

Part C

Nest Building

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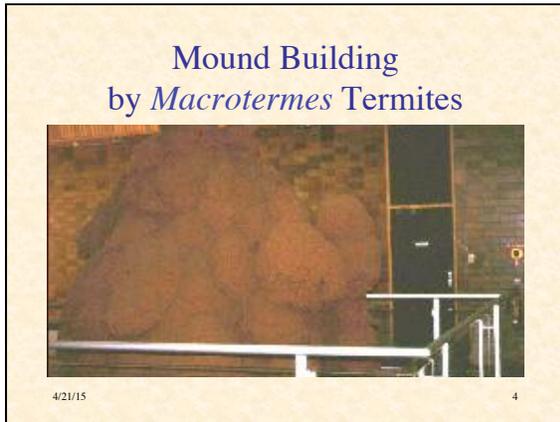
The Termes Project

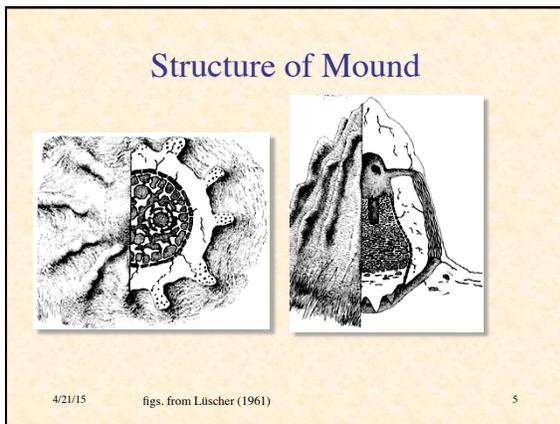
- Wyss Institute for Biologically Inspired Engineering, Harvard
- [Introduction](#)
- [Algorithmic Assembly](#)
- [The Robot](#)
- [Final Video \(2014\)](#)

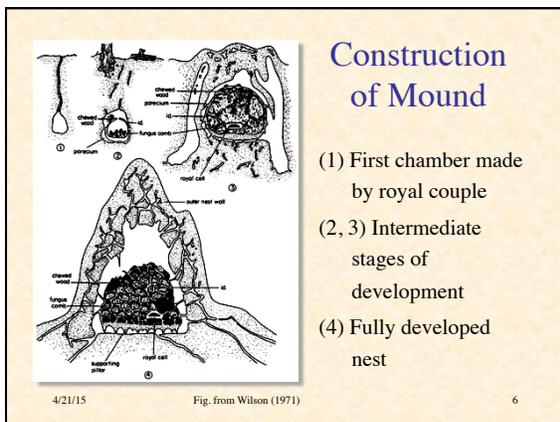
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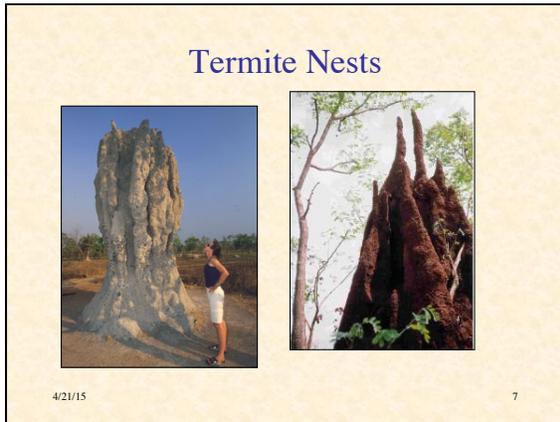
Nest Building by Termites
(Natural and Artificial)

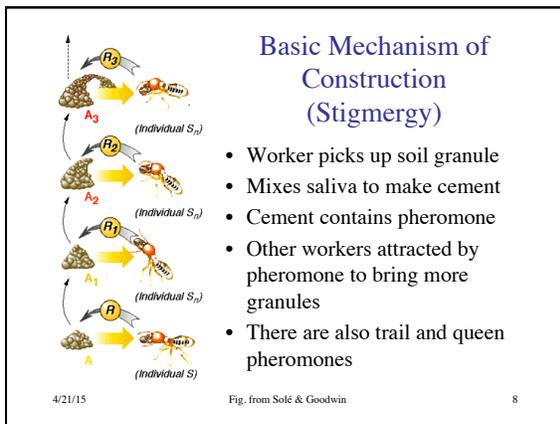
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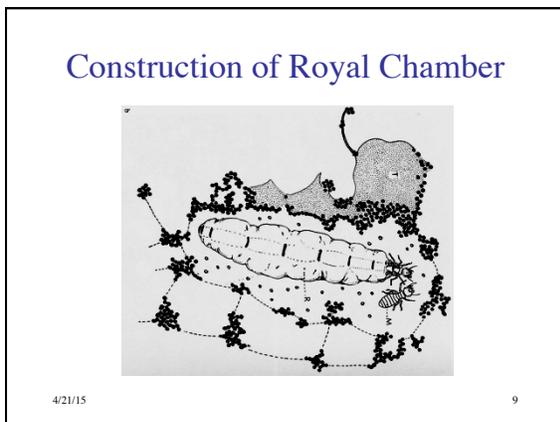


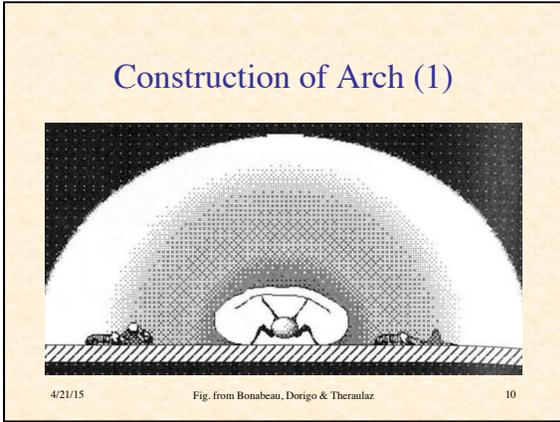


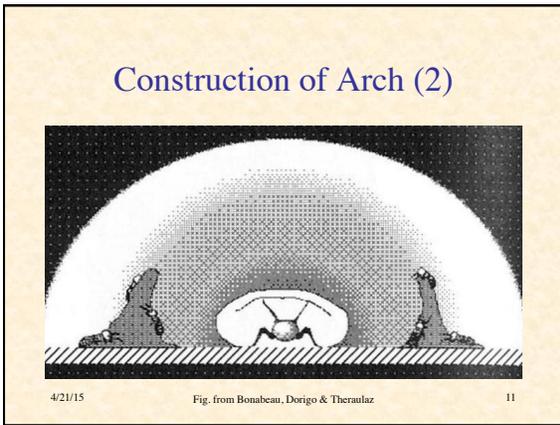


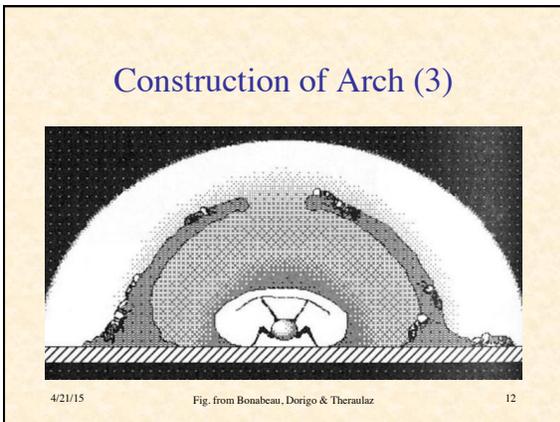












Basic Principles

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

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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

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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)

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

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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)

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

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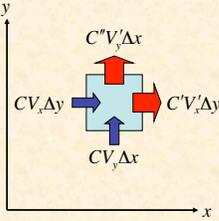
Equation for C
(Density of Laden Termites)

$\partial_t C$ (rate of change of concentration) =
 Φ (flux of laden termites)
 $- k_1 C$ (unloading of termites)
 $+ D_C \nabla^2 C$ (random walk)
 $- \gamma \nabla \cdot (CVH)$ (chemotaxis: response to pheromone gradient)

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

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

$$\rightarrow \frac{\partial(CV_x)}{\partial x} + \frac{\partial(CV_y)}{\partial y} = \nabla \cdot \mathbf{CV}$$

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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

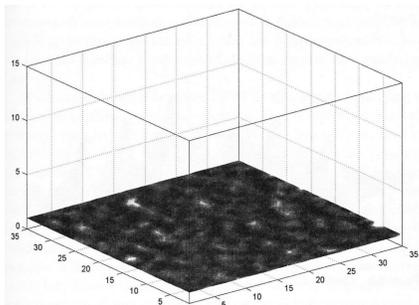
$$\mathbf{J} \propto \nabla H$$
- The flux density is proportional to the number of moving termites

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

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Simulation ($T = 0$)

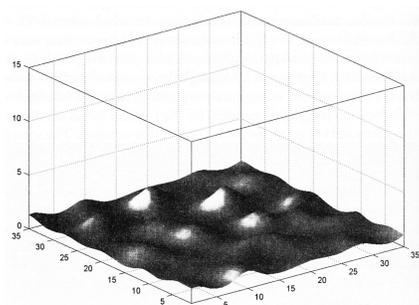


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fig. from Solé & Goodwin

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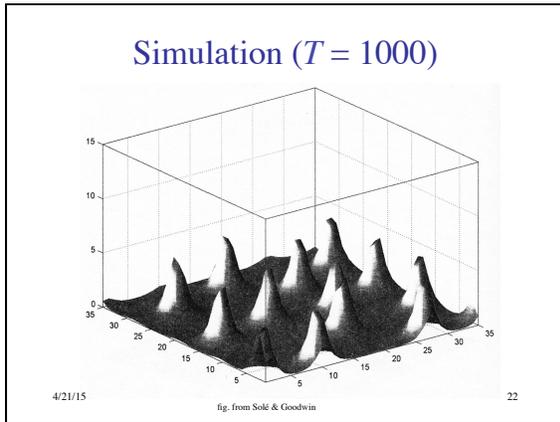
Simulation ($T = 100$)



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fig. from Solé & Goodwin

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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

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

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NetLogo Simulation of Deneubourg Model

[Run Pillars3D.nlogo](#)

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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)

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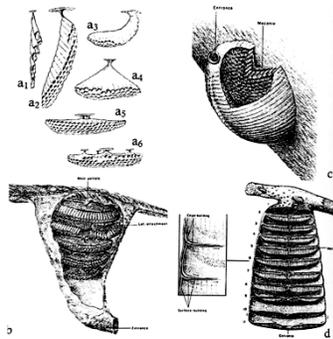
Wasp Nest Building and Discrete Stigmergy

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Fig. from Solé & Goodwin

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Structure of Some Wasp Nests

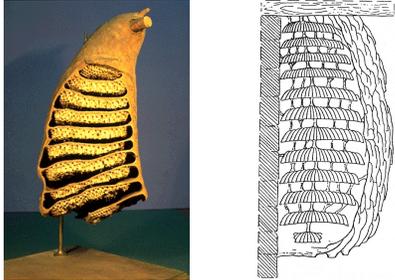


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Fig. from Self-Org. Biol. Sys.

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Adaptive Function of Nests



4/21/15 Figs. from Self-Org. Biol. Sys. 28

How Do They Do It?



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Lattice Swarms

(developed by Theraulaz & Bonabeau)

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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

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Discrete Stigmergy in Comb Construction

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

4/21/15 Fig. from Self-Org. Biol. Sys. 32

Numbers and Kinds of Building Sites

4/21/15 Fig. from Self-Org. Biol. Sys. 33

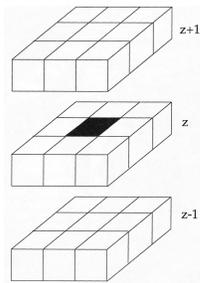
Lattice Swarm Model

- 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

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Cubic Neighborhood



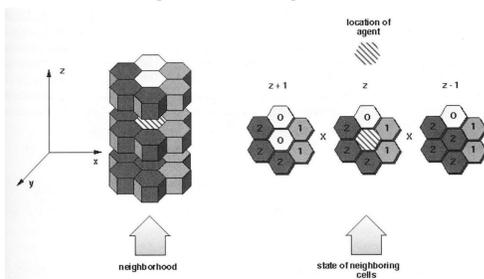
- Deposited brick depends on states of 26 surrounding cells
- Configuration of surrounding cells may be represented by matrices:

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

4/21/15 Fig. from Solé & Goodwin

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Hexagonal Neighborhood

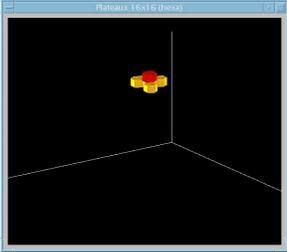


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Fig. from Bonabeau, Dorigo & Theraulaz

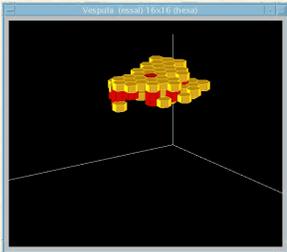
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Example Construction



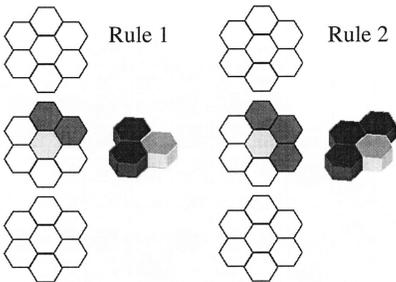
4/21/15 Fig. from IASC Dept., ENST de Bretagne. 37

Another Example

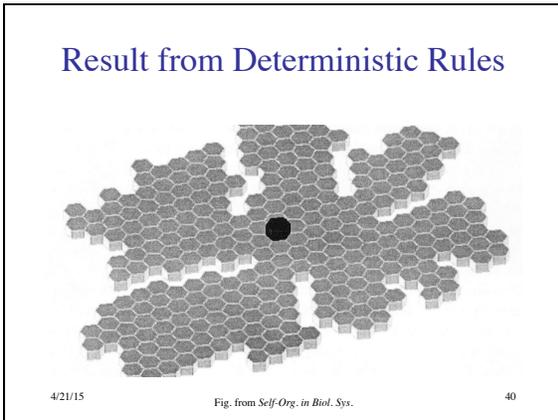


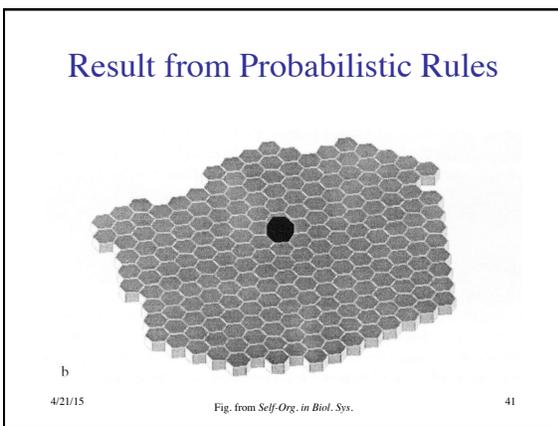
4/21/15 fig. from IASC Dept., ENST de Bretagne. 38

A Simple Pair of Rules



4/21/15 Fig. from *Self-Org. in Biol. Sys.* 39





Example Rules for a More Complex Architecture

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

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

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

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B

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

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

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

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

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

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

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

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

(2.9) $\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$

(2.10) $\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$

(2.11)* $\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$

(2.12)* $\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$

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

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

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

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

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

(2.18)* $\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$

Second Group of Rules

For these configurations, deposit a type-2 brick

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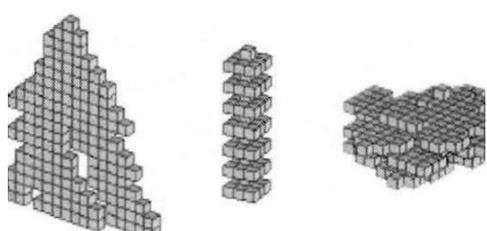
Result

- 20x20x20 lattice
- 10 wasps
- After 20 000 simulation steps
- Axis and plateaus
- Resembles nest of *Parachartergus*

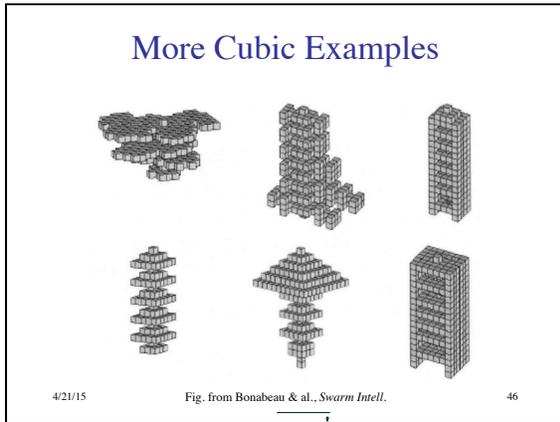


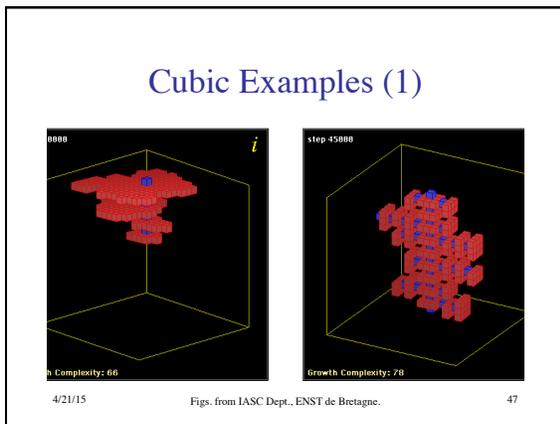
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Fig. from Bonabeau & al., *Swarm Intell.*
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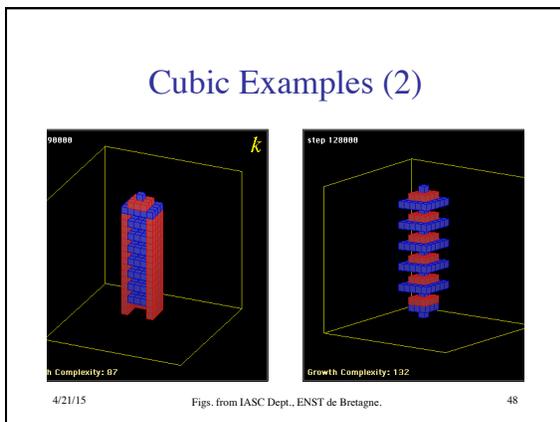
Architectures Generated from Other Rule Sets



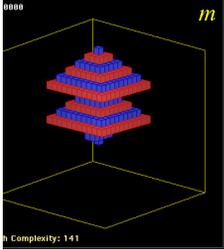
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Fig. from Bonabeau & al., *Swarm Intell.*
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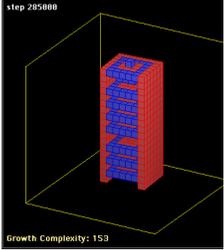




Cubic Examples (3)



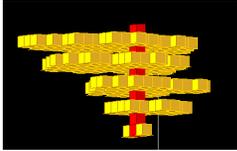
0000 *m*
Complexity: 141

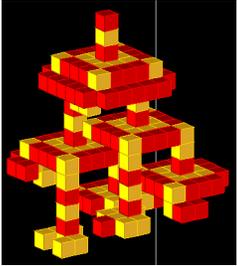


step 205000
Growth Complexity: 153

4/21/15 Figs. from IASC Dept., ENST de Bretagne. 49

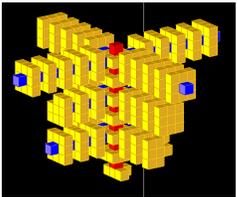
Cubic Examples (4)

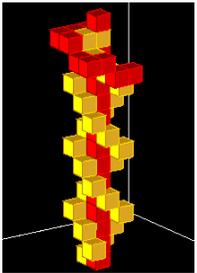




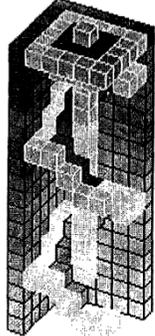
4/21/15 Figs. from IASC Dept., ENST de Bretagne. 50

Cubic Examples (5)





4/21/15 Figs. from IASC Dept., ENST de Bretagne. 51

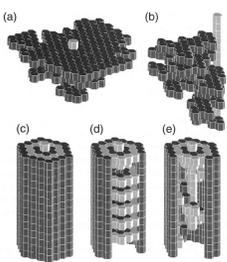


An Interesting Example

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

4/21/15 Fig. from Theraulaz & Bonabeau (1995) 52

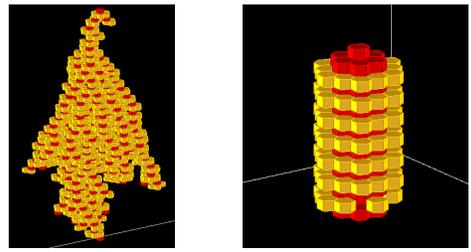
Similar Results with Hexagonal Lattice



- 20x20x20 lattice
- 10 wasps
- All resemble nests of wasp species
- (d) is (c) with envelope cut away
- (e) has envelope cut away

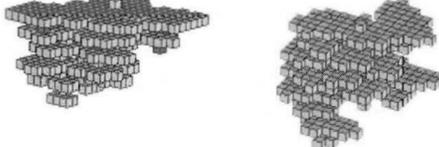
4/21/15 Fig. from Bonabeau & al., *Swarm Intell.* 53

More Hexagonal Examples



4/21/15 Figs. from IASC Dept., ENST de Bretagne. 54

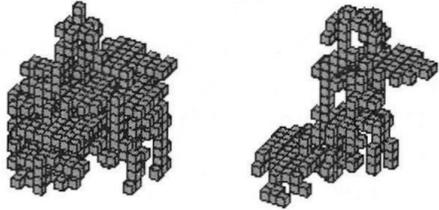
Effects of Randomness (Coordinated Algorithm)



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

4/21/15 Fig. from Bonabeau & al., *Swarm Intell.* 55

Effects of Randomness (Non-coordinated Algorithm)



4/21/15 Fig. from Bonabeau & al., *Swarm Intell.* 56

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

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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

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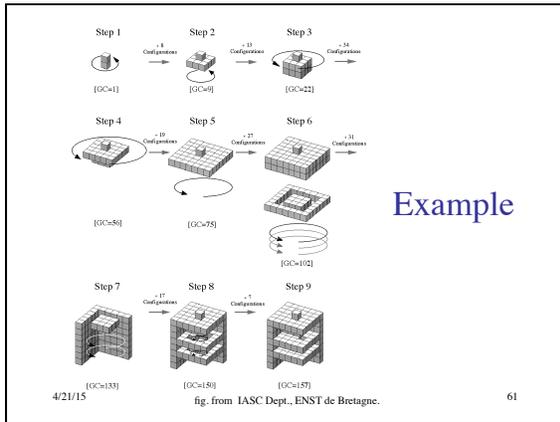
More Formally...

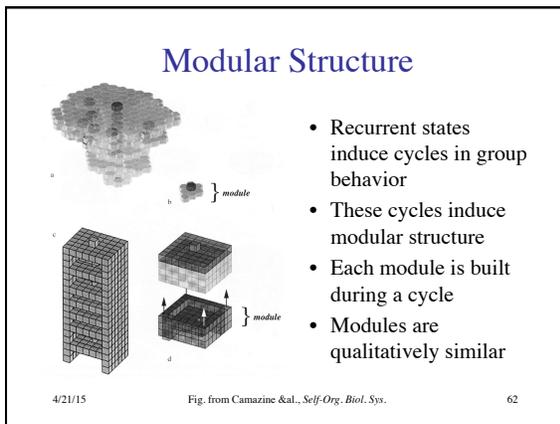
- Let $C = \{c_1, c_2, \dots, c_n\}$ be the set of local stimulating configurations
- Let (S_1, S_2, \dots, S_m) be a sequence of assembly stages
- These stages partition C into mutually disjoint subsets $C(S_p)$
- Completion of S_p signaled by appearance of a configuration in $C(S_{p+1})$

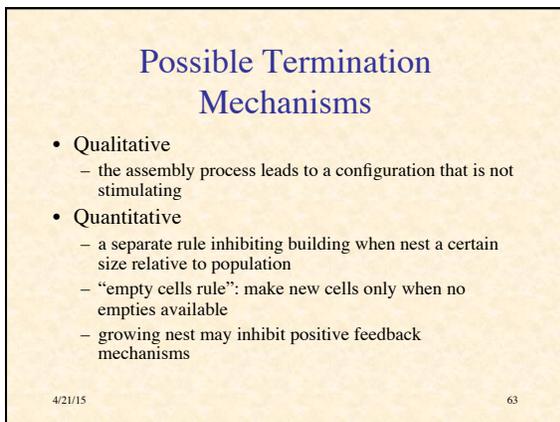
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Example

4/21/15 Fig. from Camazine et al., *Self-Org. Biol. Sys.* 60







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

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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

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

Factorial Correspondence Analysis

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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

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Additional Bibliography

1. Camazine, S., Deneubourg, J.-L., Franks, N. R., Sneyd, J., Theraulaz, G., & Bonabeau, E. *Self-Organization in Biological Systems*. Princeton, 2001, chs. 11, 13, 18, 19.
2. Bonabeau, E., Dorigo, M., & Theraulaz, G. *Swarm Intelligence: From Natural to Artificial Systems*. Oxford, 1999, chs. 2, 6.
3. Solé, R., & Goodwin, B. *Signs of Life: How Complexity Pervades Biology*. Basic Books, 2000, ch. 6.
4. Resnick, M. *Turtles, Termites, and Traffic Jams: Explorations in Massively Parallel Microworlds*. MIT Press, 1994, pp. 59-68, 75-81.
5. Kennedy, J., & Eberhart, R. "Particle Swarm Optimization," *Proc. IEEE Int'l. Conf. Neural Networks* (Perth, Australia), 1995. <http://www.engr.iupui.edu/~shi/psa.html>.

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