Part C

Nest Building

4/23/17 1
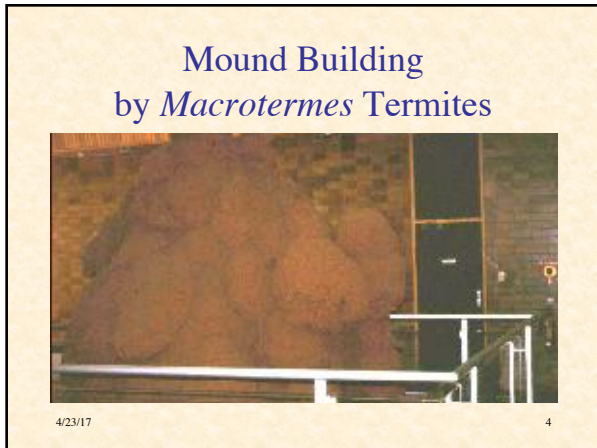
The Termes Project
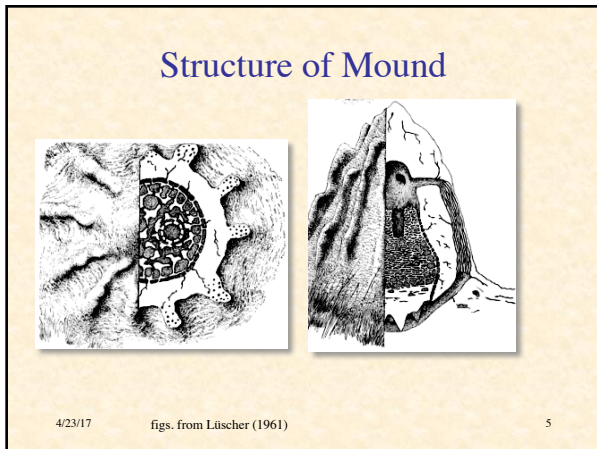
- Wyss Institute for Biologically Inspired Engineering, Harvard
- Introduction
- Algorithmic Assembly
- The Robot
- Final Video (2014)

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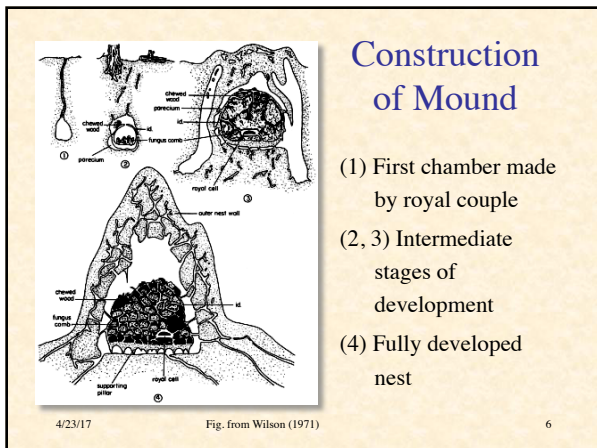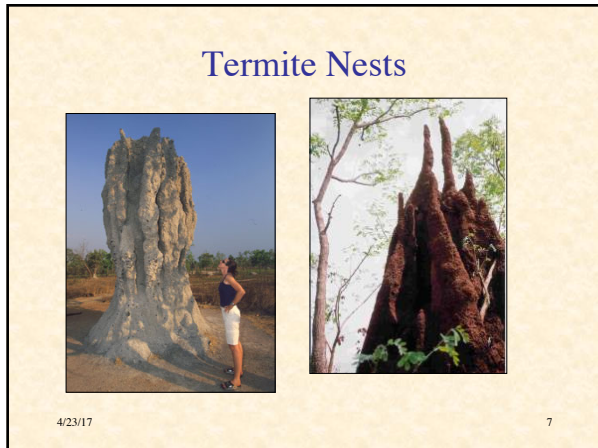Nest Building by Termites
(Natural and Artificial)

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Mound Building by *Macrotermes* Termites

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4

Structure of Mound

4/23/17   figs. from Lüscher (1961)   5

Construction of Mound

(1) First chamber made by royal couple

(2, 3) Intermediate stages of development

(4) Fully developed nest

4/23/17   Fig. from Wilson (1971)   6

Termite Nests

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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

4/23/17 Fig. from Solé & Goodwin 8

Construction of Royal Chamber

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Construction of Arch (1)
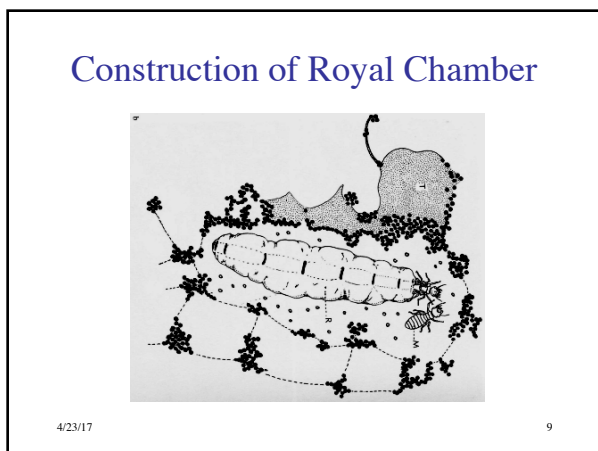
Construction of Arch (2)
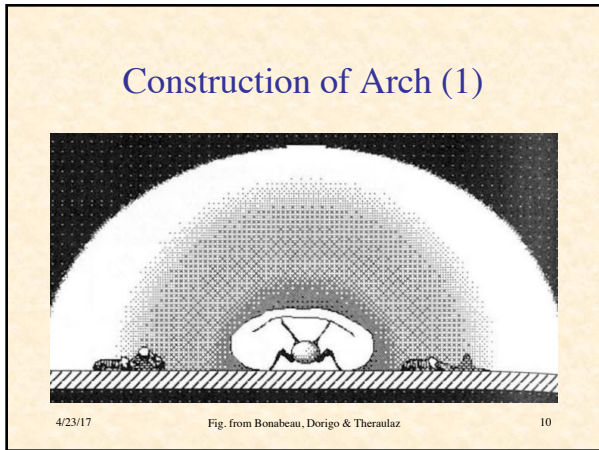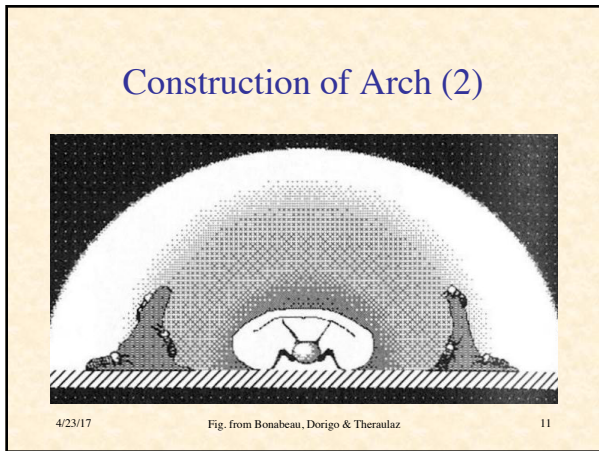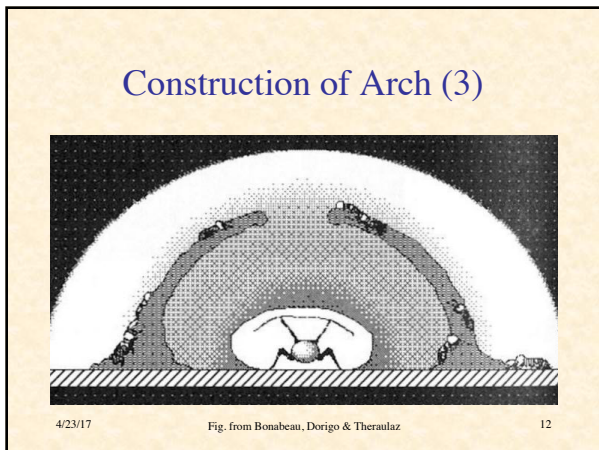
Construction of Arch (3)

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)

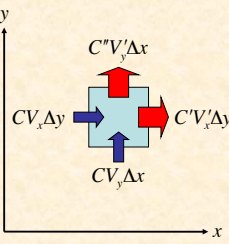$$\partial_t H = k_2 P - k_4 H + D_H \nabla^2 H$$

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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)

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

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

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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

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

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

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Explanation of Chemotaxis Term

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

  $-\nabla \cdot \mathbf{J} = -(\partial J_x / \partial x + \partial J_y / \partial y)$

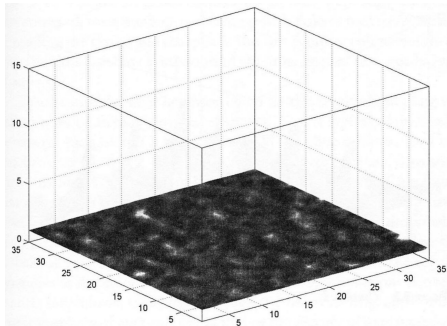- The flux velocity is proportional to the pheromone gradient

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

- The flux density is proportional to the number of moving termites

  $\mathbf{J} \propto C$

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

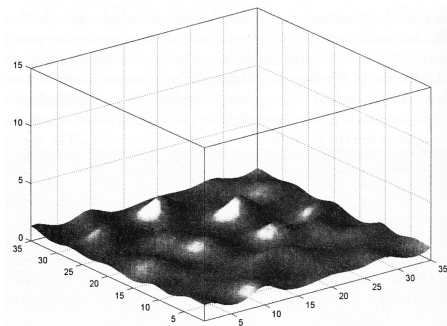4/23/17   19
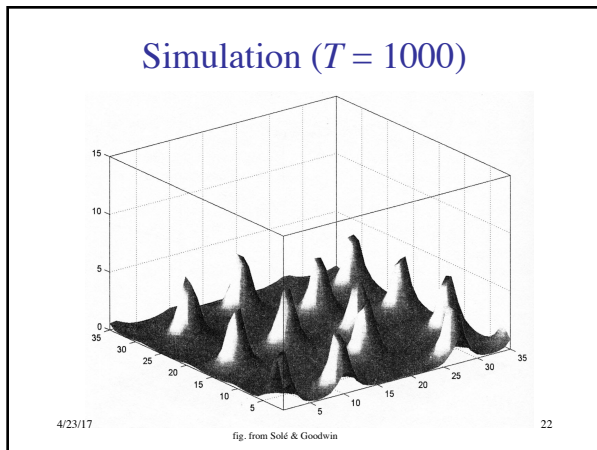
Simulation ($T = 0$)

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fig. from Solé & Goodwin

Simulation ($T = 100$)

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fig. from Solé & Goodwin

Simulation ($T = 1000$)

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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

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

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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)
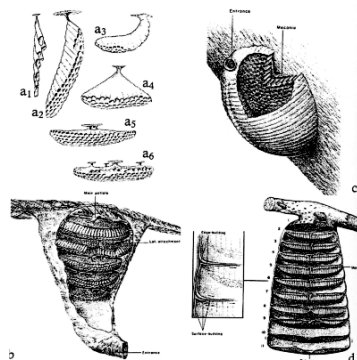 - governs sizes of galleries (template)

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Wasp Nest Building and Discrete Stigmergy

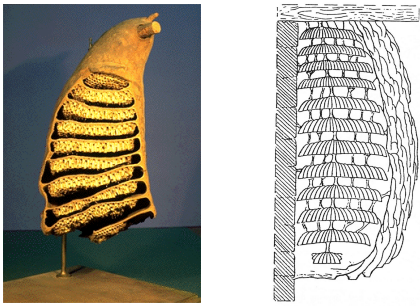4/23/17   Fig. from Solé & Goodwin   26

Structure of Some Wasp Nests

4/23/17   Fig. from *Self-Org. Biol. Sys.*   27

Adaptive Function of Nests

4/23/17   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

4/23/17   31
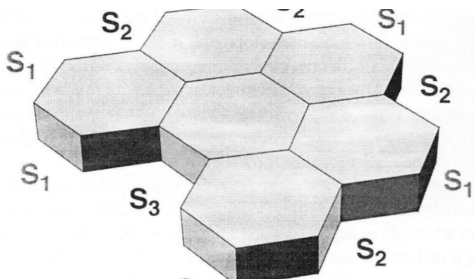
Discrete Stigmergy in Comb Construction
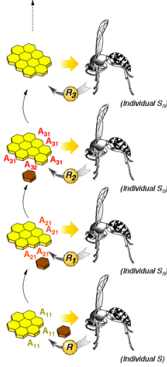
- Initially all sites are equivalent
- After addition of cell, qualitatively different sites created

4/23/17   Fig. from *Self-Org. Biol. Sys.*   32

Numbers and Kinds of Building Sites

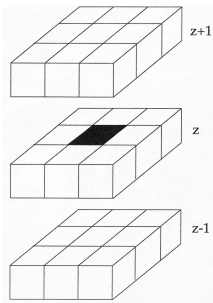4/23/17   Fig. from *Self-Org. Biol. Sys.*   33

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

4/23/17   34
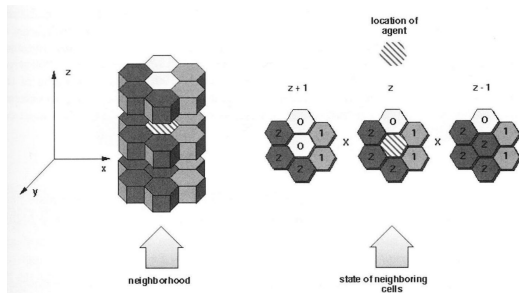
Cubic Neighborhood

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

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

4/23/17   Fig. from Solé & Goodwin   35
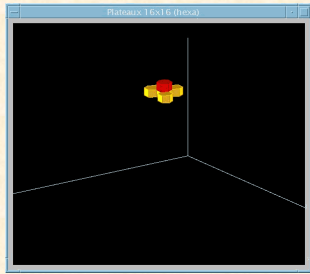
Hexagonal Neighborhood

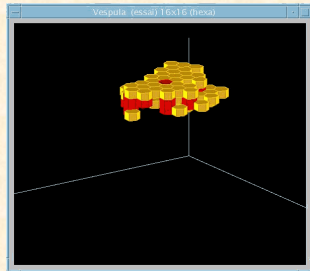4/23/17   Fig. from Bonabeau, Dorigo & Theraulaz   36

Example Construction

Plateaux 16x16 (hexa)

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Fig. from IASC Dept., ENST de Bretagne.

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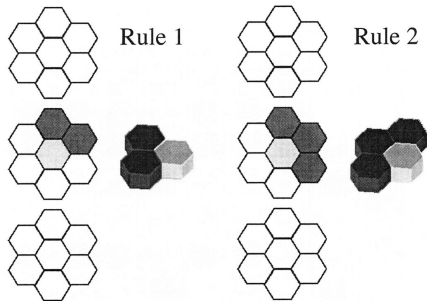## Another Example

Vespula (essai) 16x16 (hexa)

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fig. from IASC Dept., ENST de Bretagne.

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A Simple Pair of Rules

Rule 1   Rule 2

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

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Result from Deterministic Rules

4/23/17   Fig. from *Self-Org. in Biol. Sys.*   40
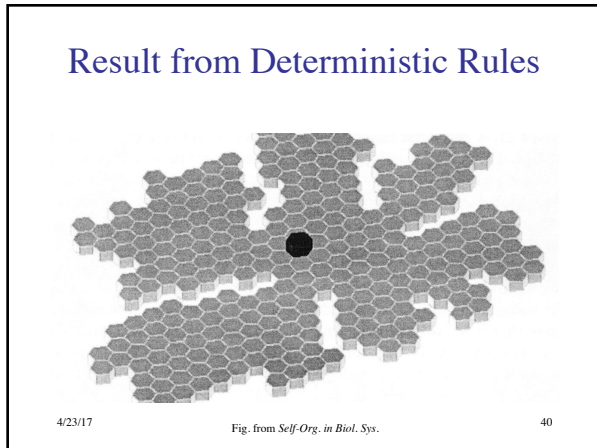
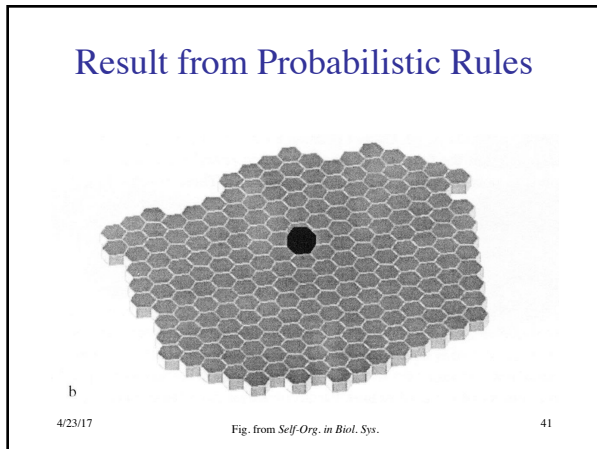## Result from Probabilistic Rules

b

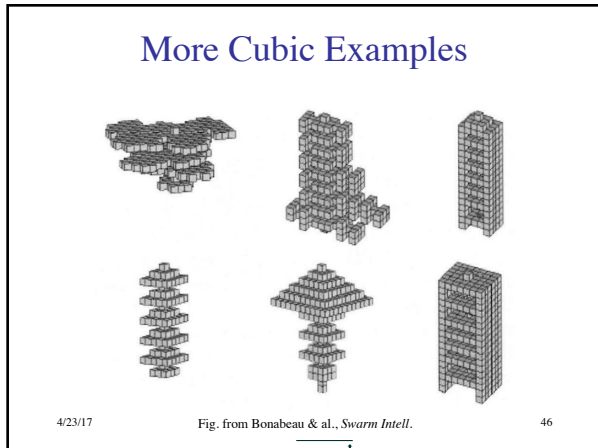4/23/17   Fig. from *Self-Org. in Biol. Sys.*   41

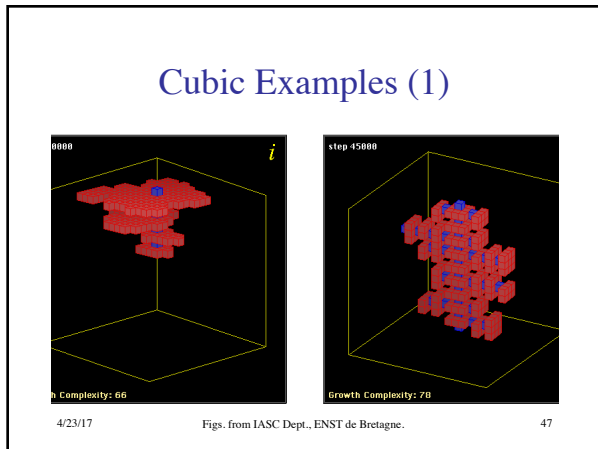## Example Rules for a More Complex Architecture

The following stimulus configurations cause the agent to deposit a type-1 brick:
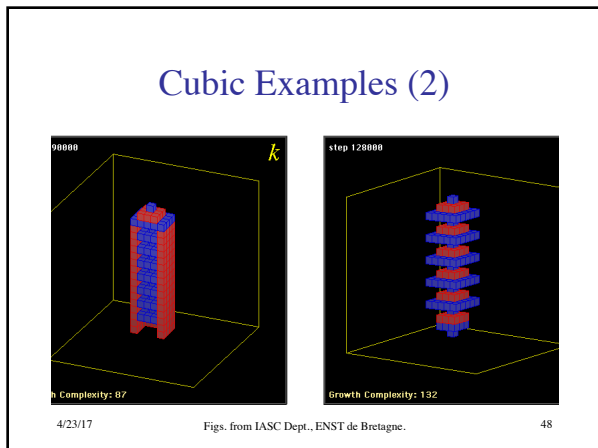
$$(1.1) \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 0 & \bullet & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$(1.2) \quad \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 1 & \bullet & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$
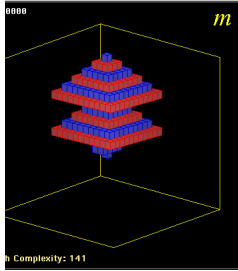
4/23/17   42

B

Second Group of Rules

For these configurations, deposit a type-2 brick

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Result

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

4/23/17   Fig. from Bonabeau & al., *Swarm Intell*.   44

Architectures Generated from Other Rule Sets

4/23/17   Fig. from Bonabeau & al., *Swarm Intell*.   45

More Cubic Examples

4/23/17   Fig. from Bonabeau & al., *Swarm Intell*.   46

Cubic Examples (1)

i

step 45000

Complexity: 66

Growth Complexity: 78

4/23/17   Figs. from IASC Dept., ENST de Bretagne.   47

Cubic Examples (2)

k

step 128000
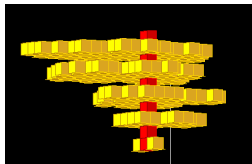
Complexity: 87

Growth Complexity: 132

4/23/17   Figs. from IASC Dept., ENST de Bretagne.   48

Cubic Examples (3)

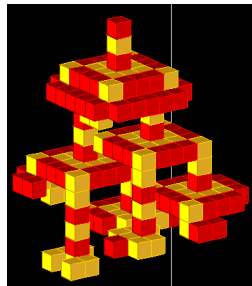4/23/17   Figs. from IASC Dept., ENST de Bretagne.   49

Cubic Examples (4)
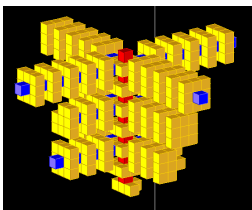

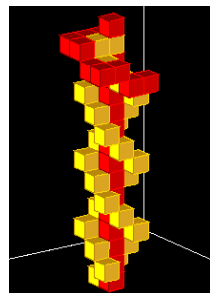4/23/17   Figs. from IASC Dept., ENST de Bretagne.   50

Cubic Examples (5)

4/23/17   Figs. from IASC Dept., ENST de Bretagne.   51
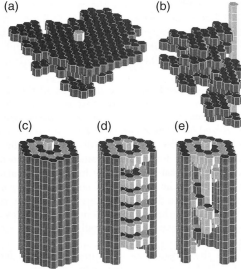
An Interesting Example

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

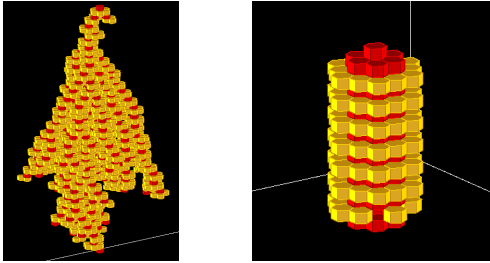4/23/17   Fig. from Theraulaz & Bonabeau (1995)   52

Similar Results with Hexagonal Lattice

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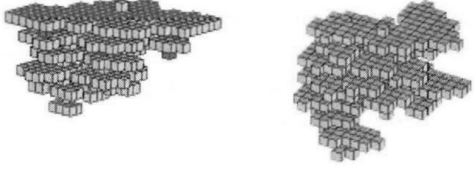- (e) has envelope cut away

4/23/17   Fig. from Bonabeau & al., *Swarm Intell*.   53

More Hexagonal Examples

4/23/17   Figs. from IASC Dept., ENST de Bretagne.   54
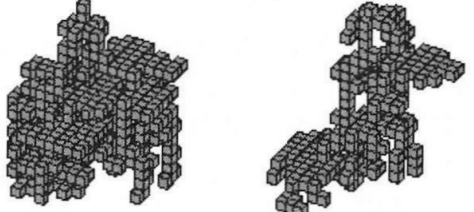
Effects of Randomness
(Coordinated Algorithm)

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

4/23/17   Fig. from Bonabeau & al., *Swarm Intell*.   55

Effects of Randomness
(Non-coordinated Algorithm)

4/23/17   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
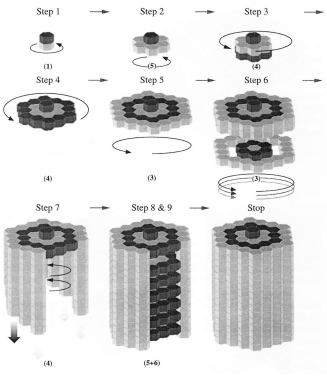 - can't prescribe two different actions for the same configuration
- Stimulating configurations for different building stages cannot overlap
- At each stage, "handshakes" and "interlocks" are required to prevent conflicts in parallel assembly

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More Formally…

- Let $C = \{c_1, c_2, \ldots, c_n\}$ 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 $C(S_{p+1})$

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Step 1 → Step 2 → Step 3 →
(1)   (5)   (4)
Step 4 → Step 5 → Step 6 →
(4)   (3)   (3)
Step 7 → Step 8 & 9 → Stop
(4)   (5+6)

Example

4/23/17   Fig. from Camazine &al., *Self-Org. Biol. Sys.*   60

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
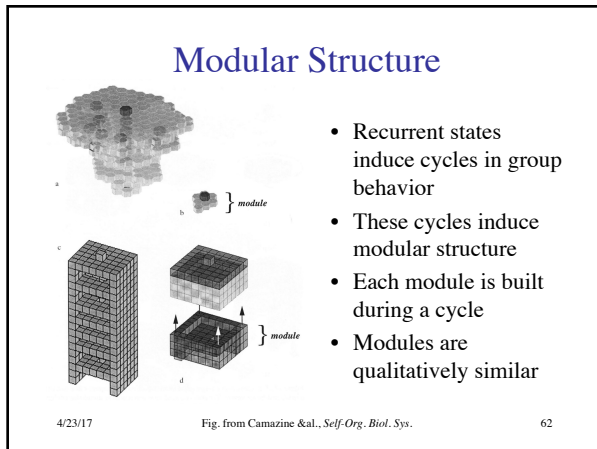- Modules are qualitatively similar

4/23/17   Fig. from Camazine &al., *Self-Org. Biol. Sys.*   62

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

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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
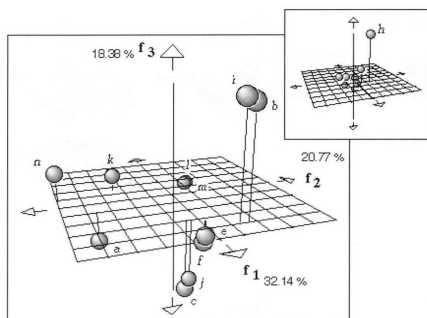 - $M_{ij} = 1$ if architecture j requires configuration i
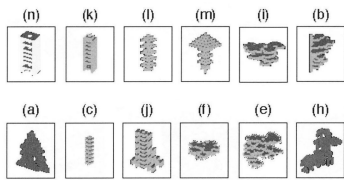
4/23/17   Fig. from Bonabeau & al., *Swarm Intell*.   65

Factorial Correspondence Analysis

4/23/17   Fig. from Bonabeau & al., *Swarm Intell*.   66

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/pso.html.

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