Fairy Circles

Fairy Circles

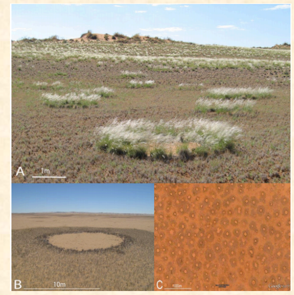
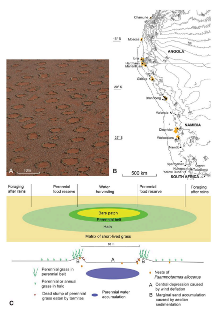


Fig. 1 (A) Spatial pattern of FCs. (B) Geographical distribution of FCs (black dots) and hotspots of FC occurrences at wider landscape scale (yellow clusters).



N Juergens Science 2013;339:1618-1621

Science AAAS
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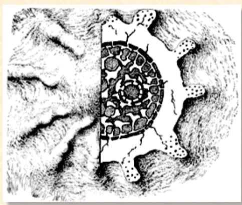
Part C

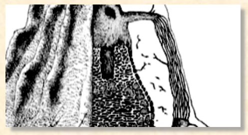
Nest Building

Nest Building by Termites (Natural and Artificial)

Mound Building by *Macrotermes* Termites

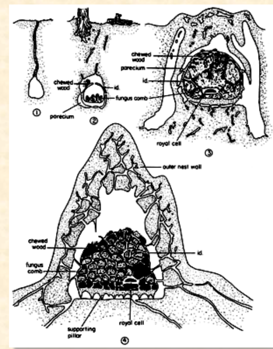
Structure of Mound





2013/4/12 figs. from Lüscher (1961) 7

Construction of Mound



(1) First chamber made by royal couple

(2, 3) Intermediate stages of development

(4) Fully developed nest

2013/4/12 Fig. from Wilson (1971) 8

Termite Nests

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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

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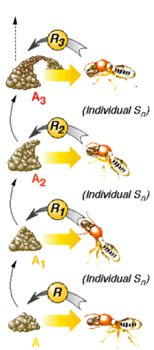
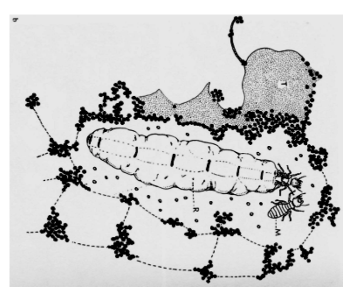
Basic Mechanism of Construction (Stigmergy)



- 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

2013/4/12 Fig. from Solé & Goodwin 11

Construction of Royal Chamber



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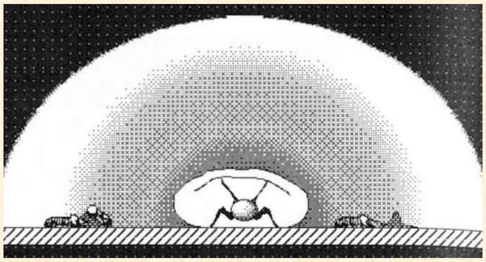
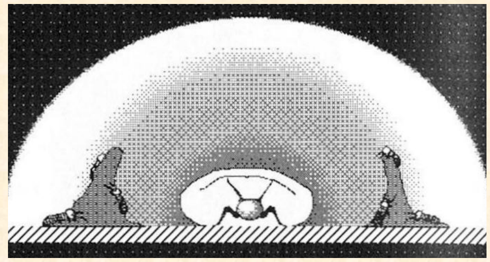
Construction of Arch (1)



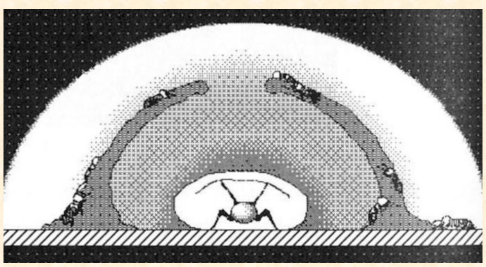
2013/4/12 Fig. from Bonabeau, Dorigo & Theraulaz 13

Construction of Arch (2)



2013/4/12 Fig. from Bonabeau, Dorigo & Theraulaz 14

Construction of Arch (3)



2013/4/12 Fig. from Bonabeau, Dorigo & Theraulaz 15

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)

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

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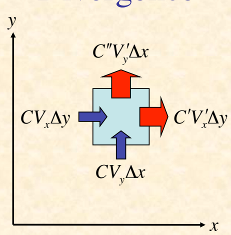
Explanation of Divergence



- 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

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

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

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

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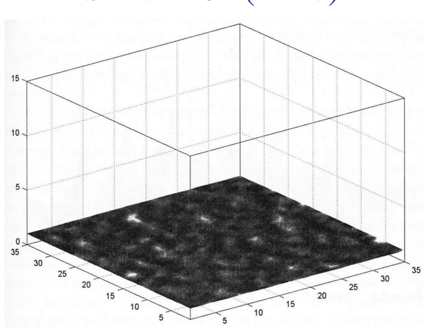
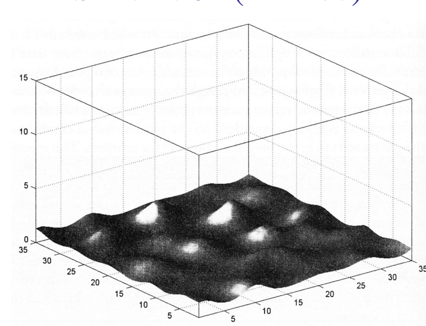
Simulation ($T = 0$)



2013/4/12 fig. from Solé & Goodwin 23

Simulation ($T = 100$)



2013/4/12 fig. from Solé & Goodwin 24

Simulation ($T = 1000$)

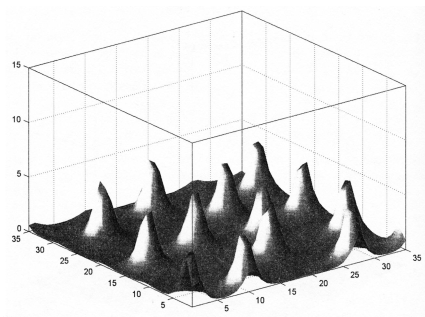


fig. from Solé & Goodwin

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

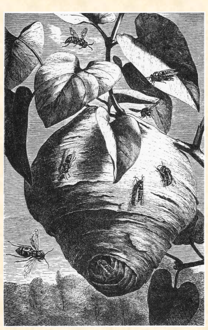
$$C_0 = \frac{\Phi}{k_1}, \quad H_0 = \frac{\Phi}{k_4}, \quad P_0 = \frac{\Phi}{k_2}$$

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

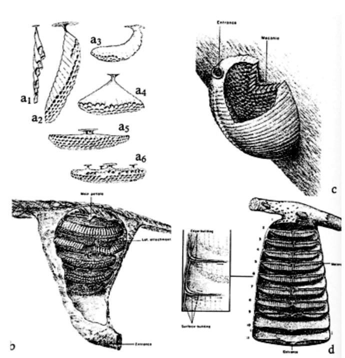
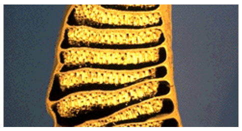
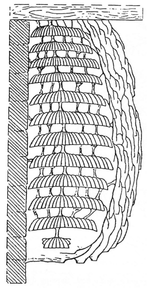


Fig. from *Self-Org. Biol. Sys.*

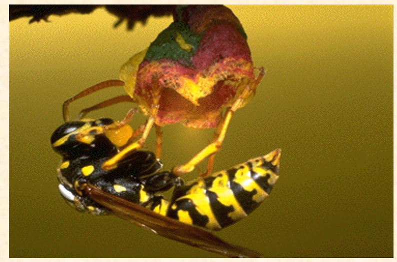
Adaptive Function of Nests





2013/4/12 Figs. from Self-Org. Biol. Sys, 31

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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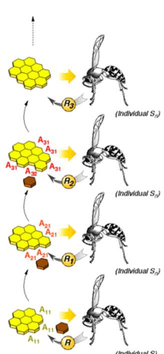
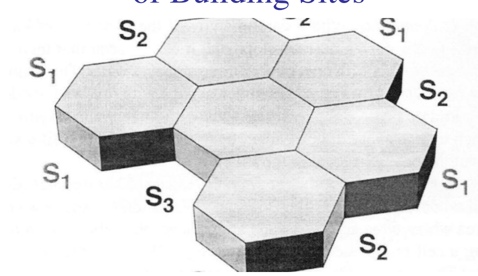


Discrete Stigmergy in Comb Construction

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

2013/4/12 Fig. from *Self-Org. Biol. Sys.* 35

Numbers and Kinds of Building Sites



2013/4/12 Fig. from *Self-Org. Biol. Sys.* 36

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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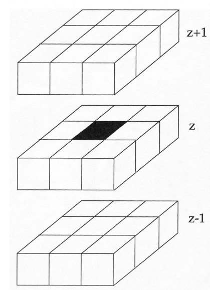
Cubic Neighborhood

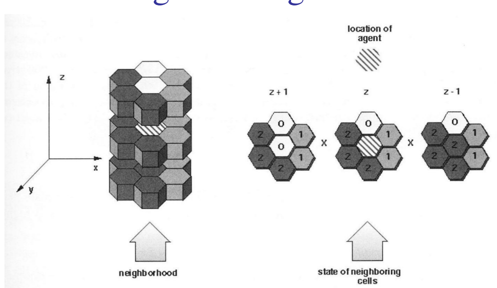


- Deposited brick depends on states of 26 surrounding cells
- Configuration of surrounding cells may be represented by matrices:

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

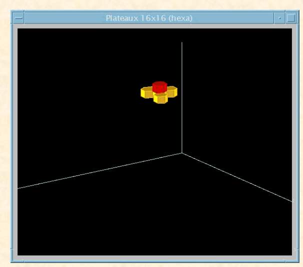
2013/4/12 Fig. from Solé & Goodwin 38

Hexagonal Neighborhood



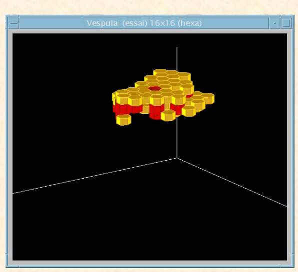
2013/4/12 Fig. from Bonabeau, Dorigo & Theraulaz 39

Example Construction



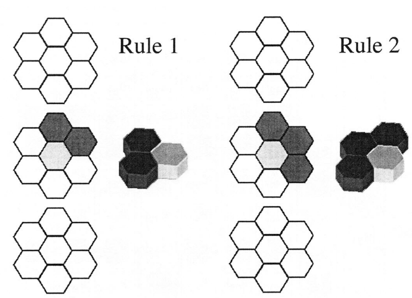
2013/4/12 Fig. from IASC Dept., ENST de Bretagne. 40

Another Example



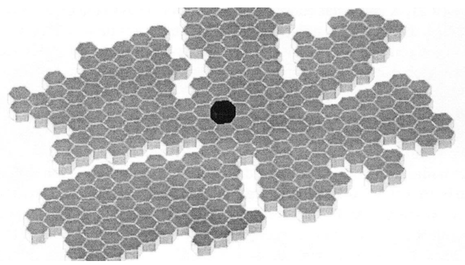
2013/4/12 fig. from IASC Dept., ENST de Bretagne. 41

A Simple Pair of Rules



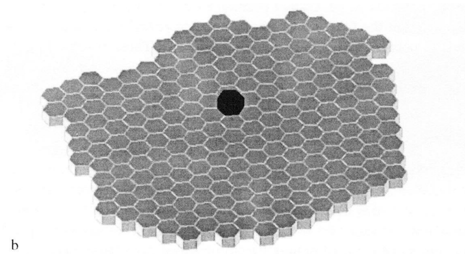
2013/4/12 Fig. from *Self-Org. in Biol. Sys.* 42

Result from Deterministic Rules



2013/4/12 Fig. from *Self-Org. in Biol. Sys.* 43

Result from Probabilistic Rules



2013/4/12 Fig. from *Self-Org. in Biol. Sys.* 44

Example Rules for a More Complex Architecture

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

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

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

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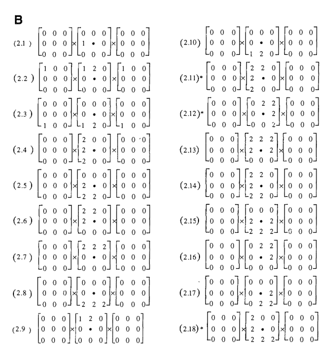

Second Group of Rules

For these configurations, deposit a type-2 brick

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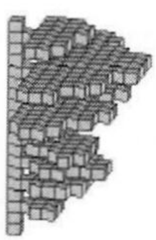
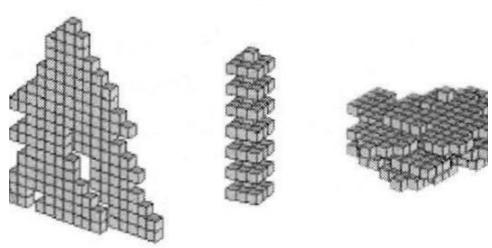
Result

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



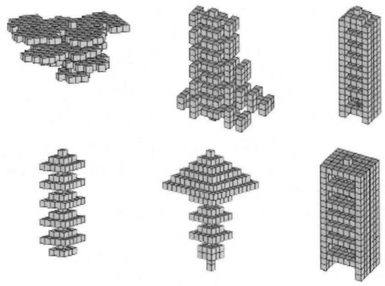
2013/4/12 Fig. from Bonabeau & al., *Swarm Intell.* 47

Architectures Generated from Other Rule Sets



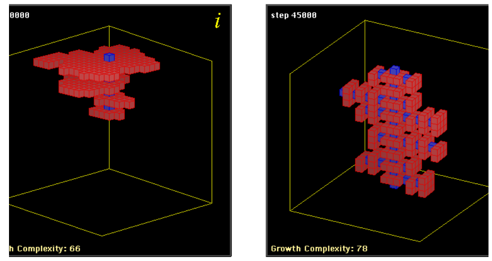
2013/4/12 Fig. from Bonabeau & al., *Swarm Intell.* 48

More Cubic Examples



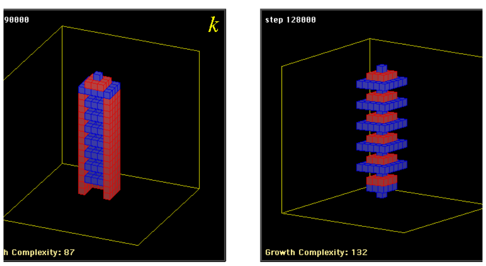
2013/4/12 Fig. from Bonabeau & al., *Swarm Intell*. 49

Cubic Examples (1)



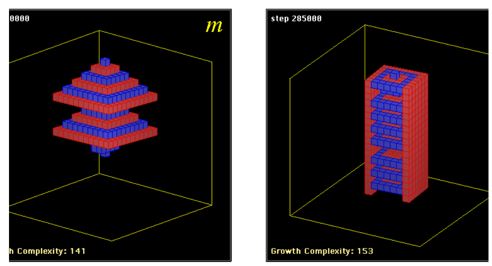
2013/4/12 Figs. from IASC Dept., ENST de Bretagne. 50

Cubic Examples (2)



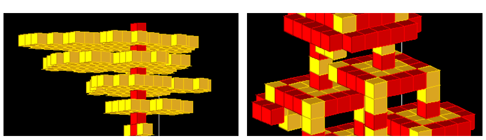
2013/4/12 Figs. from IASC Dept., ENST de Bretagne. 51

Cubic Examples (3)



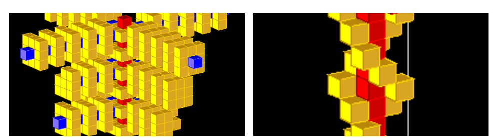
2013/4/12 Figs. from IASC Dept., ENST de Bretagne. 52

Cubic Examples (4)



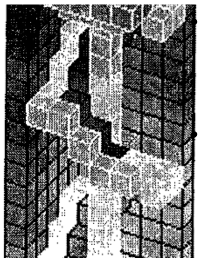
2013/4/12 Figs. from IASC Dept., ENST de Bretagne. 53

Cubic Examples (5)



2013/4/12 Figs. from IASC Dept., ENST de Bretagne. 54

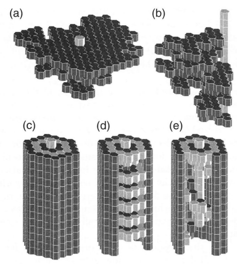
An Interesting Example



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

2013/4/12 Fig. from Theraulaz & Bonabeau (1995) 55

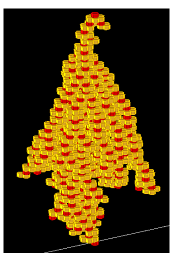
Similar Results with Hexagonal Lattice

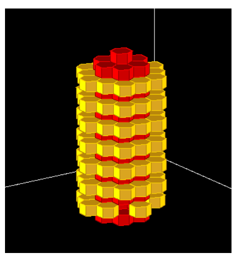


- 20×20×20 lattice
- 10 wasps
- All resemble nests of wasp species
- (d) is (c) with envelope cut away
- (e) has envelope cut away

2013/4/12 Fig. from Bonabeau & al., *Swarm Intell*. 56

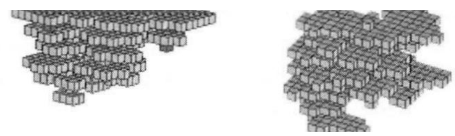
More Hexagonal Examples





2013/4/12 Figs. from IASC Dept., ENST de Bretagne. 57

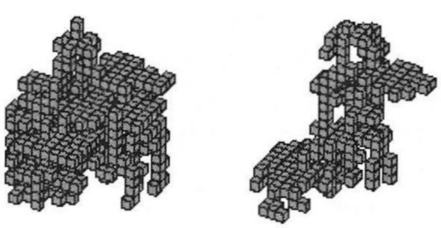
Effects of Randomness (Coordinated Algorithm)



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

2013/4/12 Fig. from Bonabeau & al., *Swarm Intell*. 58

Effects of Randomness (Non-coordinated Algorithm)



2013/4/12 Fig. from Bonabeau & al., *Swarm Intell*. 59

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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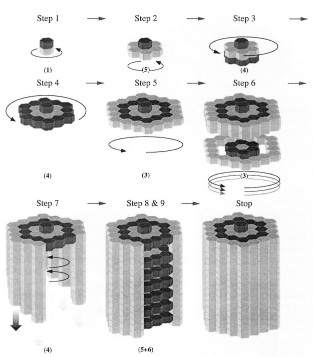
Coordinated Algorithm

- 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

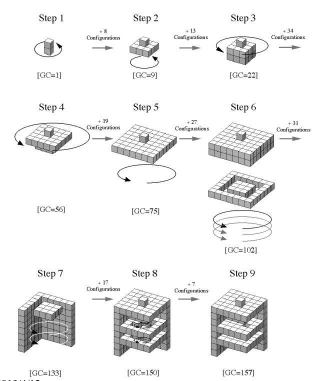
More Formally…

- 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

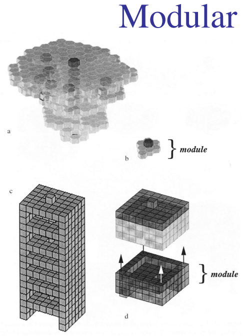
 Fig. from Camazine &al., *Self-Org. Biol. Sys.*



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

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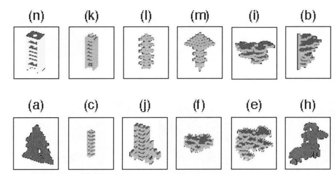
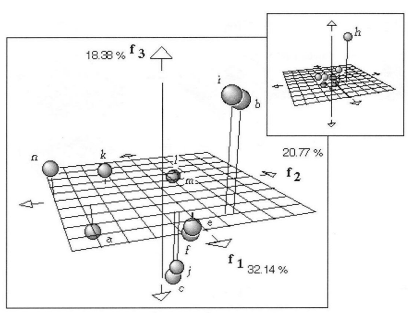
Analysis

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



2013/4/12 Fig. from Bonabeau & al., *Swarm Intell.* 68

Factorial Correspondence Analysis



2013/4/12 Fig. from Bonabeau & al., *Swarm Intell.* 69

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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The Termes Project

Wyss Institute for Biologically Inspired Engineering

Harvard

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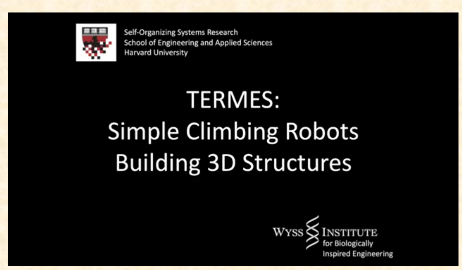
Introduction



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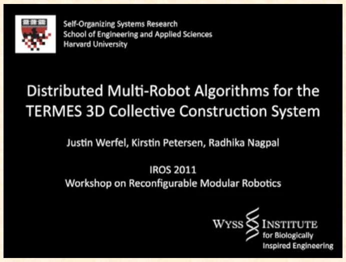
Algorithmic Assembly



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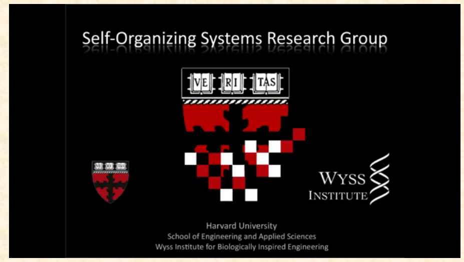
The Robot



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Additional Bibliography

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