Part C

Nest Building
The Termes Project

• Wyss Institute for Biologically Inspired Engineering, Harvard
• Introduction
• Algorithmic Assembly
• The Robot
• Final Video (2014)
Nest Building by Termites (Natural and Artificial)
Structure of Mound

figs. 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
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)

Fig. from Bonabeau, Dorigo & Theraulaz
Construction of Arch (3)

Fig. from Bonabeau, Dorigo & Theraulaz
Basic Principles

• Continuous (quantitative) stigmergy
• Positive feedback:
  – via pheromone deposition
• Negative feedback:
  – depletion of soil granules & competition between pillars
  – pheromone decay
Deneubourg Model

- $H(r, t) = \text{concentration of cement pheromone in air at location } r \& \text{ time } t$
- $P(r, t) = \text{amount of deposited cement with still active pheromone at } r, t$
- $C(r, t) = \text{density of laden termites at } r, t$
- $\Phi = \text{constant flow of laden termites into system}$
Equation for $P$
(Deposited Cement with Pheromone)

\[ \partial_t P \text{ (rate of change of active cement)} = k_1 C \text{ (rate of cement deposition by termites)} - k_2 P \text{ (rate of pheromone loss to air)} \]

\[ \partial_t P = k_1 C - k_2 P \]
Equation for $H$
(Concentration of Pheromone)

\[ \partial_t H \text{ (rate of change of concentration)} = k_2 P \text{ (pheromone from deposited material)} - k_4 H \text{ (pheromone decay)} + D_H \nabla^2 H \text{ (pheromone diffusion)} \]

\[ \partial_t H = k_2 P - k_4 H + D_H \nabla^2 H \]
Equation for $C$
(Density of Laden Termites)

$\partial_t C$ (rate of change of concentration) =

$\Phi$ (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)

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

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

- The termite flow into a region is the negative divergence of the flux through it
  \[ -\nabla \cdot \mathbf{J} = -\left( \frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} \right) \]
- 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, \[ -\gamma \nabla \cdot \mathbf{J} = -\gamma \nabla \cdot (C \nabla H) \]
Simulation ($T = 0$)

fig. from Solé & Goodwin
Simulation \( (T = 100) \)
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
Structure of Some Wasp Nests

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

Fig. from Self-Org. Biol. Sys.

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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:

\[
\begin{bmatrix}
0 & 0 & 0 \\
1 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\times
\begin{bmatrix}
0 & 0 & 0 \\
1 & \bullet & 0 \\
0 & 0 & 0
\end{bmatrix}
\times
\begin{bmatrix}
0 & 0 & 0 \\
1 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]
Hexagonal Neighborhood

Fig. from Bonabeau, Dorigo & Theraulaz
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
Example Rules for a More Complex Architecture

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

\[
\begin{align*}
(1.1) & \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 0 & \bullet & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\
(1.2) & \quad \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 1 & \bullet & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
\end{align*}
\]
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
More Cubic Examples

Fig. from Bonabeau & al., *Swarm Intell.*
Cubic Examples (1)

Figs. from IASC Dept., ENST de Bretagne.
Cubic Examples (2)
Cubic Examples (3)
Cubic Examples (4)

Figs. from IASC Dept., ENST de Bretagne.
Cubic Examples (5)

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Figs. from IASC Dept., ENST de Bretagne.
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**

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
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
Analysis

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

Fig. from Bonabeau & al., *Swarm Intell.*
Factorial Correspondence Analysis

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


