Collective Building and Self-Assembly in Natural and Artificial Systems
Collective building and self-assembly in natural systems
  - Examples
  - Mechanisms
  - Modeling
  - Reverse engineering with GA

Collective building and self-assembly in artificial systems
  - Passive bricks
  - Active mechatronic units
Collective Building and Self-Assembly in Natural Systems
Natural Examples of Collective Building

Nest building in the wasp
Polistes dominulus

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Natural Examples of Collective Building

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Natural Examples of Collective Building
Natural Examples of Collective Building

© Masson
Natural Examples of Collective Digging

Digging a network of galleries in the ant *Messor sancta*

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Building behaviour in the ant *Lasius niger*

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Coordination Mechanisms for the Building Activity
Collective Building Mechanisms

1. The plan
2. Environmental template
3. Stigmergy
Collective Building Mechanisms

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Collective Building Mechanisms

The plan
Collective Building Mechanisms

1. The plan
2. Environmental template
3. Stigmergy
Environmental template

- The building plan pre-exists in the environment under the form of spatial heterogeneities.

- The social insect activity only outlines these pre-existing environmental template. Environmental changes performed by insects play a minimal role in the building activity itself.

- There are several forms of environmental template:
  - gradients naturally existing in the environment (humidity, temperature …)
  - chemical gradients generated by one or more individuals of the colony
Nest Structure in the Ant *Acantholepis Custodiens*

3.00 a.m.

3.00 p.m.

- Eggs
- Larvae
- Pupae
Exemple de gabarit chez le termite Macrotermes subhyalinus

La reine émet une phéromone qui crée autour d’elle un gradient décroissant dont la forme générale épouse les contours de son corps.
Convective Air Flows and Complex Chemical Templates
Convective Air Flows and Complex Chemical Templates

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1. The plan
2. Environmental template
3. Stigmergy
It defines a class of mechanisms exploited by social insects to coordinate and control their activity via indirect interactions.

Stigmergic mechanisms can be classified in two different categories: quantitative (or continuous) stigmergy and qualitative (or discrete) stigmergy.
The role of the two different stigmergic mechanisms in collective building

1. Sequence of stimuli and answers quantitatively different

Positive feedback and self-organization

2. Sequence of stimuli and answers qualitatively different
The successive stimuli quantitatively differentiate in their amplitude and merely modify the answer probability of other individuals.

Examples:
- Mass recruitment in ants
- Dead ant aggregation in ant cemetery
- Pillar building in termites

**Features**
**Quantitative Stigmergy**

*Pillar building in termites*

Spatial distribution of insects and their building activity are locally controlled by the pheromone density.

- Termites impregnate with pheromones the building material
- Pheromones diffuse in the environment
- Individuals carrying ground bullets follow the chemical gradient; they climb towards the highest pheromonal concentration and drop there their bullets
- Material drop rate is proportional to the number of active insects in the local region (positive feedback)
Quatre étapes d’une simulation montrant l’auto-organisation de la construction des piliers dans la phase initiale de construction du nid chez les termites
Evolution de la structure construite dans la simulation en présence d’un vent unidirectionnel
The role of the two different stigmergic mechanisms in collective building

1. Sequence of stimuli and answers quantitatively different

2. Sequence of stimuli and answers qualitatively different

Self-assembly process
Successive stimuli are qualitatively different. This process generates a self-assembly dynamics.

No pheromone involved?

**Features**

- Successive stimuli are qualitatively different. This process generates a self-assembly dynamics.
- No pheromone involved?
Nest Building in Polist Wasps
Nest Building in Polist Wasps

Organisation of the building activity

- It is indirectly carried out via the different, local configurations a wasp can find in the nest
- A probability of deposing a new cell is associated to each configuration
Nest Building in Polist Wasps

Potential sites for building
Nest Building in Polist Wasps

Probability of creating a new cell given the configuration of neighboring cells

Number of adjacent cell walls
Nest-Building Modeling
Swarm on a 3D Lattice

A swarm of nest builders … agent features

- Reactive actions
- Random movements on a 3D lattice, no trajectories
- No embodiment (1 agent = 1 single cell), no interference (however 2 agents cannot occupy the same cell)
- n agents working together means n actions (not necessarily n dropped bricks) before next iteration starts; all n agents see the same configuration at a given iteration
- Agents’ team is homogeneous
- No global plan of the whole building
- Local perception of the environment
Definition of agent’s neighborhood for hexagonal cells

The neighborhood of each agent is defined as the 20 cells around it (7 above, 6 around, and 7 below).
Swarm on a 3D Lattice

Distributed nest building: several sites are active simultaneously
Swarm on a 3D Lattice

Examples of building rules

- Building process is irreversible (no cell can be removed)
- Deposit rules can be strictly deterministic or probabilistic
Swarm on a 3D Lattice

Example of a rule set (Polist wasps, 7 rules)
FIGURE 6.9 Successive building steps in the construction of an *Epipona* nest with a lattice swarm. The completion of each step gives rise to stimulating configurations belonging to the next step. All stimulating configurations are organized to ensure a regular building process. In particular, within a given step, the stimulating configurations do not have to be spatially connected and can occur simultaneously at different locations. In steps 7 to 9, the front and right portions of the external envelope have been cut away. After Theraulaz and Bonabeau [311]. Reprinted by permission © Academic Press.
Nest-building Modeling

Obtained structures (Polists wasps, 7 rules)

With deterministic rules  
With probabilistic rules
Looking for Stable Nest Architectures

What kind of nest architectures can we build with the same method?

• What are the rules to implement in order to obtain stable architectures?

• An architecture is considered stable when several runs of a simulation with the same rule set generate architectures with the same global structure.

• Mechanisms of stigmergic coordination reduce the number of stable architectures.
Examples of Stable Architectures

Agelaia (13 rules)
Examples of Stable Architectures

Parachatergus (21 rules)

Vespa (13 rules)

Stelopolybia (12 rules)
Examples of Stable Architectures

Chatergus (39 rules)

Artificial Nest Structure (35 rules)
How to build a stable architecture?

- The building process is carried out in successive steps. The current local configuration generate a stimulus different from that of the previous and of the successive configuration (qualitative stigmergy).

- Only this type of building algorithms generate coherent architectures.

- The whole set of these algorithms generates a limited number of nest shapes.
Reverse-Engineering: From the Building to the Individual Rules using GA
Similarities to Controller Evolution

Prey-Predator (GA, Floreano 98)   Obstacle avoidance (RL, Kelly 97)

Area Integration (RL, Versino 97)
Exploration (RL, Hayes 01)
Nest-building (Bonabeau, GA 00)

Exploration (RL, Millan 97)   Foraging (GA, Jefferson 93)
Evolutionary Encoding of the Distributed Nest Building Problem

- **Phenotype**: agent endowed with set of microrules
- **Genotype**: set of microrules (one-to-one mapping with phenotype); chromosome of variable length; 1 gene = 1 microrule.
- **Life span**: number of iteration (e.g. 30,000 iterations, 1 iteration = all 10 agents have applied their microrule) or exhausting of max amount of bricks available (e.g. 500 bricks).
- **Population**: 80 individuals
- **Generations**: 50
- **Fitness function**: weighted sum of space filling and pattern replication (arbitrary criteria based on 17 human observers who were asked to evaluate the amount of structure in a set of 29 different patterns, [Bonabeau 2000]);
- **Selection**: roulette wheel
- **Crossover**: two-points, \( p_{\text{crossover}} = 0.2 \)
- **Mutation**: \( p_{\text{mutation1}} = 0.9 \) (during life span inactive microrule);
  \( p_{\text{mutation2}} = 0.01 \) (during life span active microrule).
Swarm Intelligence: Bonabeau et al
Evolutionary Encoding of the Distributed Nest Building Problem

• **Biased evolution:**
  - Probabilistic templates (reduction of stimulating configurations containing a large number of bricks).
  - Start microrule.
  - No diagonal deposits (space not filled).

• **Problems:**
  - Episthatic interactions (sequence of microrules needed for coordinated algorithms).
Collective Building and Self-Assembly in Artificial Systems
Applications

- Obstacle avoidance in highly constrained and unstructured environments
- Formation of bridges, buttresses, stairs and other structures for emergencies
- Envelopment of objects
  - Recovering satellites from space
- Inspections in constrained environments
  - Nuclear reactors
- Self-organizing unfolding structures
  - Space stations
  - Satellites
  - Scaffolds
Passive Bricks
Passive Bricks

- In-line 2D structures using Kheperas [Martinoli 99] -> [Easton ??]
- Lionel Penrose (1898 – 1972)
  - Self-assembly mechanisms of genetic relevant molecules reproduced with passive wood bricks
  - External energy source (shaking, human action)
  - Evolution and self-assembly tightly coupled
  - Video-tape!
Passive Bricks

Evolutionary architecture: Nicolas Reeves (UQAM Montreal, Canada)

- Cellular automata approach.
- No genetic operator: population manager replaced by direct intervention of the human being.

3D CAD simulations

Stereolytographic sculptures
**Passive Bricks**

**Evolutionary architecture: Pablo Funes (Brandeis University, US)**
- GA approach, geometry- and force-based fitness functions
- Off-board evolution and reproduction of results with Lego® bricks
- 2D (bridge, crane) and 3D structures (table)

**Set-up and objective**

**Diagram of forces**
Passive Bricks

Evolutionary architecture: Pablo Funes (Brandeis University, US)

2D Ex.: Bridge

Simulated bridge

Real Lego bridge
Passive Bricks

Evolutionary architecture: Pablo Funes (Brandeis University, US)

2D Ex.: Crane

3D Ex.: Table
Active Mechatronic Units
Research on Self-Reconfigurable Mechatronic Systems in MEL

Eiichi Yoshida    Satoshi Murata
Haruhisa Kurokawa  Kohji Tomita
Shigeru Kokaji
http://www.mel.go.jp/
Distributed mechanical system composed of many identical units using local communication only dynamically reconfigurable

Self-assembly / Self-repair using spare units trouble cut off
• Self-assembly and Self-repair
2D Self-Reconfigurable Systems

- **SMA Torsion Coil Springs**
- **Male:** Rotating Drum
- **Female:** Auto-locking (releasing by SMA)
- **Pin holes**
- **Vertical Direction**
- **Weight:** 50[g] (approx.)
- **Span:** 50[mm]

Basic Motion
Self-repairing machine

自己修復する機械
2D Self-Reconfigurable Systems

- Experiment using 6 units
2D Self-Reconfigurable Systems
3D Self-Reconfigurable Systems

- Basic Motion
Grey: distance from target different from zero -> to be moved
Green: distance from target = 0 -> ok!
Red: current moved unit (once at the time)
3D Self-Reconfigurable Systems

- 3D Mechanical Unit

  connecting hand  rotating arm

  span:  27.5cm
  weight:  6.8kg
  DC motor: 7W
Modular Robotics (PolyPod)

Mark Yim (Stanford University, Xerox Park Research Center, 1994- …)

Parallel structure, 10 links

Two types of modules: segment and nodes
- Nodes: power modules
- Segments: HC11 microcontroller, angle position (potentiometer), IR local communication
Modular Robotics (PolyPod)

Mark Yim (Stanford University, Xerox Park Research Center, 1994- ...)

Modular Robotics (PolyPod)
This generation of PolyBot included onboard computing (Power PC 555) as well as the ability to reconfigure automatically via shape memory alloy (SMA) actuated latches.
Self-Configurable and Modular Robotics

Other researchers:

- Hajime Asama, RIKEN Center, Saitama, Japan
  - Distributed assembling and disassembling of stair-like structures
- Peter Will and Wei-Min Shen, ISI-USC, L.A., US
  - http://www.isi.edu/conro
  - Modular robotics
Crystalline Atomic Modular Self-reconfigurable Robot

- [http://www.ai.mit.edu/~vona/xtal](http://www.ai.mit.edu/~vona/xtal)
- Autonomous self-reconfiguring robots
- Simulator (Xtalsim) created
  - 2D and 3D
- Automated planning algorithm developed
  - Melt-Grow planner: $O(n^2)$ for $n$ atoms
Conclusion
Self-Assembly, Distributed Building, Modular Robotics

Very promising domain but

- **System design** and hardware development are crucial
- **Energetic problem** still unsolved
- **Scalability** and **distributed** control still unsolved
  problems: how to control individual units for obtaining a given team performance?

**Evolution and bio-inspiration can help:**
incremental/modular evolution, reverse engineering