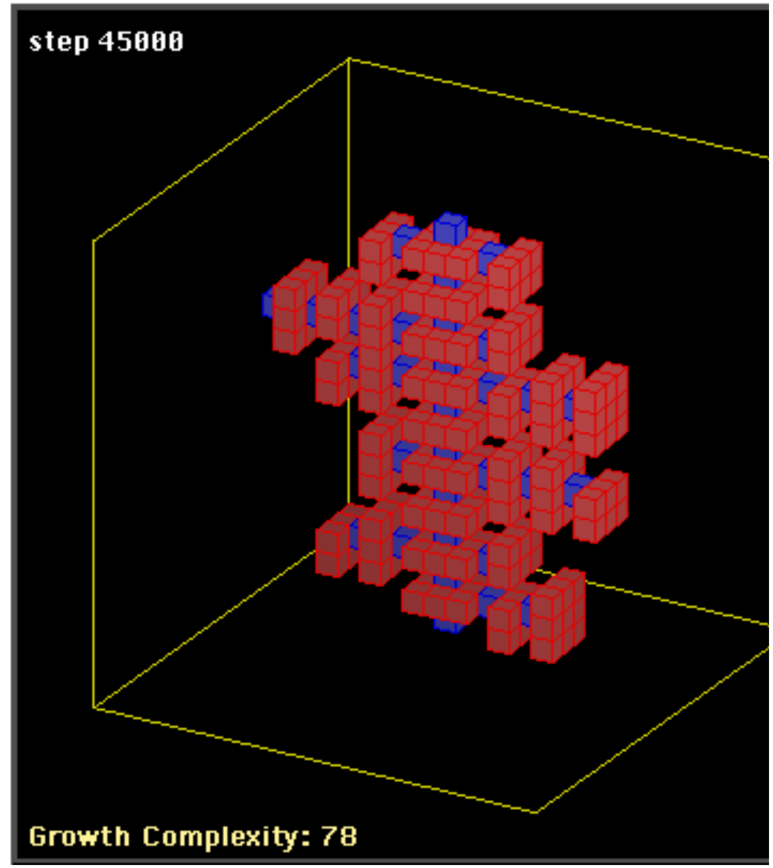


Fig. from Bonabeau & al., *Swarm Intell*.

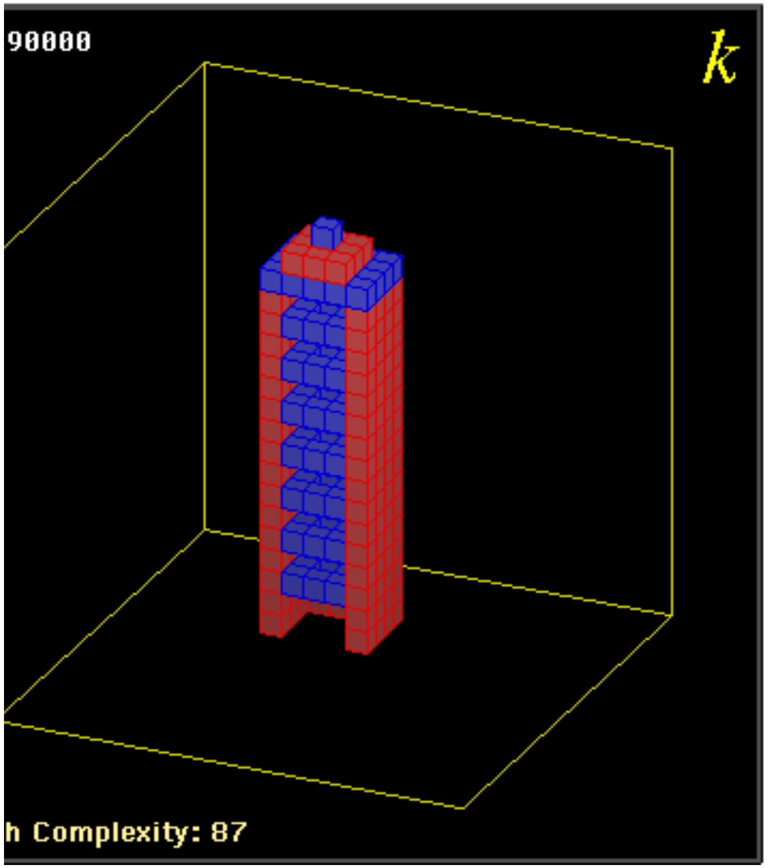
Cubic Examples (1)

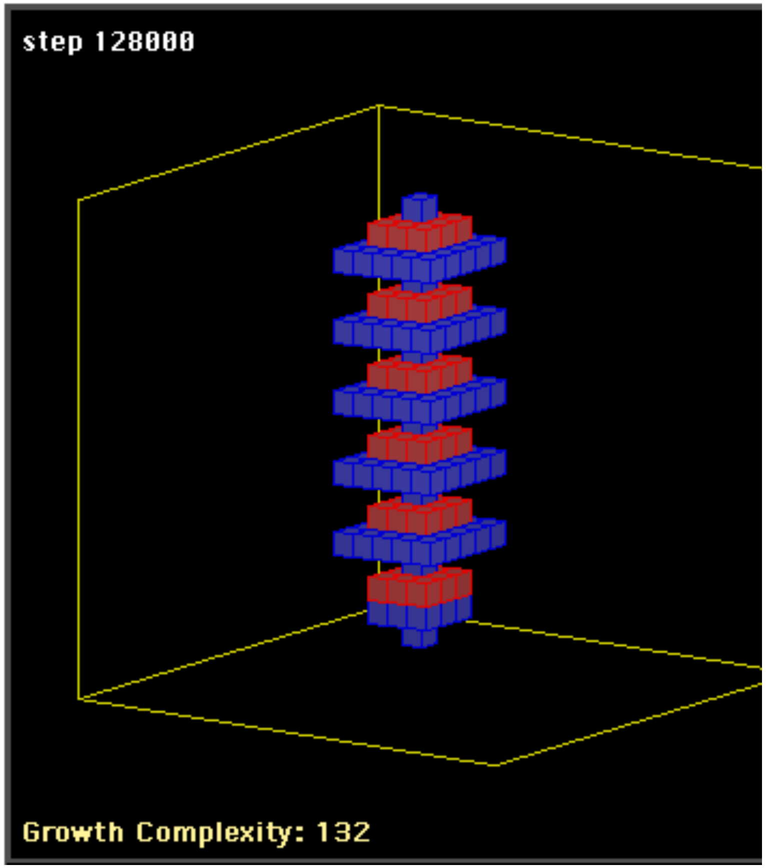




Figs. from IASC Dept., ENST de Bretagne.

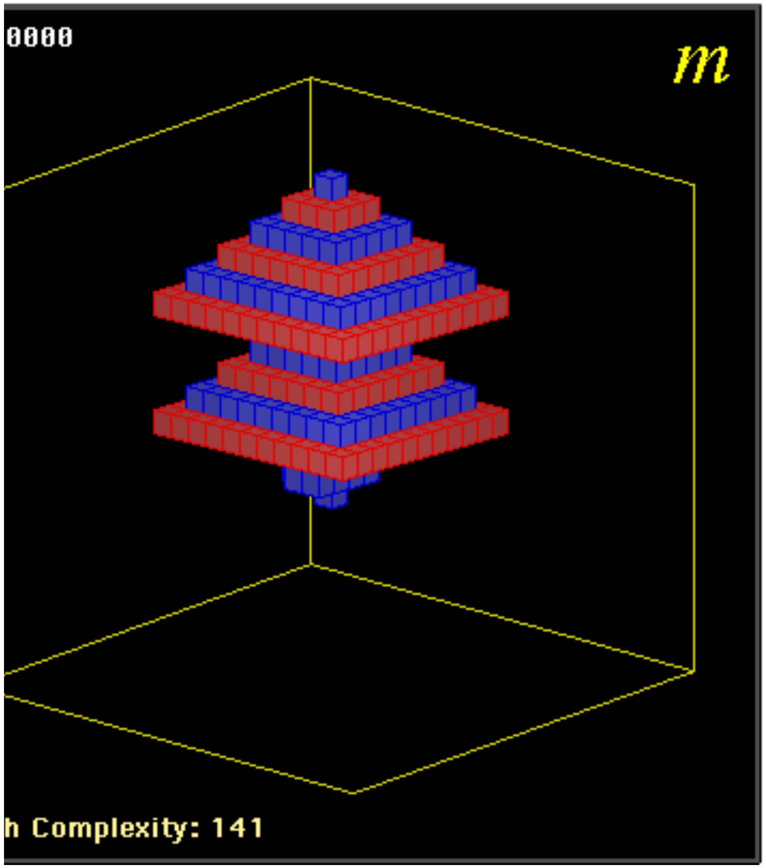
Cubic Examples (2)

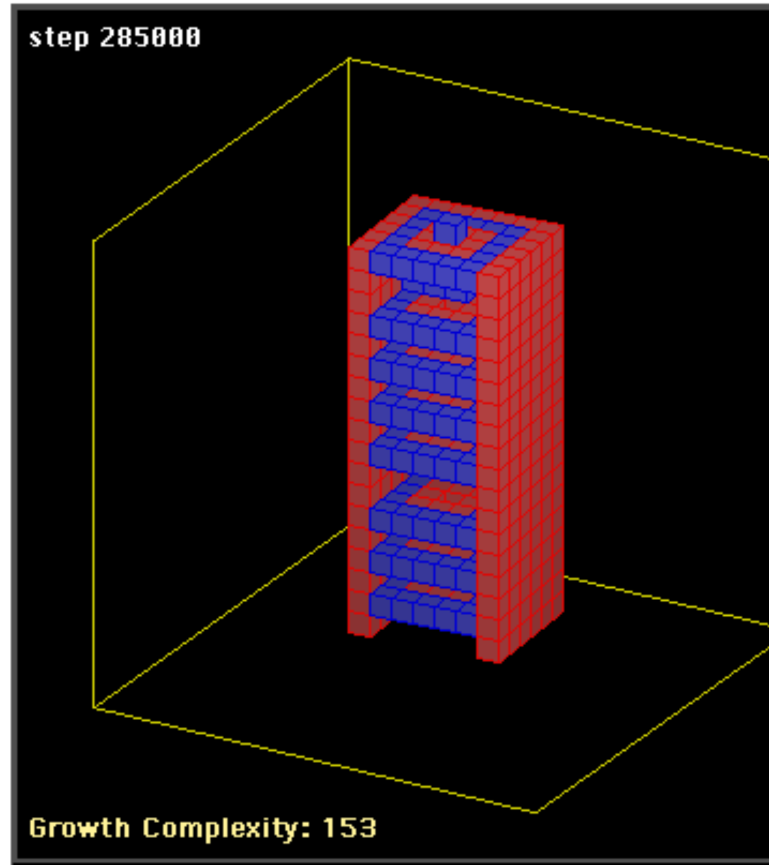




Figs. from IASC Dept., ENST de Bretagne.

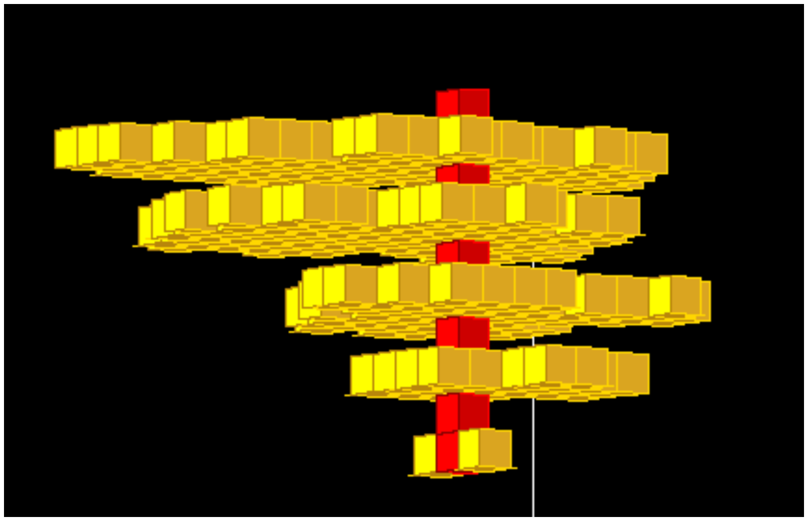
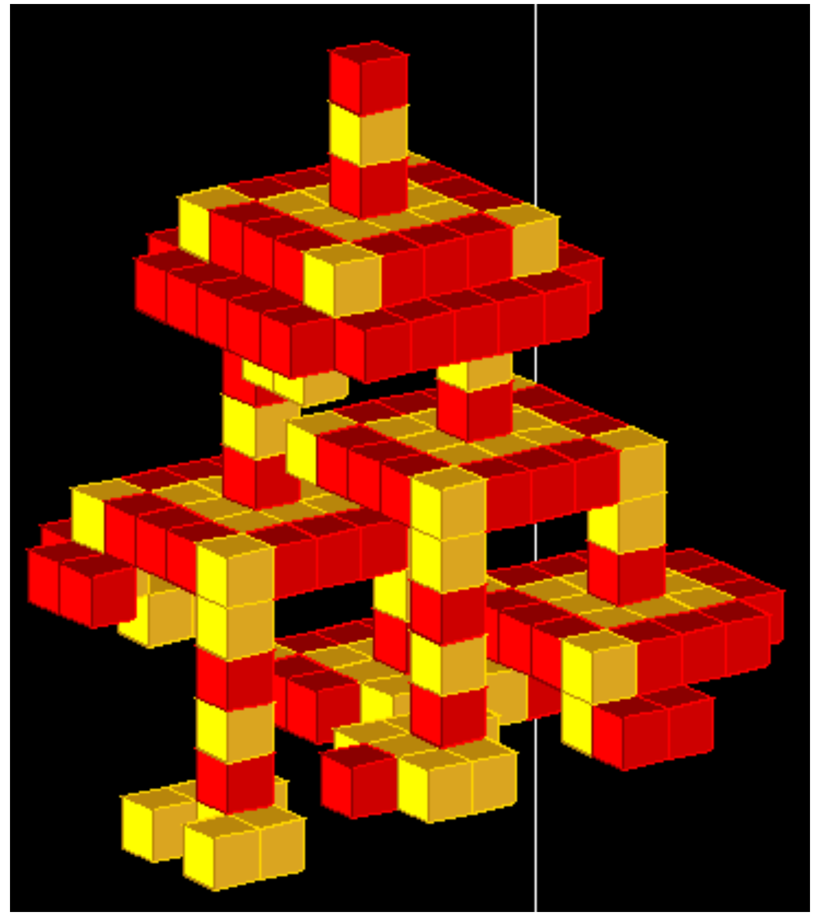
Cubic Examples (3)





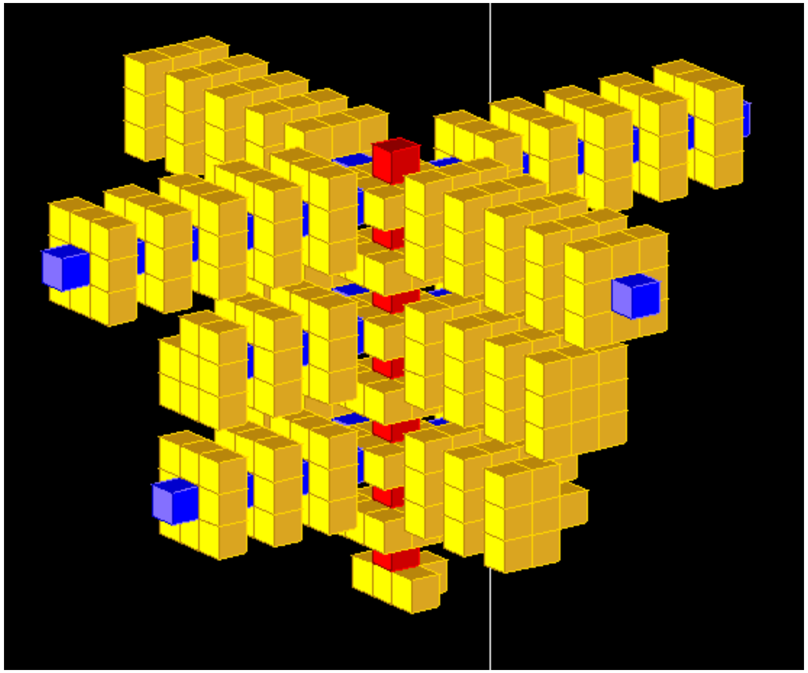
Figs. from IASC Dept., ENST de Bretagne.

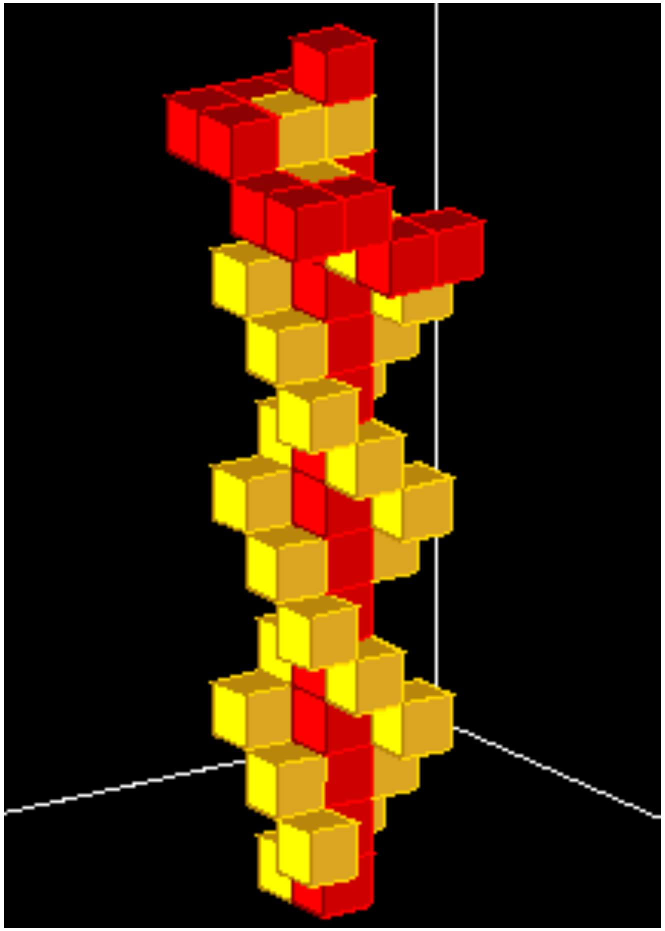
Cubic Examples (4)

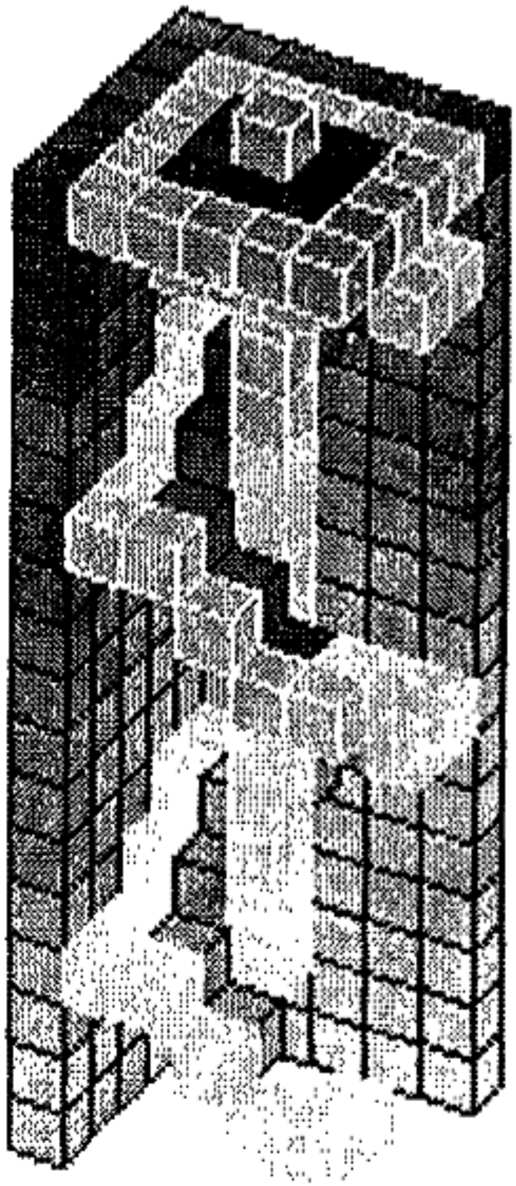
Figs. from IASC Dept., ENST de Bretagne.

Cubic Examples (5)





Figs. from IASC Dept., ENST de Bretagne.

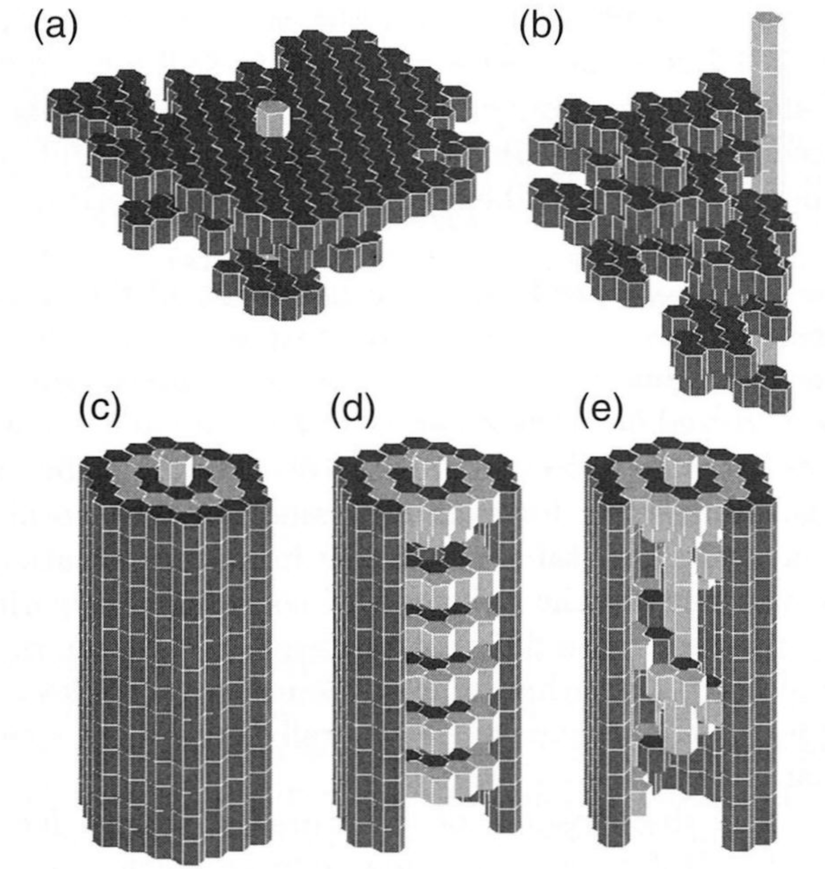


An Interesting Example

- Includes
  - central axis
  - external envelope
  - long-range helical ramp
- Similar to *Apicotermes* termite nest

Fig. from Theraulaz & Bonabeau (1995)

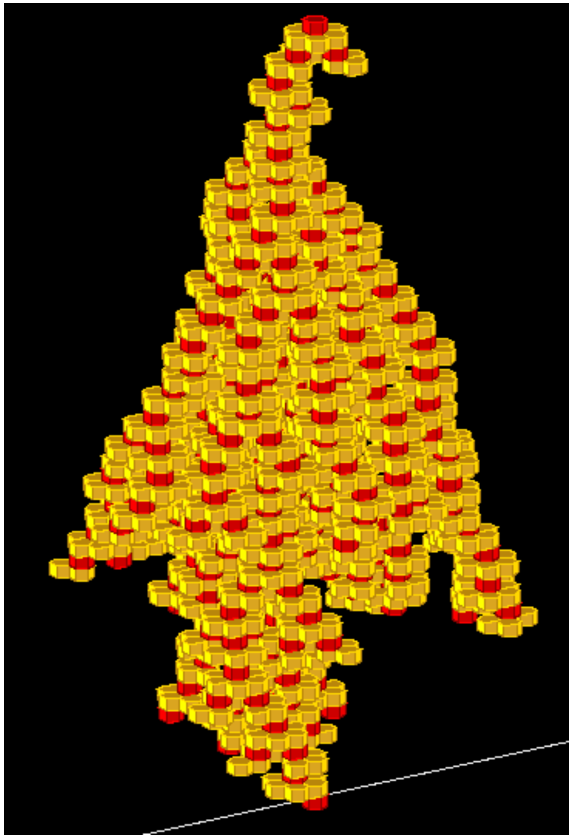
Similar Results with Hexagonal Lattice

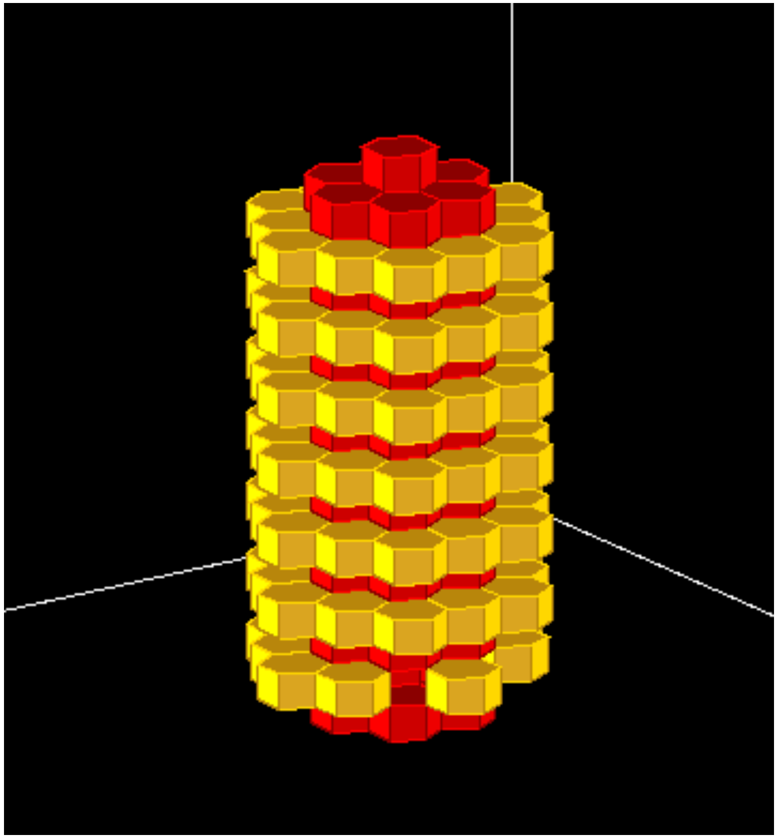


- 20×20×20 lattice
- 10 wasps
- All resemble nests of wasp species
- (d) is (c) with envelope cut away
- (e) has envelope cut away

Fig. from Bonabeau & al., *Swarm Intell*.

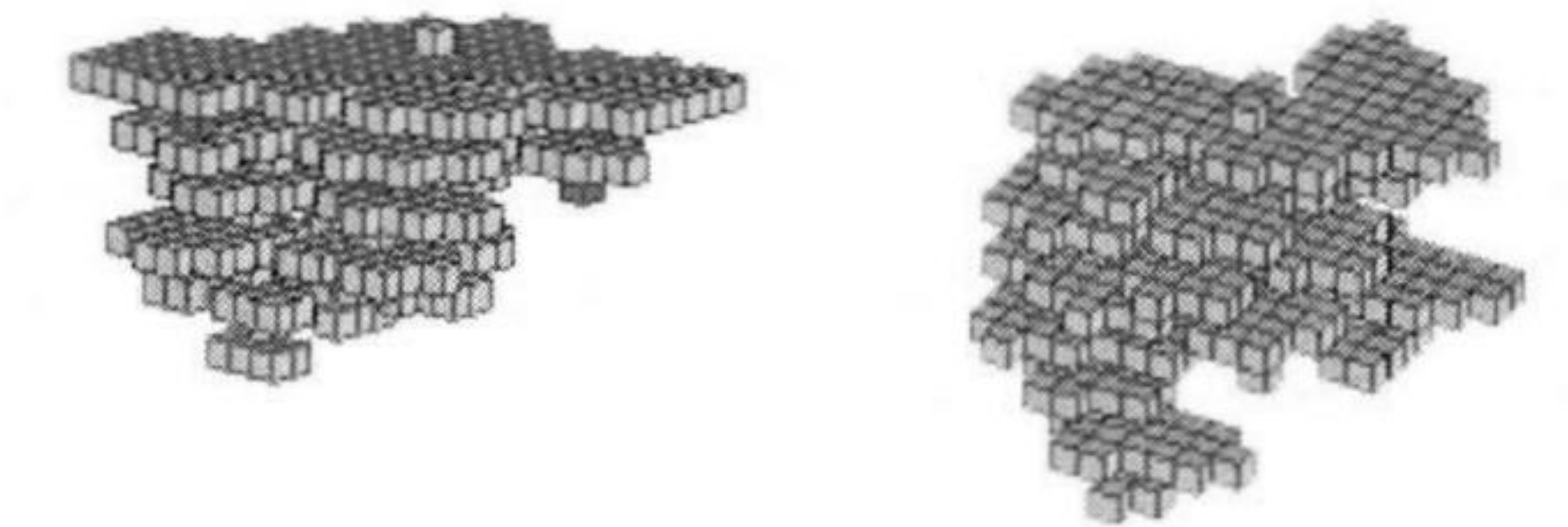
More Hexagonal Examples





Figs. from IASC Dept., ENST de Bretagne.

Effects of Randomness (Coordinated Algorithm)



- Specifically different (i.e., different in details)
- Generically the same (qualitatively identical)
- Sometimes results are fully constrained

Fig. from Bonabeau & al., *Swarm Intell*.

Effects of Randomness (Non-coordinated Algorithm)

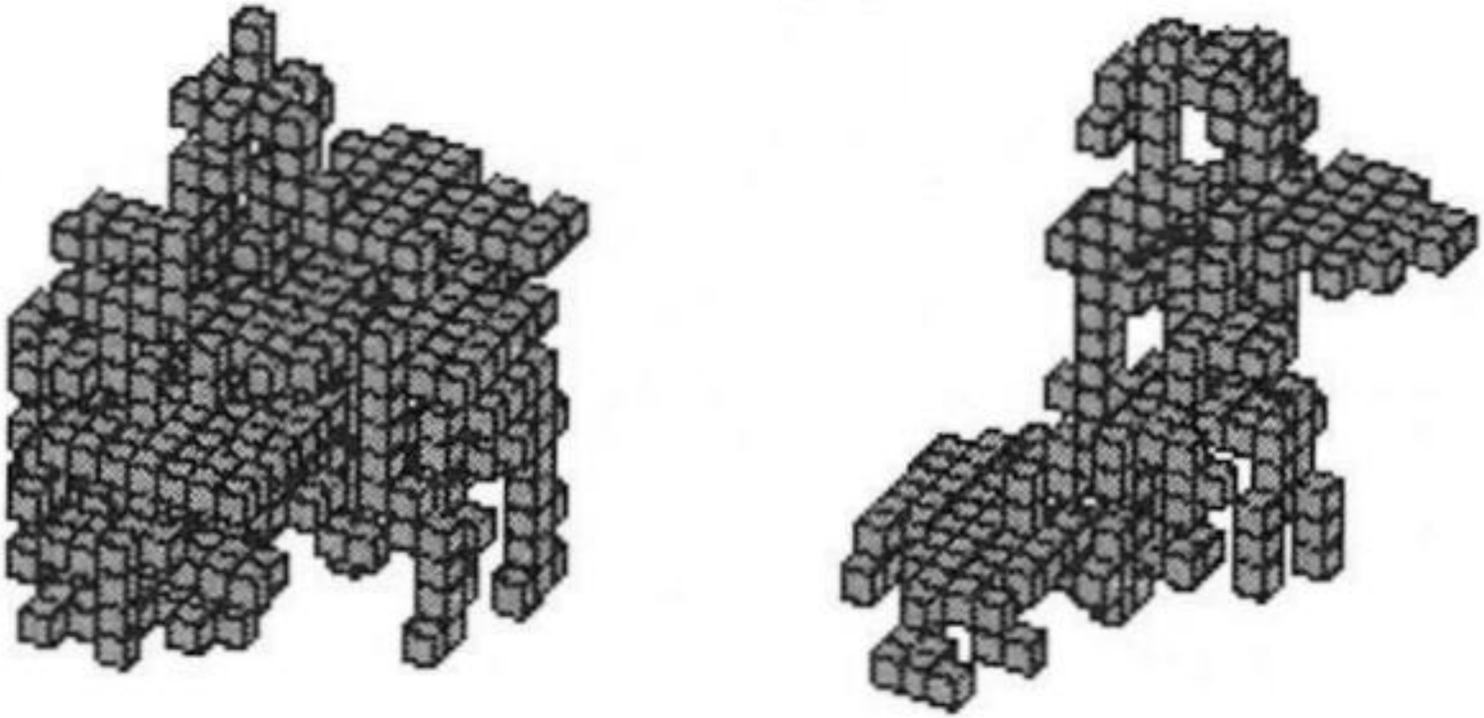


Fig. from Bonabeau & al., *Swarm Intell*.

Non-coordinated Algorithms

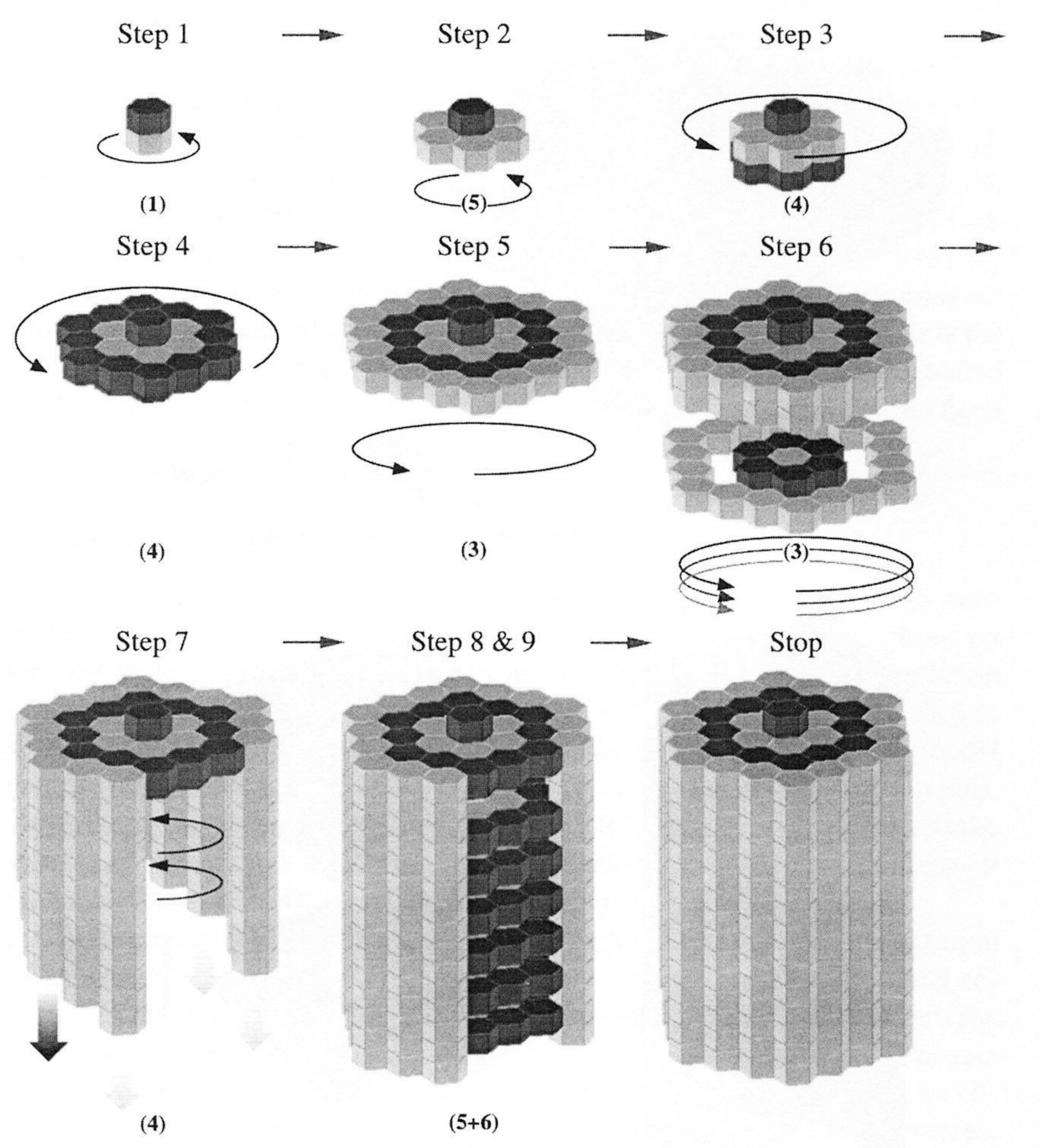
- Stimulating configurations are not ordered in time and space
- Many of them overlap
- Architecture grows without any coherence
- May be convergent, but are still unstructured

Coordinated Algorithm

- Non-conflicting rules
  - can't prescribe two different actions for the same configuration
- Stimulating configurations for different building stages cannot overlap
- At each stage, "handshakes" and "interlocks" are required to prevent conflicts in parallel assembly

More Formally…

- Let $C = \{c_1, c_2, \ldots, c_n\}$ be the set of local stimulating configurations
- Let $(S_1, S_2, \ldots, S_m)$ be a sequence of assembly stages
- These stages partition C into mutually disjoint subsets $C(S_p)$
- Completion of S_p signaled by appearance of a configuration in $C(S_{p+1})$



Example

Fig. from Camazine &al., *Self-Org. Biol. Sys.*

Example

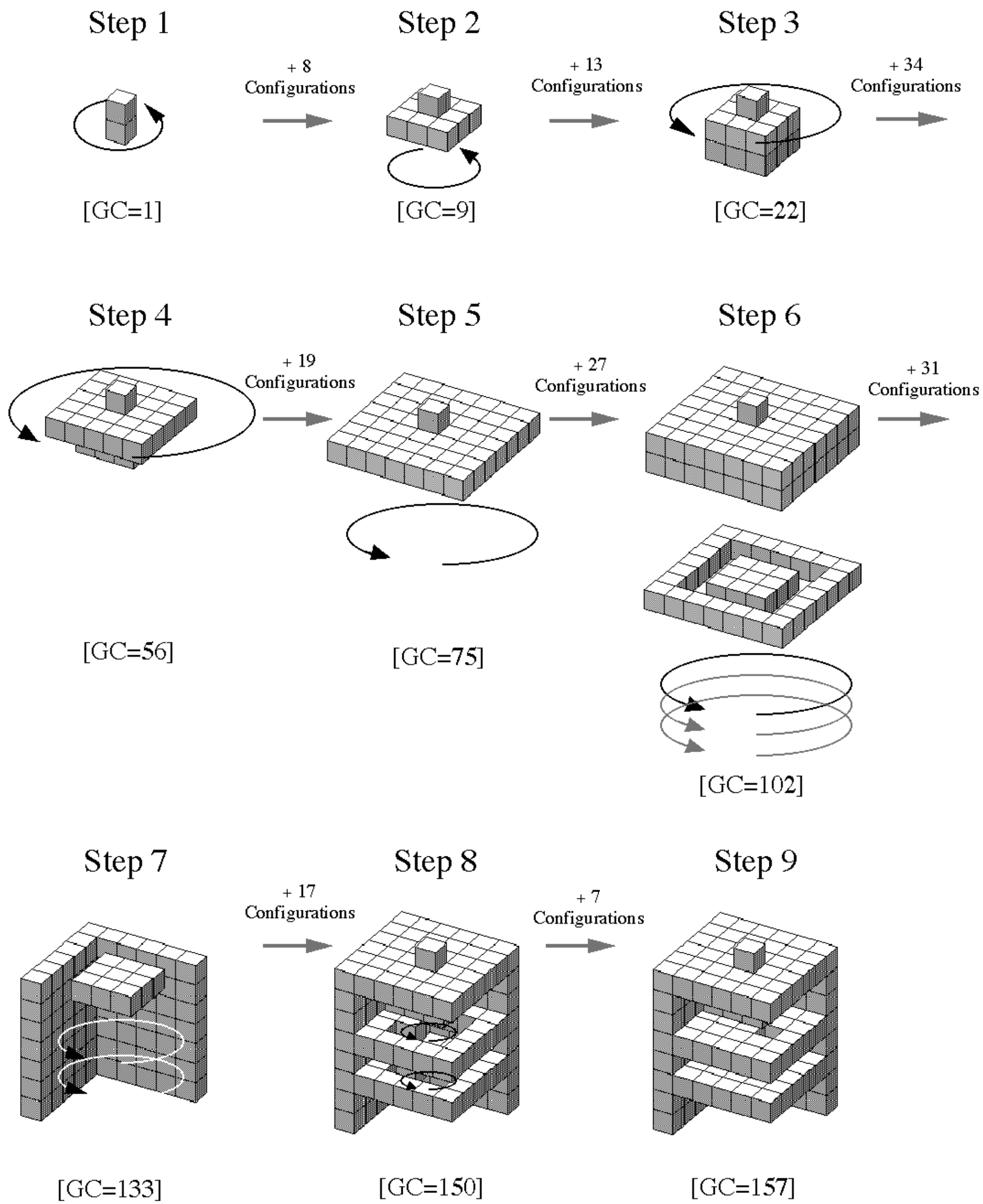
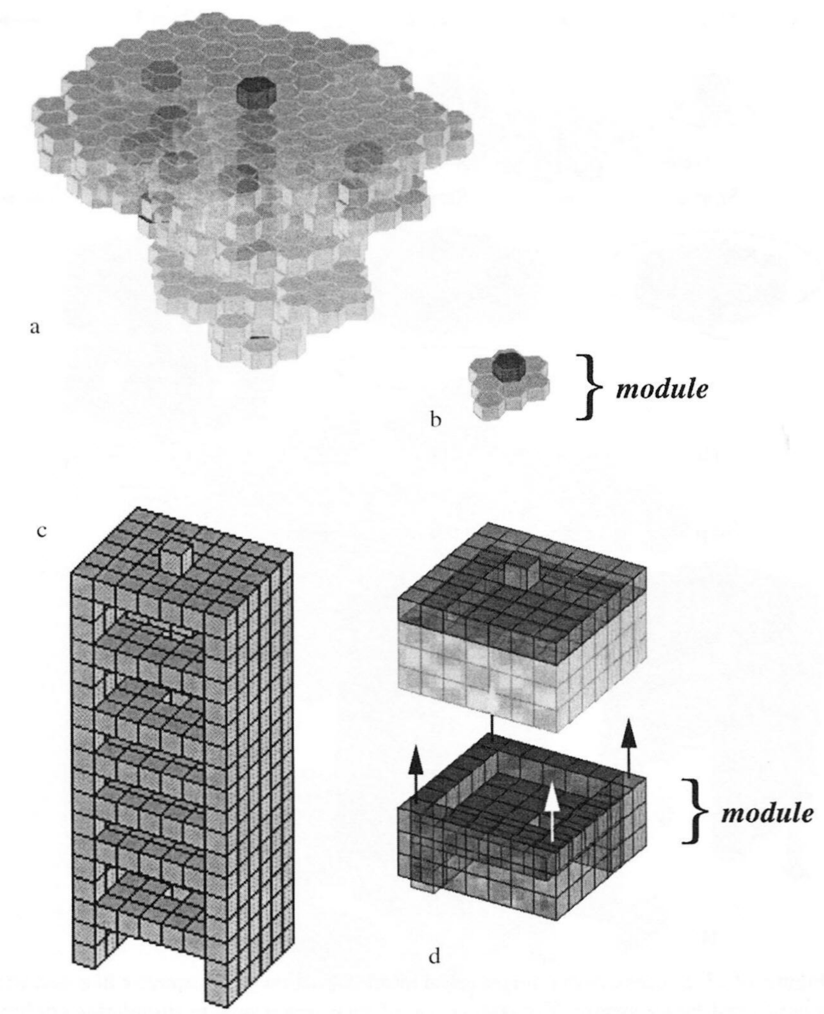


fig. from IASC Dept., ENST de Bretagne.

Modular Structure



- Recurrent states induce cycles in group behavior
- These cycles induce modular structure
- Each module is built during a cycle
- Modules are qualitatively similar

Fig. from Camazine &al., *Self-Org. Biol. Sys.*

Possible Termination Mechanisms

- Qualitative
  - the assembly process leads to a configuration that is not stimulating
- Quantitative
  - a separate rule inhibiting building when nest a certain size relative to population
  - "empty cells rule": make new cells only when no empties available
  - growing nest may inhibit positive feedback mechanisms

Observations

- Random algorithms tend to lead to uninteresting structures
  - random or space-filling shapes
- Similar structured architectures tend to be generated by similar coordinated algorithms
- Algorithms that generate structured architectures seem to be confined to a small region of rule-space

Analysis

- Define matrix M:
  - 12 columns for 12 sample structured architectures
  - 211 rows for stimulating configurations
  - $M_{ij} = 1$ if architecture j requires configuration i

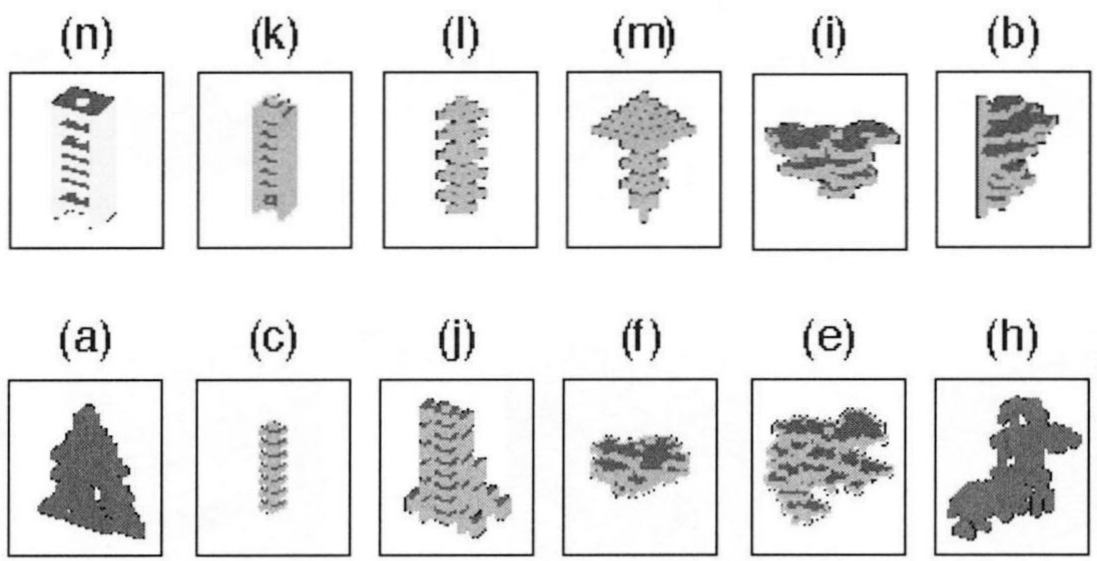


Fig. from Bonabeau & al., *Swarm Intell*.

Factorial Correspondence Analysis

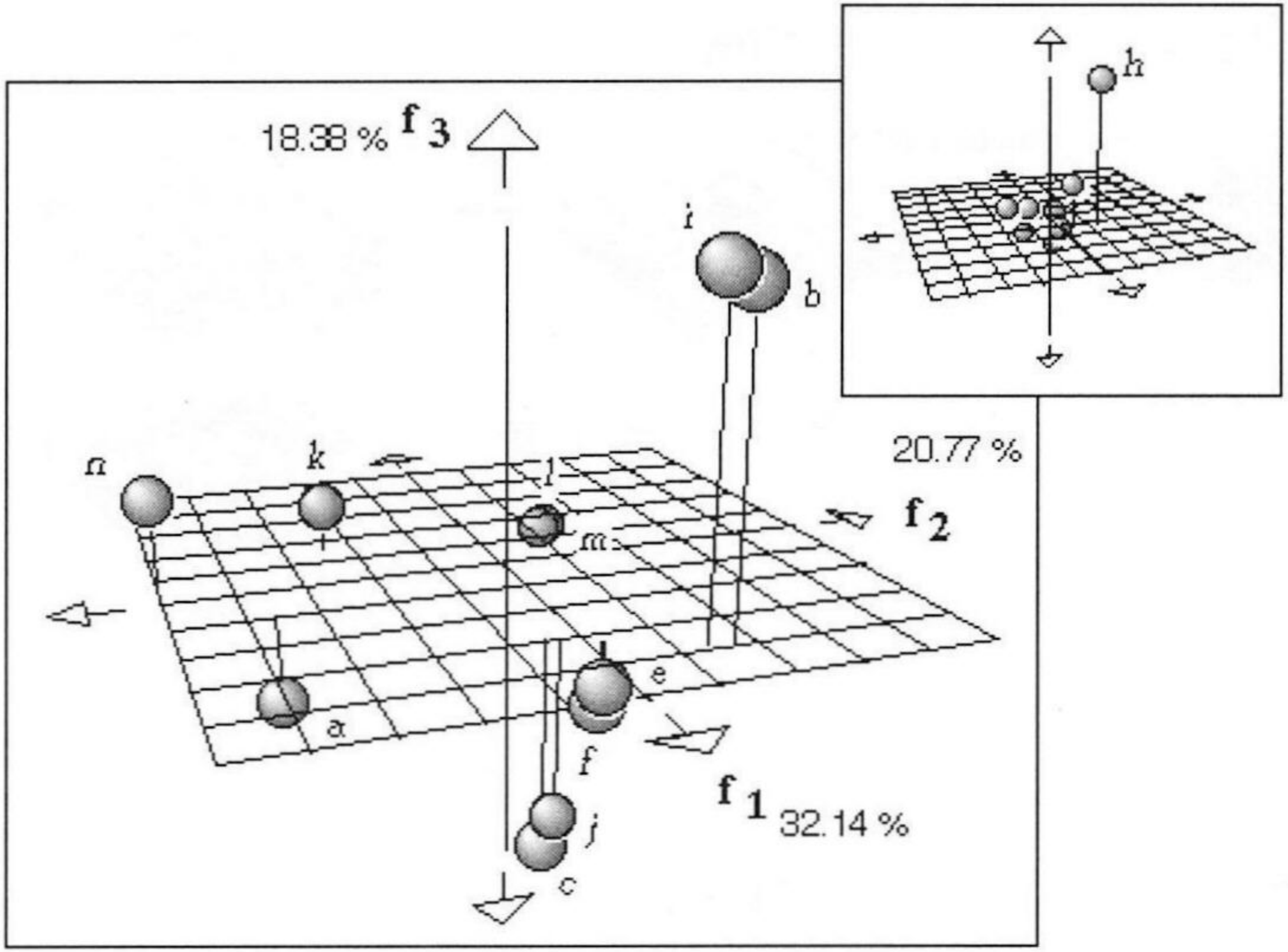


Fig. from Bonabeau & al., *Swarm Intell*.

Conclusions

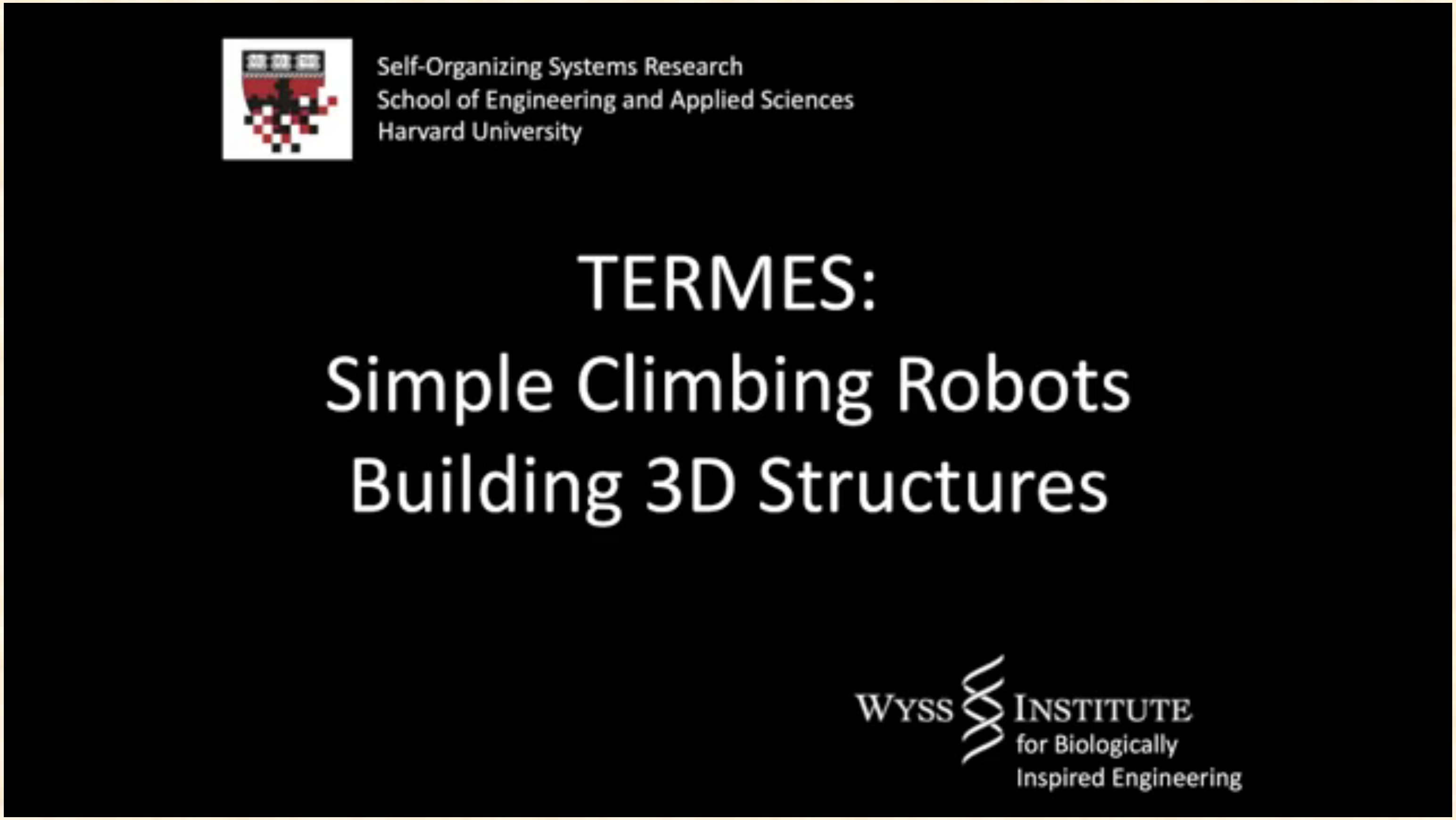
- Simple rules that exploit discrete (qualitative) stigmergy can be used by autonomous agents to assemble complex, 3D structures
- The rules must be non-conflicting and coordinated according to stage of assembly
- The rules corresponding to interesting structures occupy a comparatively small region in rule-space

The Termes Project

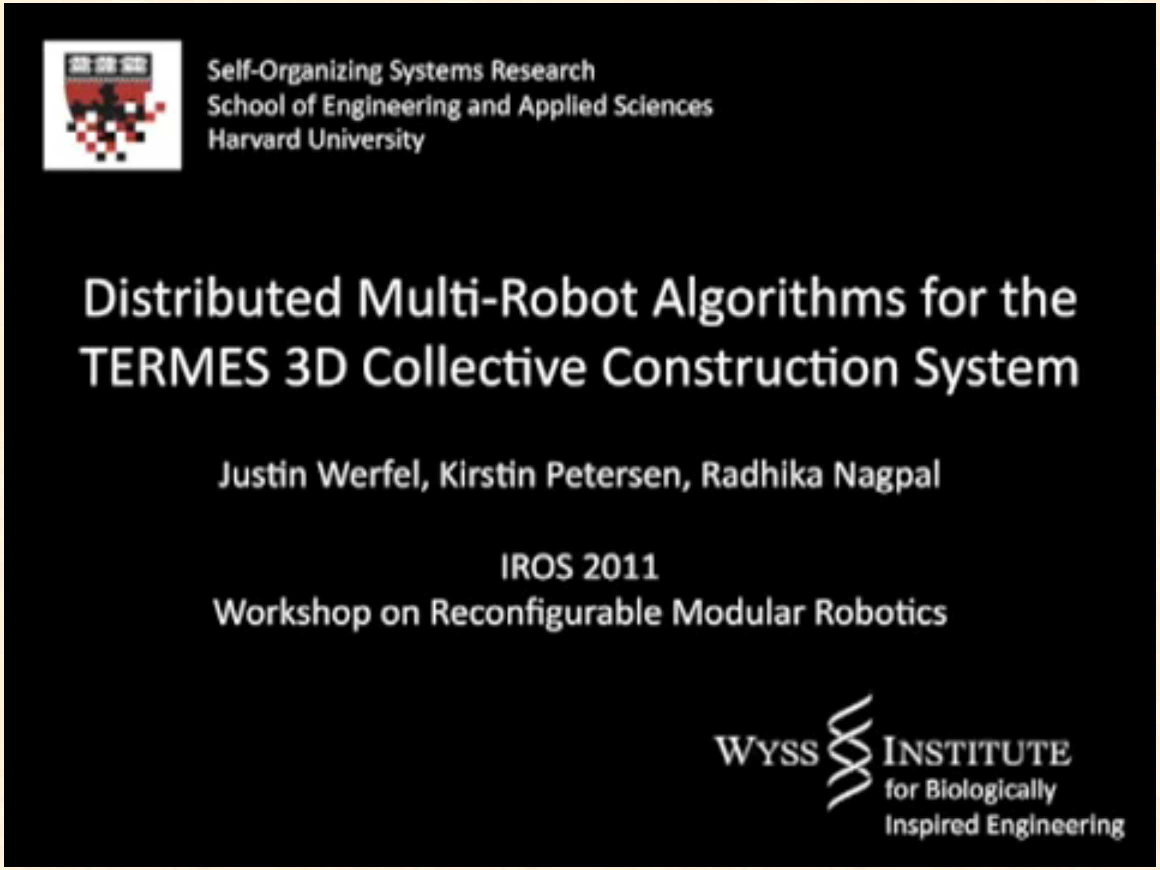
Wyss Institute for Biologically Inspired Engineering

Harvard

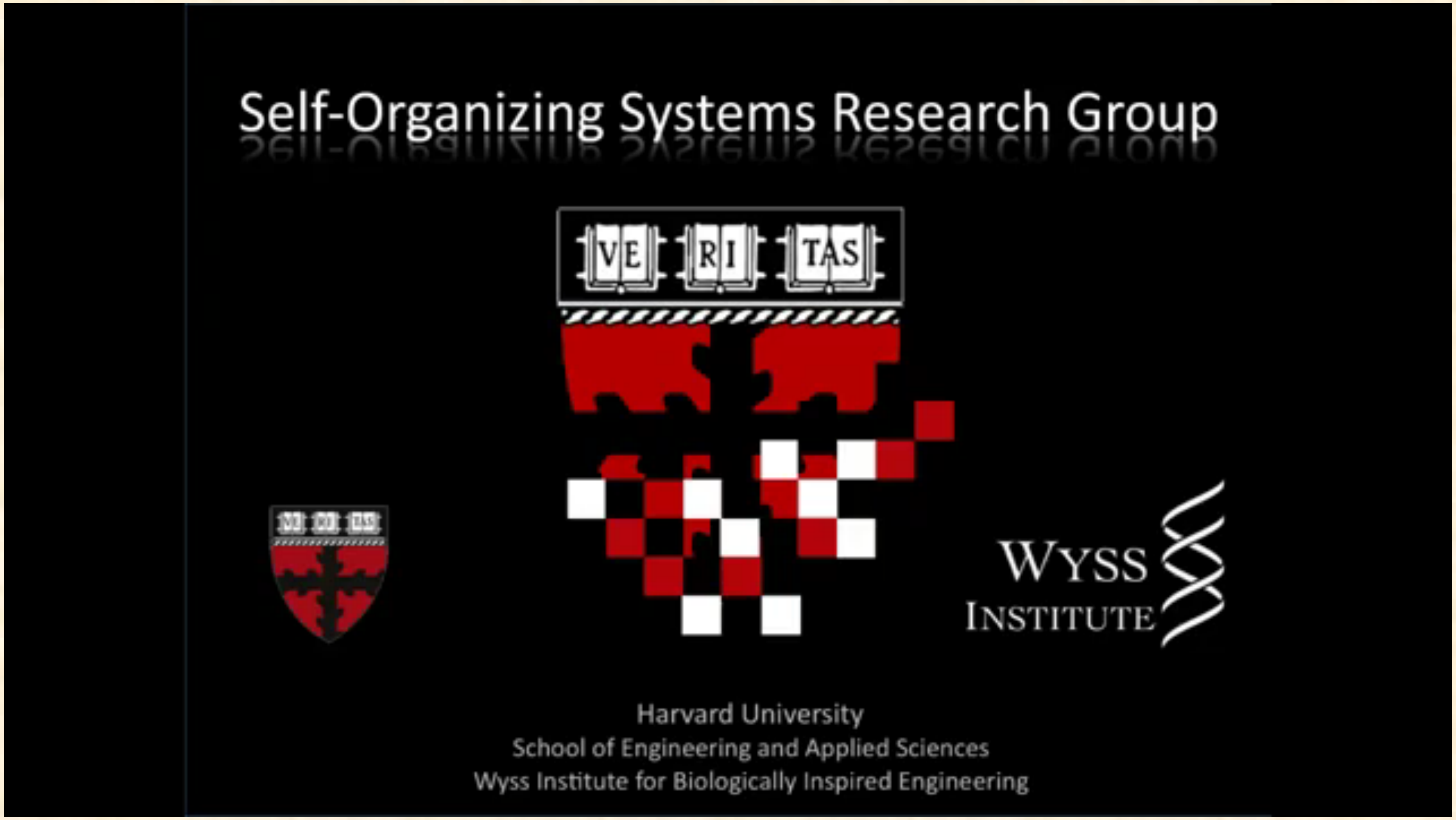
Introduction



Algorithmic Assembly



The Robot



Self-Organizing Systems Research Group
VE RI TAS
WYSS INSTITUTE
Harvard University
School of Engineering and Applied Sciences
Wyss Institute for Biologically Inspired Engineering

Final Video (2014)

Additional Bibliography

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