VI
Autonomous Agents &
Self-Organization

Part A
Nest Building

Autonomous Agent
• “a unit that interacts with its environment (which probably consists of other agents)
• but acts independently from all other agents in that it does not take commands from some seen or unseen leader,
• nor does an agent have some idea of a global plan that it should be following.”
  —Flake (p. 261)

Nest Building by Termites (Natural and Artificial)

Resnick’s Termites (“Turmites”)

Basic procedure
• Wander randomly
• If you are not carrying anything and you bump into a wood chip, pick it up.
• If you are carrying a wood chip and you bump into another wood chip, put down the woodchip you are carrying

  —Resnick, Turtles, Termites, and Traffic Jams
**Microbehavior of Termites**

1. **Search for wood chip:**
   a) If at chip, pick it up
   b) otherwise wiggle, and go back to (a)

2. **Find a wood pile:**
   a) If at chip, it’s found
   b) otherwise wiggle, and go back to (a)

3. **Find an empty spot and put chip down:**
   a) If at empty spot, put chip down & jump away
   b) otherwise, turn, take a step, and go to (a)

**Demonstration**

- Run Termites.nlogo

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**Decrease in Number of Piles**

![Graph showing decrease in number of piles over iterations](image)

**Why does the number of piles decrease?**

- A pile can grow or shrink
- But once the last chip is taken from a pile, it can never restart
- Is there any way the number of piles can increase?
- Yes, and existing pile can be broken into two

**Termite-Mediated Condensation**

- Number of chips is conserved
- Chips do not move on own; movement is mediated by termites
- Chips preferentially condense into piles
- Increasing termites, increases number of chips in fluid (randomly moving) state
- Like temperature

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**More Termites**

<table>
<thead>
<tr>
<th>Termites</th>
<th>2000 steps</th>
<th>10 000 steps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>num. piles</td>
<td>avg. size</td>
</tr>
<tr>
<td>1000</td>
<td>102</td>
<td>15</td>
</tr>
<tr>
<td>4000</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>
An Experiment to Make the Number Decrease More Quickly

- Problem: piles may grow or shrink
- Idea: protect “investment” in large piles
- Termites will not take chips from piles greater than a certain size
- Result: number decreases more quickly
- Most chips are in piles
- But never got less than 82 piles

Conclusion

- In the long run, the “dumber” strategy is better
- Although it’s slower, it achieves a better result
- By not protecting large piles, there is a small probability of any pile evaporating
- So the smaller “large piles” can evaporate and contribute to the larger “large piles”
- Even though this strategy makes occasional backward steps, it outperforms the attempt to protect accomplishments

Mound Building by *Macrotermes* Termites

Structure of Mound

Fig. from Lüscher (1961)

Construction of Mound

(1) First chamber made by royal couple
(2, 3) Intermediate stages of development
(4) Fully developed nest

Termite Nests

Fig. from Wilson (1971)
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

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

Construction of Royal Chamber

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

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 $r,t$
- $\Phi =$ constant flow of laden termites into system

Equation for $P$
(Deposited Cement with Pheromone)

$$\frac{\partial}{\partial t} P = k_1 C - k_2 P$$

Equation for $H$
(Concentration of Pheromone)

$$\frac{\partial}{\partial t} H = k_2 P - k_4 H + D_H \nabla^2 H$$

Equation for $C$
(Density of Laden Termites)

$$\frac{\partial}{\partial t} C = \Phi - k_1 C + D_C \nabla^2 C - \gamma \nabla \cdot (C \nabla H)$$

Explaination of Divergence

- velocity field $= V(x,y)$
  $= iV_x(x,y) + jV_y(x,y)$
- $C(x,y) =$ density
- outflow rate $= \Delta_x (CV_x) \Delta y + \Delta_y (CV_y) \Delta x$
- outflow rate / unit area
  $\frac{\Delta_x (CV_x)}{\Delta x} + \frac{\Delta_y (CV_y)}{\Delta y} = \nabla \cdot CV$
### Explanation of Chemotaxis Term

- The termite flow into a region is the negative divergence of the flux through it:
  \[ -\nabla \cdot J = -(\frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y}) \]
- The flux velocity is proportional to the pheromone gradient:
  \[ J \propto \nabla H \]
- The flux density is proportional to the number of moving termites:
  \[ J \propto C \]
- Hence, \[ -\nabla \cdot J = -\nabla(CVH) \]

### 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:
  \[ C_0 = \frac{\Phi}{k_1}, \quad H_0 = \frac{\Phi}{k_2}, \quad P_0 = \frac{\Phi}{k_3} \]

### Simulation ($T = 0$)

![Simulation ($T = 0$)](fig_from_Sole_Goodwin)

### Simulation ($T = 100$)

![Simulation ($T = 100$)](fig_from_Sole_Goodwin)

### Simulation ($T = 1000$)

![Simulation ($T = 1000$)](fig_from_Sole_Goodwin)

### NetLogo Simulation of Deneubourg Model

Run Pillars3D.nlogo
Part 3A: Nest Building

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

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

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

Hexagonal Neighborhood

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

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]
Example Construction

Fig. from IASC Dept., ENST de Bretagne.

Another Example

Fig. from IASC Dept., ENST de Bretagne.

A Simple Pair of Rules

Rule 1

Rule 2

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

Result from Deterministic Rules

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

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:

\[
\begin{align*}
(1) & : \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\
(2) & : \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
\end{align*}
\]
Part 3A: Nest Building

Second Group of Rules

For these configurations, deposit a type-2 brick

Result

- $20 \times 20 \times 20$ lattice
- 10 wasps
- After 20,000 simulation steps
- Axis and plateaus
- Resembles nest of *Parachartergus*

Architectures Generated from Other Rule Sets

More Cubic Examples

Cubic Examples (1)

Cubic Examples (2)
Cubic Examples (3)

Cubic Examples (4)

Cubic Examples (5)

An Interesting Example

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

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

More Hexagonal Examples
Part 3A: Nest Building

Effects of Randomness (Coordinated Algorithm)

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

Fig. from Bonabeau & al., Swarm Intell.

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 $C(S_{p+1})$

Example

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

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**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 $M_i$:
  - 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