## Homework for CS 594

- See: cs.utk.edu/~mclennan/Classes/420/handouts/Homework-594-1.pdf
- or look under “Projects and Assignments”
- Due Sept. 29
- Required for CS 594 students
- Extra-credit for CS 420 students

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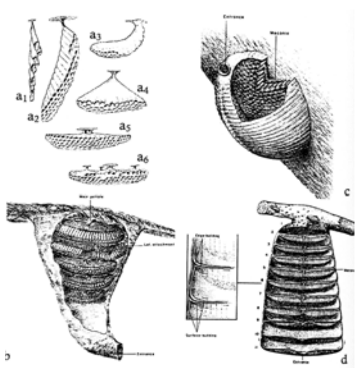
## Wasp Nest Building and Discrete Stigmergy

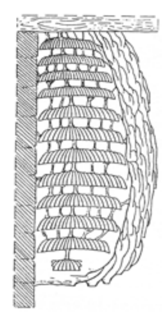
9/22/04 Fig. from Solé & Goodwin 2

## Structure of Some Wasp Nests



9/22/04 Fig. from *Self-Org. Biol. Sys.* 3

## Adaptive Function of Nests



9/22/04 Figs. from Self-Org. Biol. Sys, 4

## How Do They Do It?



## Lattice Swarms

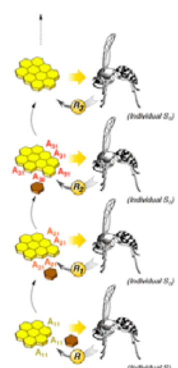
(developed by Theraulaz & Bonabeau)



## 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



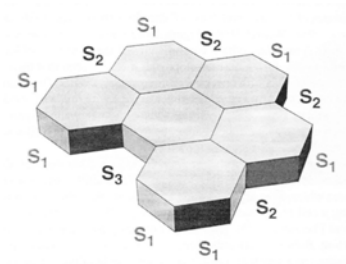


## Discrete Stigmergy in Comb Construction

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

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

## Numbers and Kinds of Building Sites




9/22/04 Fig. from *Self-Org. Biol. Sys.* 9

## 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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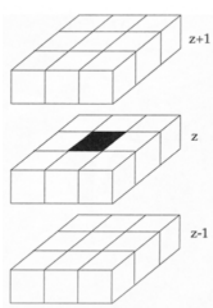
## Cubic Neighborhood

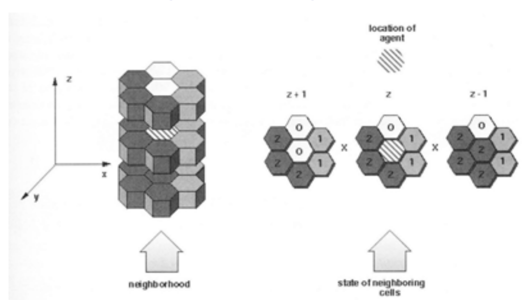



- Deposited brick depends on states of 26 surrounding cells
- Configuration of surrounding cells may be represented by matrices:

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

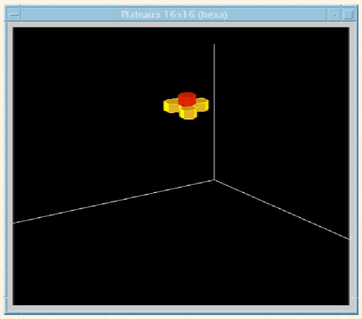
9/22/04 Fig. from Solé & Goodwin 11

## Hexagonal Neighborhood



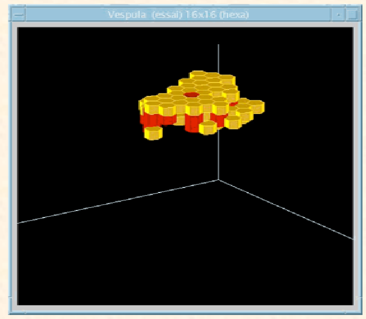

9/22/04 Fig. from Bonabeau, Dorigo & Theraulaz 12

## Example Construction



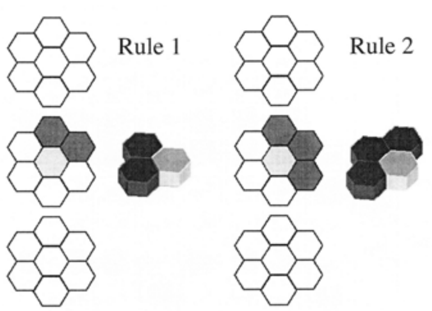
9/22/04 Fig. from IASC Dept., ENST de Bretagne. 13

## Another Example



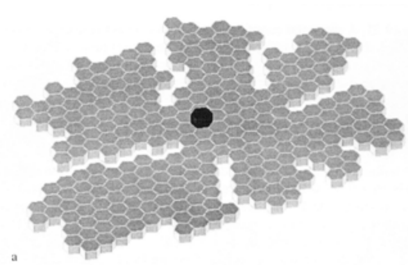
9/22/04 fig. from IASC Dept., ENST de Bretagne. 14

## A Simple Pair of Rules




9/22/04 Fig. from *Self-Org. in Biol. Sys.* 15

## Result from Deterministic Rules



9/22/04 Fig. from *Self-Org. in Biol. Sys.* 16

## Result from Probabilistic Rules

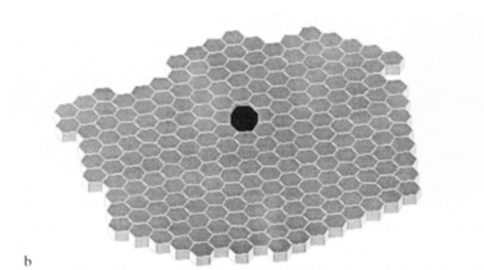



Fig. from *Self-Org. in Biol. Sys.*

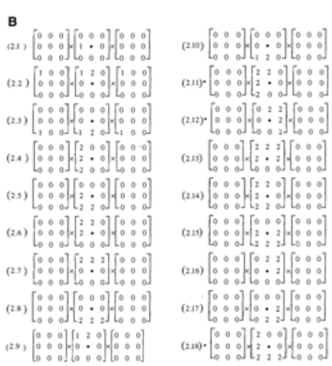

## Example Rules for a More Complex Architecture

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

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

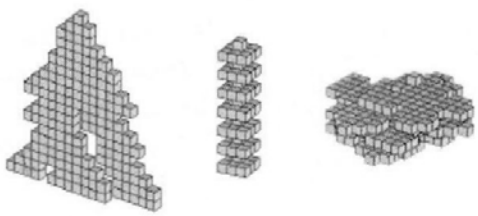


 Fig. from Bonabeau & al., *Swarm Intell*. 

## More Cubic Examples

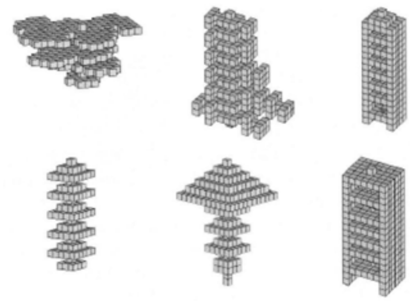
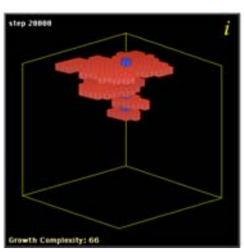
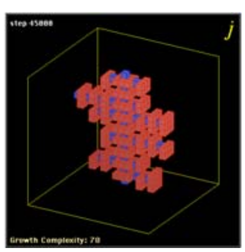


 Fig. from Bonabeau & al., *Swarm Intell*. 

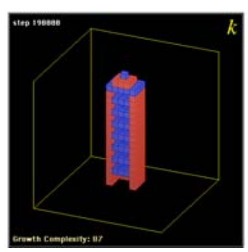
## Cubic Examples (1)

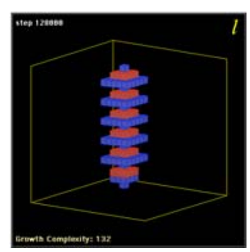



 Figs. from IASC Dept., ENST de Bretagne. 

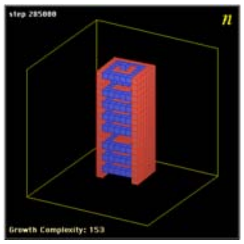
## Cubic Examples (2)



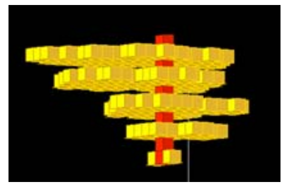

 Figs. from IASC Dept., ENST de Bretagne. 

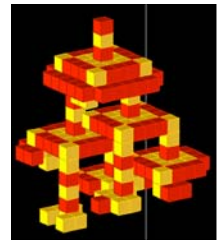
## Cubic Examples (3)


9/22/04 Figs. from IASC Dept., ENST de Bretagne. 25

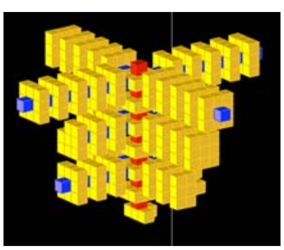
## Cubic Examples (4)

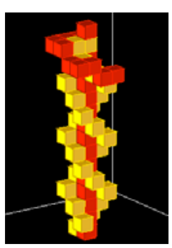




9/22/04 Figs. from IASC Dept., ENST de Bretagne. 26

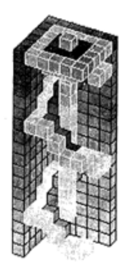
## Cubic Examples (5)





9/22/04 Figs. from IASC Dept., ENST de Bretagne. 27

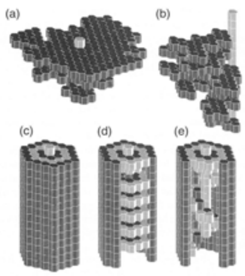
## An Interesting Example



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

9/22/04 Fig. from Theraulaz & Bonabeau (1995) 28

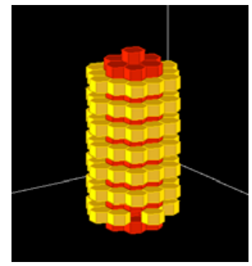
## Similar Results with Hexagonal Lattice




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

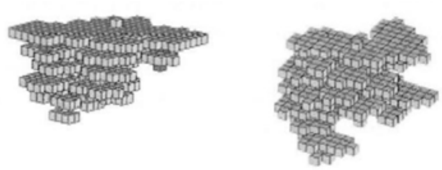
9/22/04 Fig. from Bonabeau & al., *Swarm Intell*. 29

## More Hexagonal Examples



9/22/04 Figs. from IASC Dept., ENST de Bretagne. 30

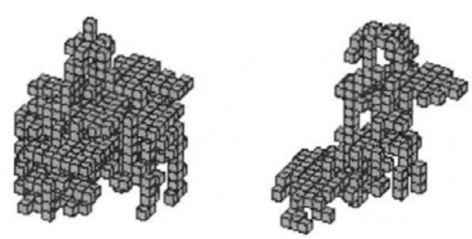
## Effects of Randomness (Coordinated Algorithm)



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

9/22/04 Fig. from Bonabeau & al., *Swarm Intell*. 31

## Effects of Randomness (Non-coordinated Algorithm)



9/22/04 Fig. from Bonabeau & al., *Swarm Intell*. 32

## 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

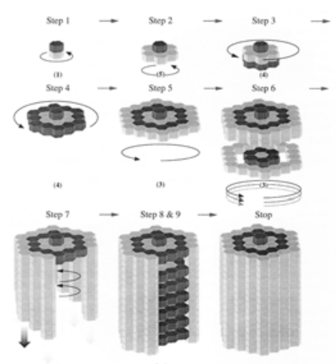
- Non-conflicting rules
  - can't prescribe two different actions for the same configuration
- Stimulating configurations for different building stages cannot overlap
- At each stage, "handshakes" and "interlocks" are required to prevent conflicts in parallel assembly



## More Formally…

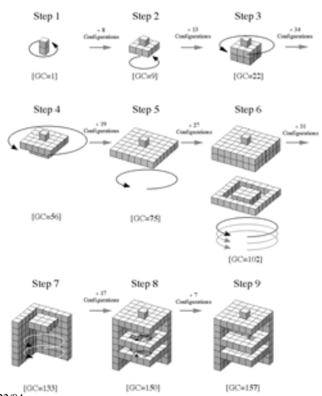
- Let $C = \{c_1, c_2, \ldots, c_n\}$ be the set of local stimulating configurations
- Let $(S_1, S_2, \ldots, S_m)$ be a sequence of assembly stages
- These stages partition $C$ into mutually disjoint subsets $C(S_p)$
- Completion of $S_p$ signaled by appearance of a configuration in $C(S_{p+1})$






## Example

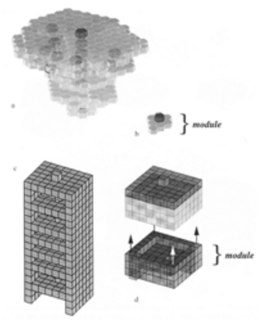
9/22/04 Fig. from Camazine &al., *Self-Org. Biol. Sys.* 




## Example

9/22/04 fig. from IASC Dept., ENST de Bretagne. 37

## 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

9/22/04 Fig. from Camazine &al., *Self-Org. Biol. Sys.* 38

## 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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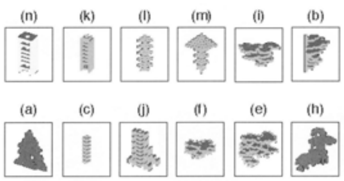
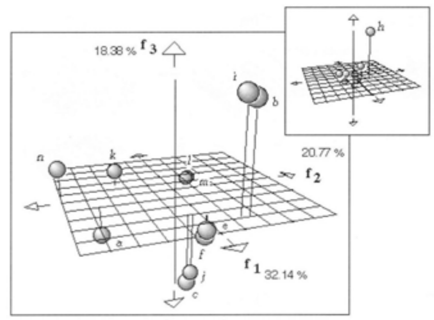
## Analysis

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




9/22/04 Fig. from Bonabeau & al., *Swarm Intell.* 41

## Factorial Correspondence Analysis




9/22/04 Fig. from Bonabeau & al., *Swarm Intell.* 42

## 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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