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

Wasp Nest Building and Discrete Stigmergy

Structure of Some Wasp Nests

Adaptive Function of Nests
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**

![Diagram of building sites](image1)

**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:

```
<table>
<thead>
<tr>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
```

**Hexagonal Neighborhood**

![Diagram of hexagonal neighborhood](image2)
Part 3: Autonomous Agents

Example Construction

Another Example

A Simple Pair of Rules

Result from Deterministic Rules
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:

\[
\begin{align*}
\text{(11)} & : \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\
\text{(1.2)} & : \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
\end{align*}
\]

Second Group of Rules

For these configurations, deposit a type-2 brick

Result

- 20x20x20 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

More Cubic Examples

Cubic Examples (1)

Cubic Examples (2)
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

More Hexagonal Examples

Effects of Randomness (Coordinated Algorithm)

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

Effects of Randomness (Non-coordinated Algorithm)
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 $C(S_{p+1})$
Part 3: Autonomous Agents

Example

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

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
Part 3: Autonomous Agents

Analysis

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

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