Artificial Life & Complex Systems

Lecture 6

Swarms and Collective Intelligence

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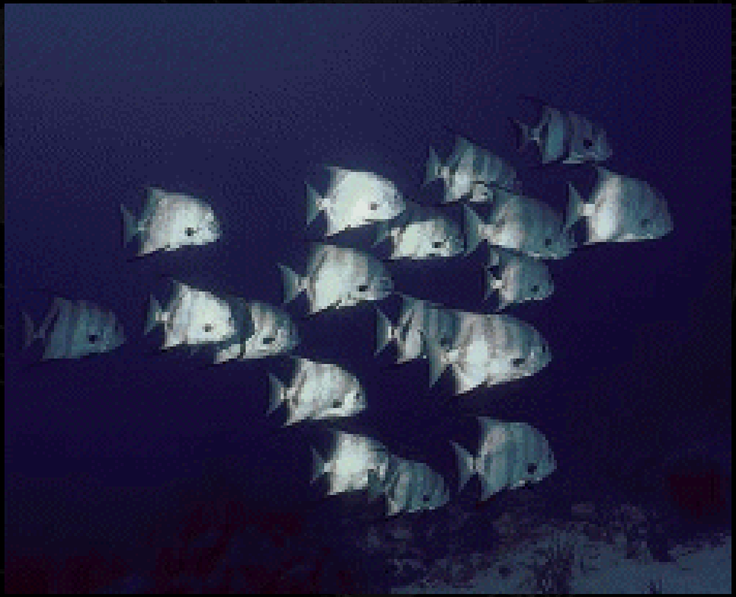
- Swarms
- Swarm Intelligence
- Insect Societies
- Self-organization
- Stigmergy
- Ants, Termites and Honeybees
- Didabots
- Boids

Swarms in Nature

Birds flocking in V-formation (CORO, Caltech)

Swarms in Nature

Swarms in Nature



Swarms in Nature

School of anchovies

Human Swarms

Human Swarms

Artificial Swarm

Heap building by Didabots

Characteristics of a Swarm?

- behavior-based
- adaptive
- situated in environment
- limited time to act (reactive)
- autonomous
- system-level behavior transcends behavioral repertoire of single agent (problem solving is emergent behavior)
- interaction rules seem to be simple
- multiple lower level competencies

Characteristics of a Swarm?

- minimalist but fully autonomous individuals
- fully distributed control, no central control or data source
- no (explicit) model of the environment
- ability to change environment
- exploitation of explicit and implicit (stigmergic) communication
- scalability (from a few up to thousands of individuals)
- enhanced robustness through redundancy and minimalist design of the individuals

What is Collective/Swarm Intelligence?

... what do we mean by intelligence?

Intelligence

- What do we mean by intelligence?
  - Ability to ‘solve problems’ in some abstract or real domain
  - Ability to produce behavior appropriate to a situation
- What do we call intelligent?
  - A natural system composed of one or more agents
  - An artificial system composed of one or more agents (computational entities or robots)
- At opposite ends of the scale:
  - Human intelligence vs. insect intelligence
- How useful is each of these as a model for intelligent artificial systems?

Different Types of "Intelligence"

- Individual human intelligence
  - Highly capable, extremely flexible
  - Consciously reason about the problem, seeking new information where necessary, and generate and execute a plan.
- Individual artificial intelligence
  - Capable in niche areas, inflexible
  - Apply rules of logic and reason to an abstract representation of the problem situation, seeking new information where necessary, and generate and execute a plan.
- Conventional robot
  - Incapable compared with humans, inflexible.
  - Build a representation of the problem situation, and apply rules of logic and reason to it, seeking new information where necessary, and generate and execute a plan.

Different Types of "Intelligence"

- Individual insect intelligence
  - Extremely capable and flexible within niche (specialist) situations, generally incapable outside them. Cued to environment – incapable outside
  - Specialised behaviours triggered by specialised sensing; chaining of behaviours by internal or external cues; suppression of some behaviours by others.
- Insect level (behaviour based) robots
  - MIT 85 "insect lab" Rod Brooks AI lab
  - Excellent at low level tasks in particular environments, often flexible, easy to build, often robust to component failure.
  - Mimic individual insect intelligence - Specialised behaviours triggered by specialised sensing; chaining of behaviours by internal or external cues; suppression of some behaviours by others.

What about Software Agents?

Real swarms ...

- do not have a global controller
- are immersed in environment
  - no symbolic view of the world
  - environment is memory
- do not communicate directly
  - no KQML (“Knowledge Query and Manipulation Language”), dialogs or “contract net” protocols

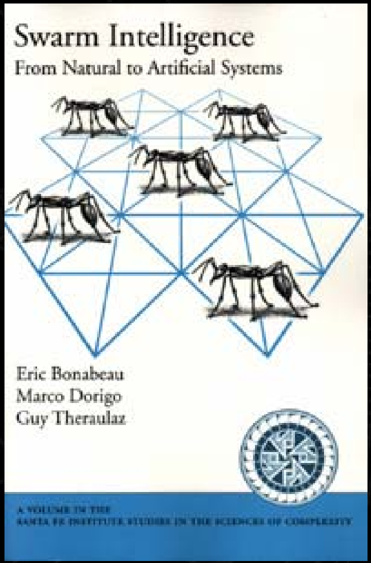
The Dark Side of Swarms

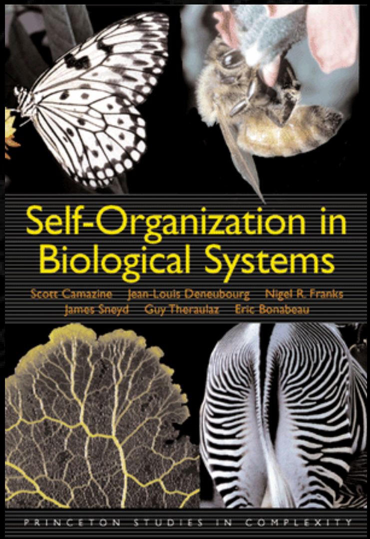
- Predictability is a problem in distributed bottom-up approaches
- How efficient is a swarm?
- What’s the overall cost?
- Loads of parameters to assign (how many agents?)
- How do we design a swarm-intelligent system? Nature had millions of years to “design” effective systems but we have less time ...

What is Collective/Swarm Intelligence?

Definition 1: "Swarm Intelligence (SI) is the property of a system whereby the collective behaviors of (unsophisticated) agents interacting locally with their environment cause coherent functional global patterns to emerge."

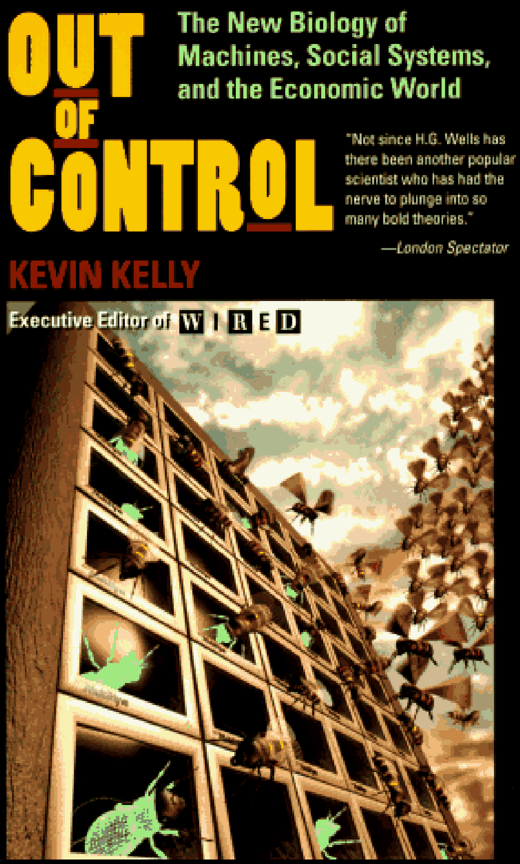
Definition 2: "Any attempt to design algorithms or distributed problem-solving devices inspired by the collective behavior of social insect colonies and other animal societies." *(Bonabeau, Dorigo, and Theraulaz, 1999).*





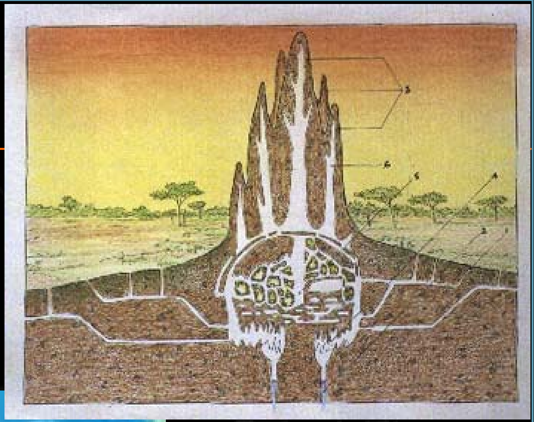
Biological Motivation

- Biological inspiration from: social insects (ants, bees, termites), flocks of birds, herds of mammals, schools of fish, packs of wolves, pedestrian, traffic
- Colonies of social insects can achieve flexible, reliable, intelligent, complex system level performance from insect elements which are stereotyped, unreliable, unintelligent, and simple
- Insects follow simple rules, use simple local communication (scent trails, sound, touch) with low computational demands
- Global structure (e.g. nest) reliably emerges from the unreliable actions of many

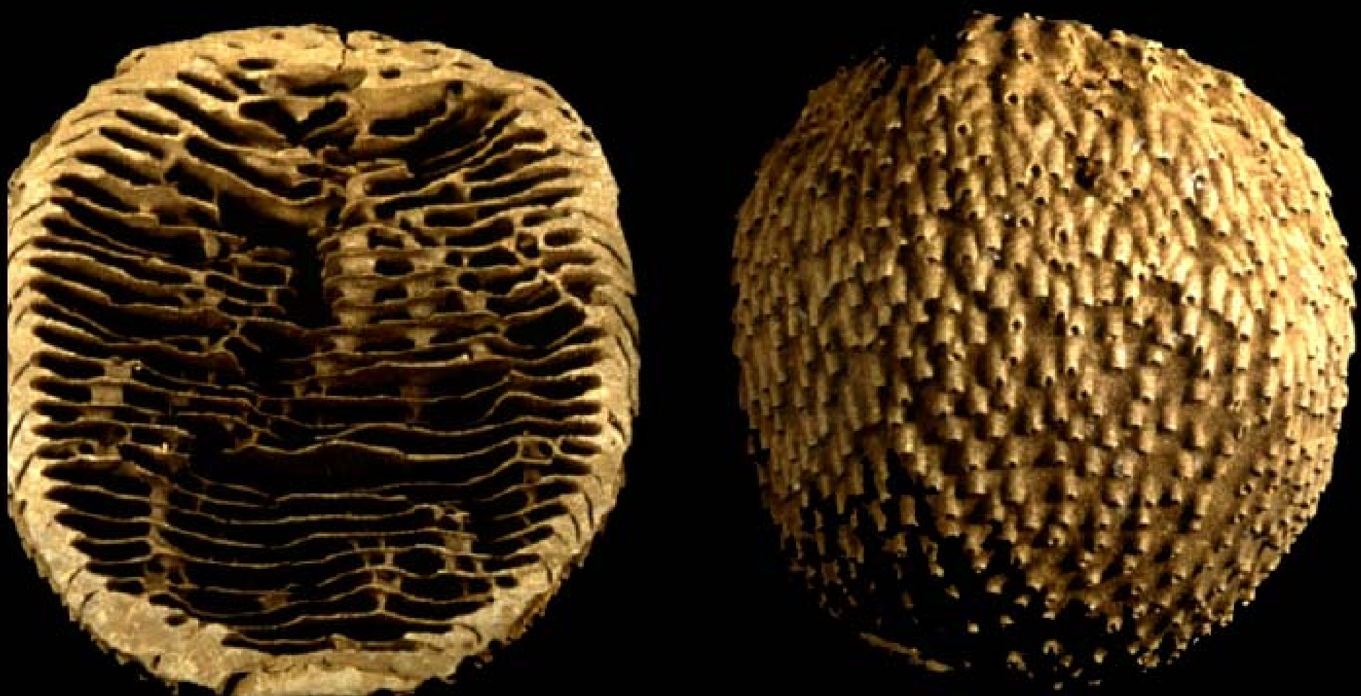


(1994)

Insect Societies

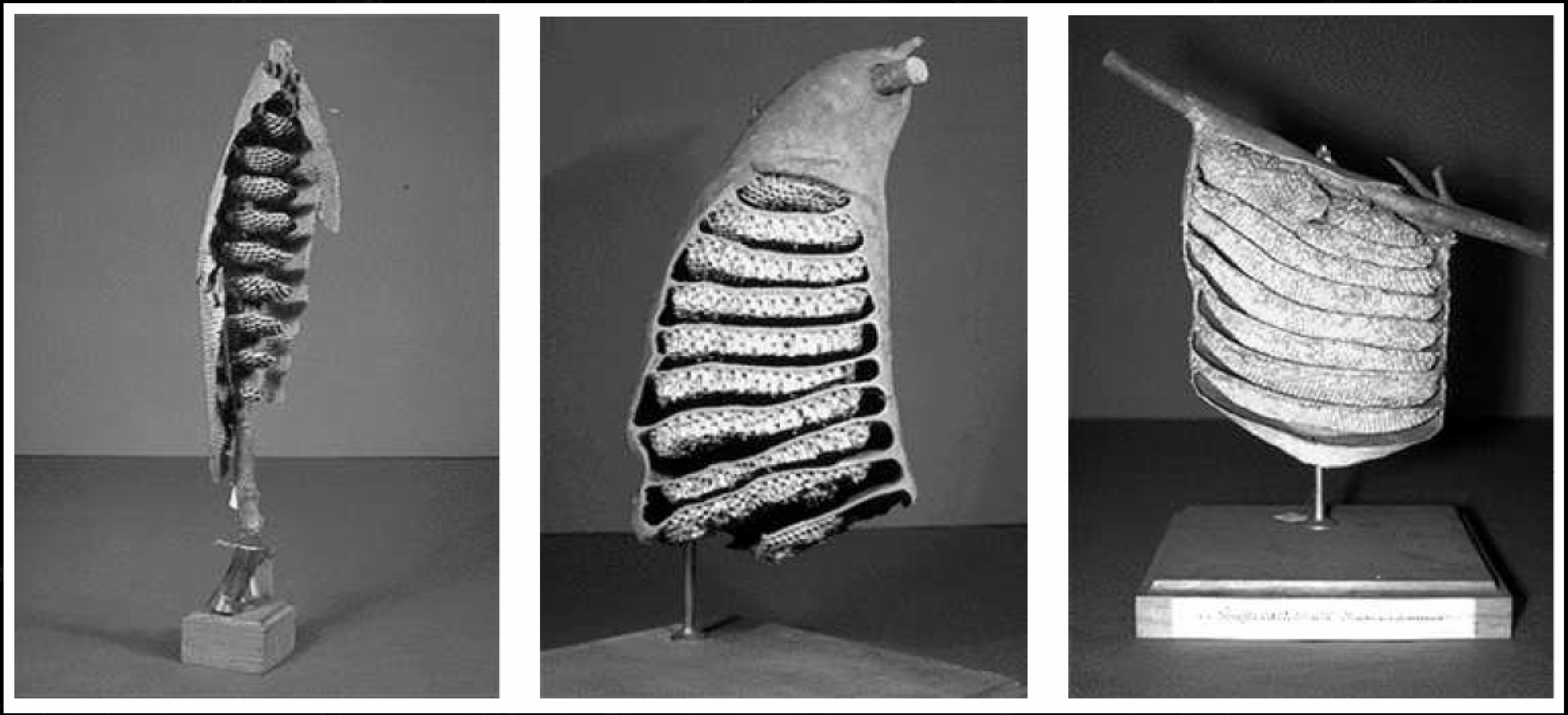


Insect Societies



Termite nest (Theraulaz et al., 2003)

Insect Societies



(Photos by Guy Theraulaz)

Insect Societies

1. Natural model of problem solving

- Collective systems are capable of accomplishing difficult tasks, in dynamic and varied environments, without any external guidance or control and with no central coordination
- Achieving a collective performance which could not normally be achieved by any individual acting alone
- Constitute a natural model particularly suited to distributed problem solving
- Many studies have taken inspiration from the mode of operation of social insects to solve various problems in the artificial domain

Insect Societies

2. Individual simplicity vs. collective complexity

- Behavioral repertoire of the insects is limited
- Their cognitive systems are not sufficiently powerful to allow a single individual with access to <u>all the necessary information</u> about the state of the colony to guarantee the appropriate division of labor and the advantageous progress of the colony
- The colony as a whole is the seat of a stable and <u>self-regulated organization</u> of individual behavior which adapts itself very easily to the unpredictable characteristics of the environment within which it evolved

Self-Organization in Collective Systems

Systems of collective decision-making

- Insect societies have developed systems of collective decision making operating without symbolic representations, exploiting the physical constraints of the environment in which they evolved, and using communications between individuals, either directly when in contact, or indirectly using the environment as a channel of communication (stigmergy)
- Through these direct and indirect interactions, the society self-organizes and, faced with a problem finds a solution with a complexity far greater than that of the insects of which it is composed

Self-Organization: Main Features

- Local interactions, local information
- Decentralized (no leader)
- Positive and negative feedback mechanisms
- Random fluctuations

Swarm and Collective Intelligence

Goals:

1) Biological understanding

- generally: the distributed nature of intelligence
- The emergence of structure in societies
- The principles of self-organization in the evolution of intelligence

2) Engineering

- Exploitation of ideas of collective intelligence for optimal task performance

Collective or Swarm Intelligence

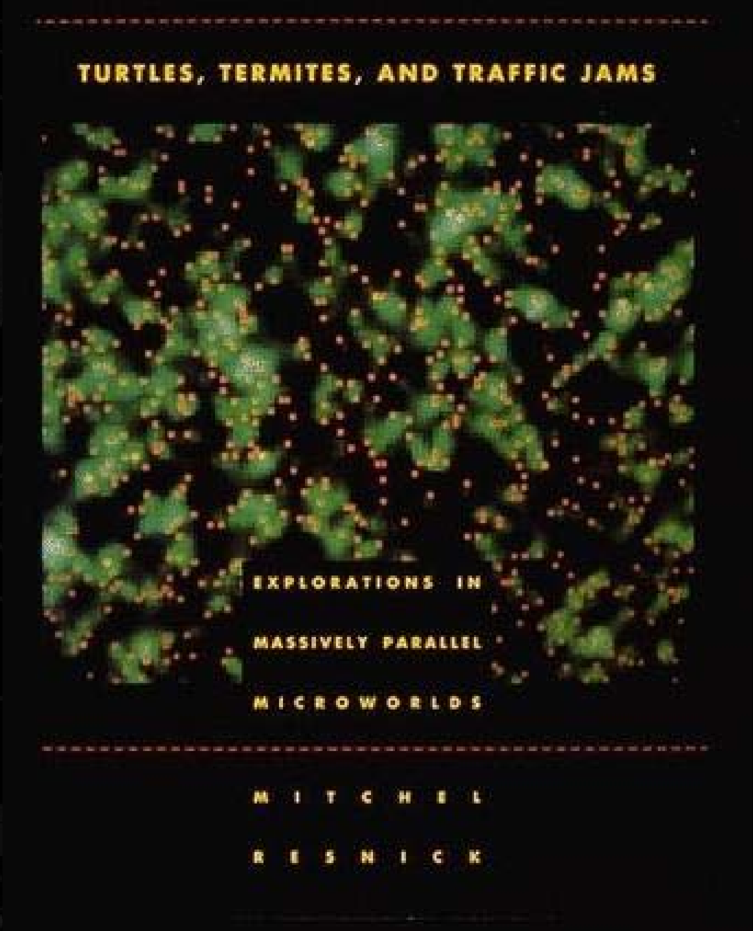
Some questions ...

- How can a large number of entities with only partial information about their environment solve problems?
- How do insect societies manage to perform difficult tasks, in dynamic and varied environments, without any external guidance or control, and with no central coordination?
- How can collective cognitive capacities emerge from individuals with limited cognitive capacities?

Decentralized Control / Thinking

- Activities in a honey bee colony arise without any centralized decision making (no leaders)
- In a decentralized system, each individual <u>gathers information on its own</u> and decides for itself what to do (situatedness)

Manifesto of decentralized thinking

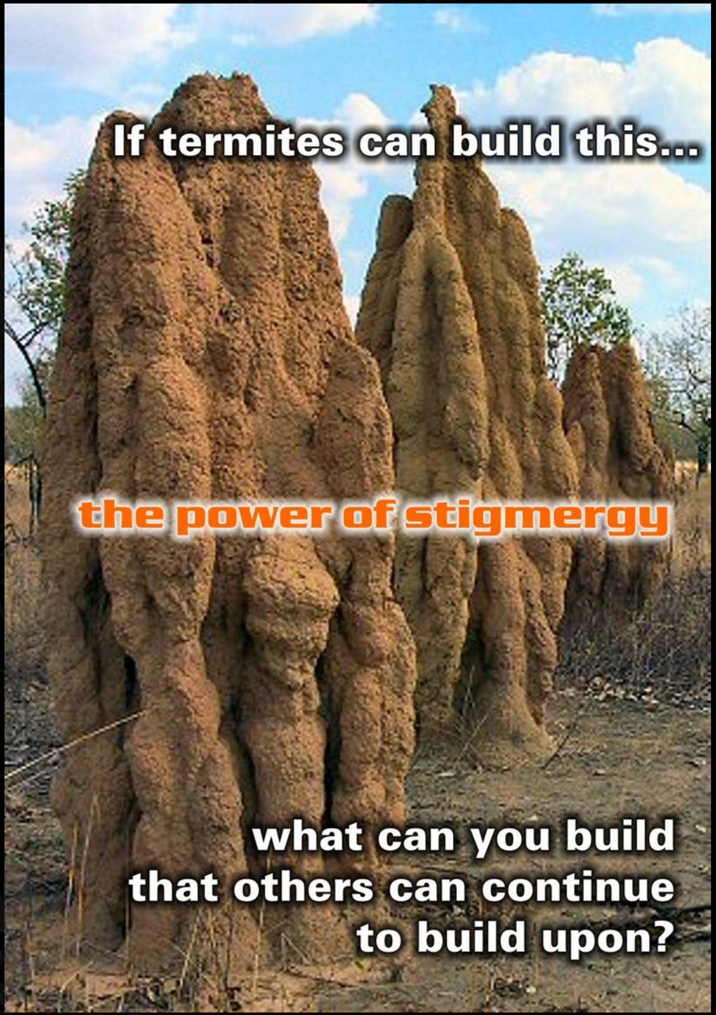


(Mitchel Resnick, 1997)

Sources of Information

1) Information gathered from one's neighbor
2) Information gathered from work in progress (stigmergy):
3) Information from the local environment and work in progress (e.g. stimuli provided by emerging structures).

For example: termites building a nest; termites "communicate" through common medium of the emerging nest instead of through direct communication among nest-mates



Stigmergy

- Term introduced by Grasse (1959) to explain nest building in termite societies
- At the core of a lot of amazing collective behaviors exhibited by ant/termite colonies
- Mechanism by which members of a termite colony coordinate their nest building activities
- Captures the notion that the agents actions (“ergon”) leave signs (“stigma”) in the environment; signs that it and other agents sense and that determine their subsequent actions
- Alternatively, one might speak of “indirect social interactions” (Michener, 1974)
- Recursive control system that uses stimuli from the work in progress to elicit a particular building response, which in turn acts as a stimulus for a further response, and so on

How Does Stigmergy Work?

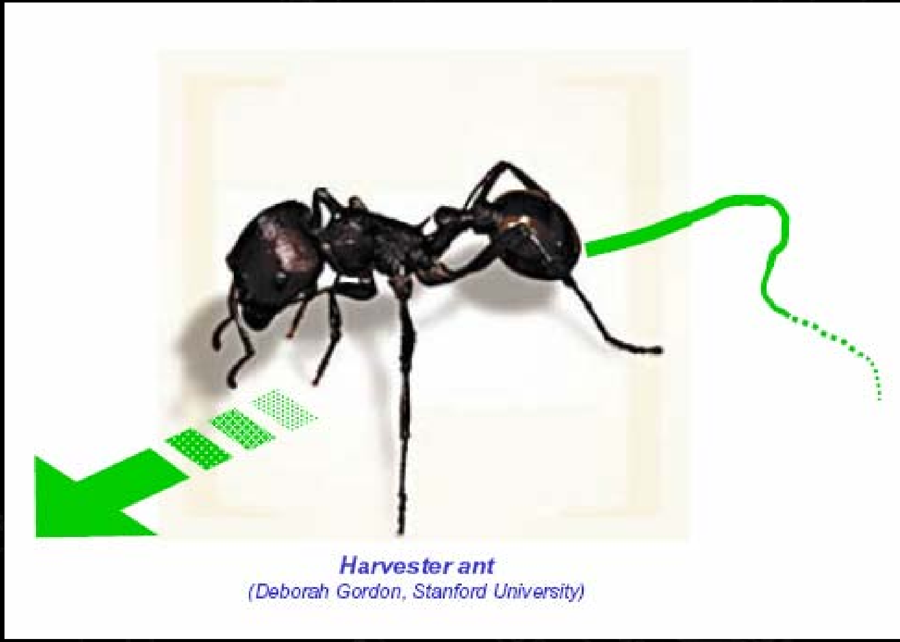
Pheromone Laying-Attraction is Key

- While walking, the ants lay on the ground a volatile chemical substance called pheromone
- Pheromone distribution modifies the (perceived) environment creating a sort of attractive potential field for the ants
- This is useful for attracting the way back, for mass recruitment, for labor division and coordination, to find shortest paths ….

Stigmergy

- Goss, Aron, Deneubourg, and Pasteels (1989) showed how stigmergy allows ant colonies to find shortest paths between nest and sources of food
- These mechanisms have been reverse engineered and have originated a multitude of ant colony inspired algorithms

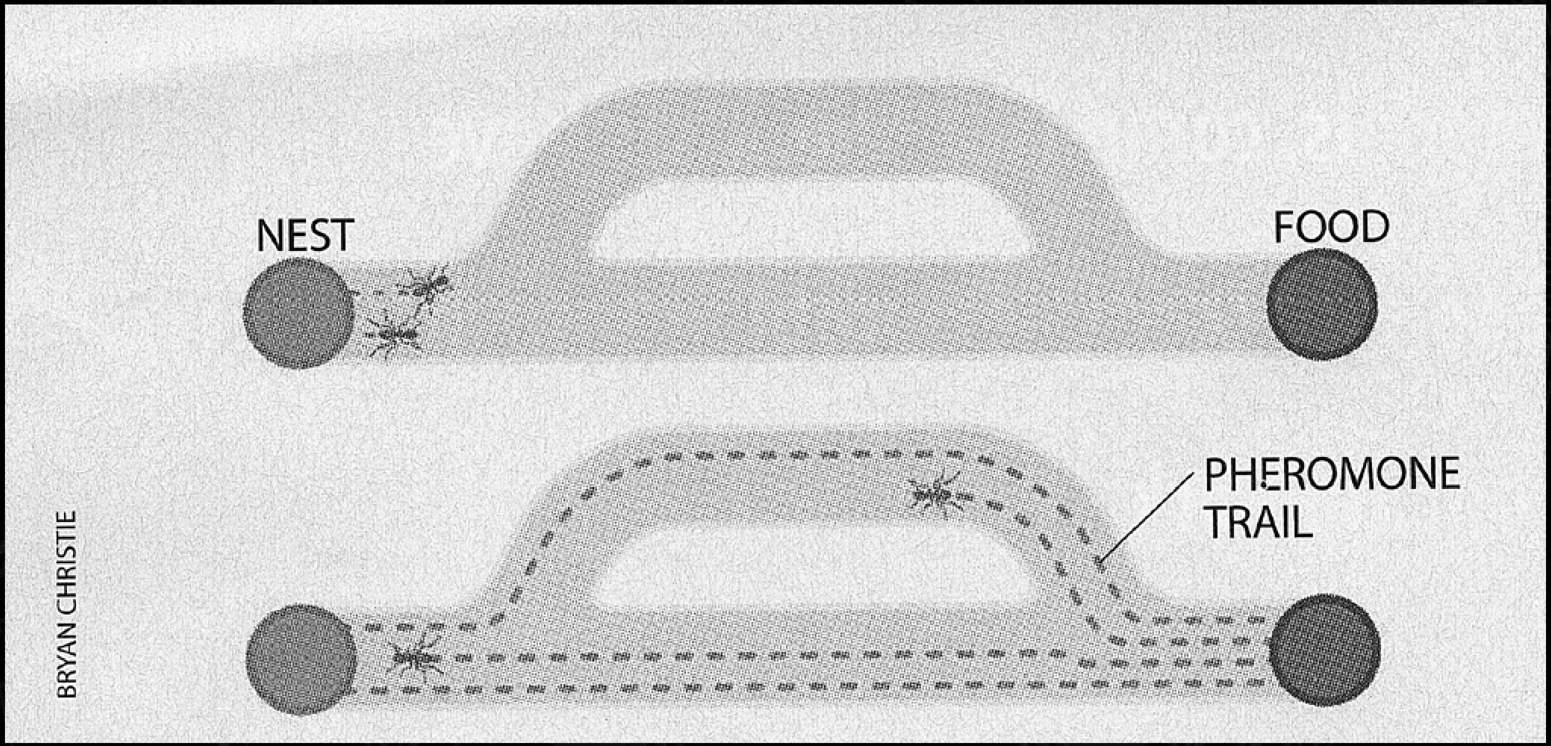
Trail Formation in Ants



Basic mechanism

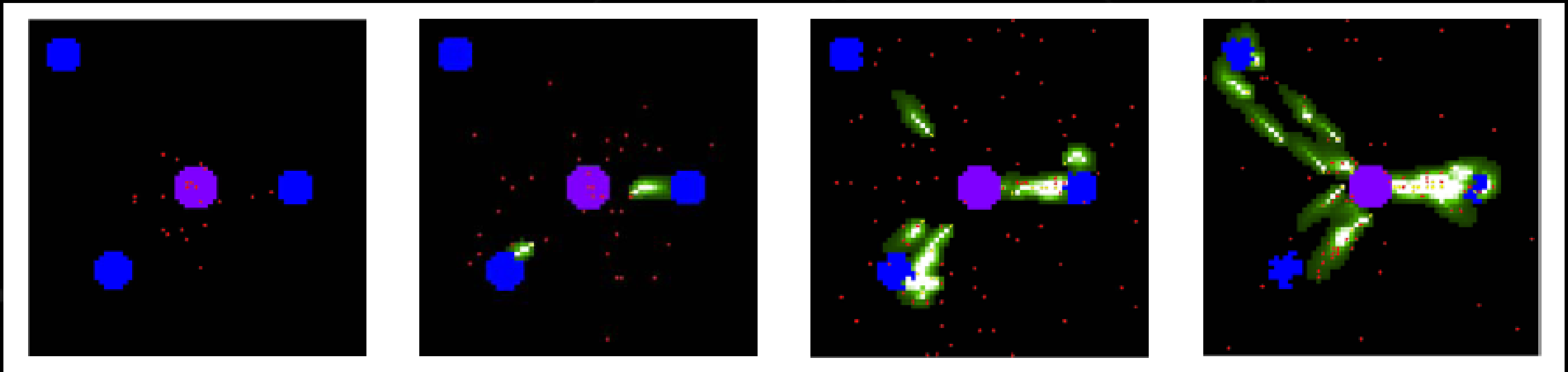
- While moving, each ant deposits a chemical ("pheromone") to signal the path to other ants
- Each ant also "smells" and follows the pheromone gradient laid down by others

Trail Formation in Ants



Lower trail is marked with twice as much pheromone → attracts other ants more than the longer route

Trail Formation in Ants



Modeling & Simulation

Setup:

- 1 nest (violet)
- 3 food sources (blue)
- 100 to 200 ants

Ant's behavior

- Walk round randomly
- If bump into food, pick it up and return to nest
- If carrying food, deposit pheromone (green-white gradient; pheromone diffuses and evaporates)
- If not carrying food, follow pheromone gradient

Observations

- Food sources are exploited in order of increasing distance and decreasing richness
- Emergence of a collective decision

Trail Formation in Ants

Questions:

- What happens if there is more than one food source?
- What happens if two food sources are equidistant from the nest? ("perfect rational donkey situation")

Trail Formation in Ants

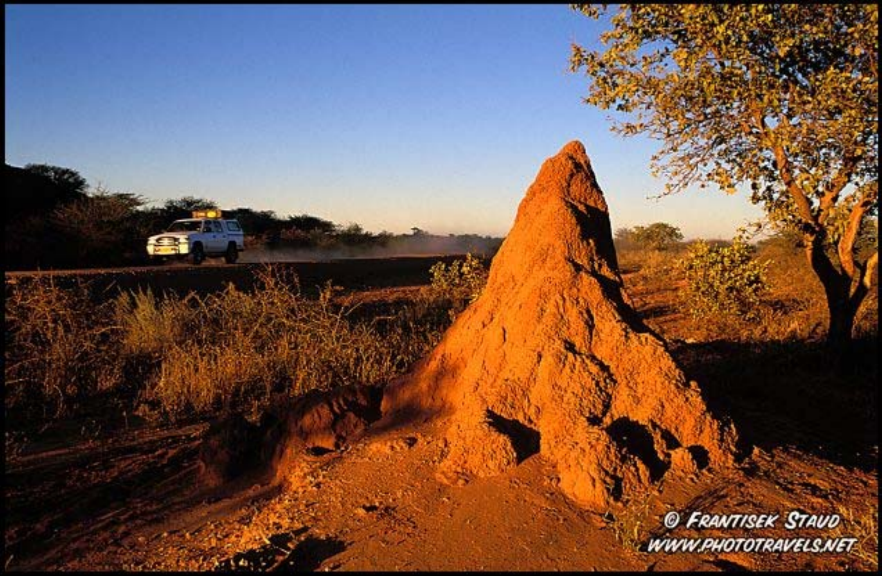
Concepts collected from this example:

- simple individual rules
- high-level, sequential behavior arises from low-level, parallel interactions
- emergence of collective computation
- no leader, no map (decentralization)
- amplification of small fluctuations (positive feedback)
- local interactions (ant ↔ environment)
- phase transition (critical mass = minimal number of ants)

Mound Formation in Termites

Phenomenon

- Termites among master architects.
- Nests up to 4m tall (thousands of times taller than termites)
- Intricate networks of tunnels and chambers
- Elaborate air-conditioning systems
- Termites are practically blind

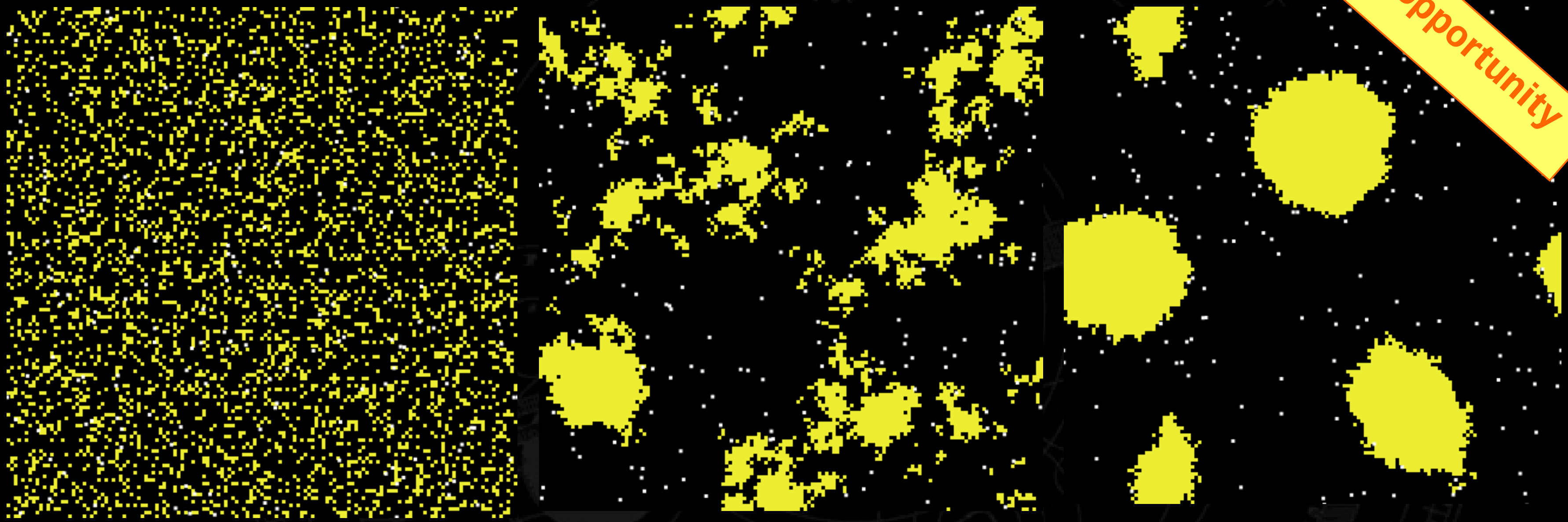


Mound Formation in Termites

Show simulation first …

Mound Formation in Termites

Project opportunity



NetLogo termite mound building simulation, after Mitchel Resnick

Modeling & Simulation

Simplified setup:

- Randomly scattered wood chips (or soil pellets)
- Termites moving among the chips

Termites's behavior

- Walk around randomly
- If bump into wood chip, pick it up and move away
- If carrying wood chip, drop it where other wood chips are

- Typical result: wood chips are stacked in piles of growing size
- Explains one aspect of mound formation through collective activity

Mound Formation in Termites

Concepts collected from this example:

- Sorting is achieved with simple (probabilistic) rules
- No direct communication between ants (example of stigmergy)
- Sorting behavior is an emergent property

Sorting Behavior in Ants

Phenomenon

- How do ants sort eggs, larvae, cocoons, etc?

Sorting Behavior in Ants

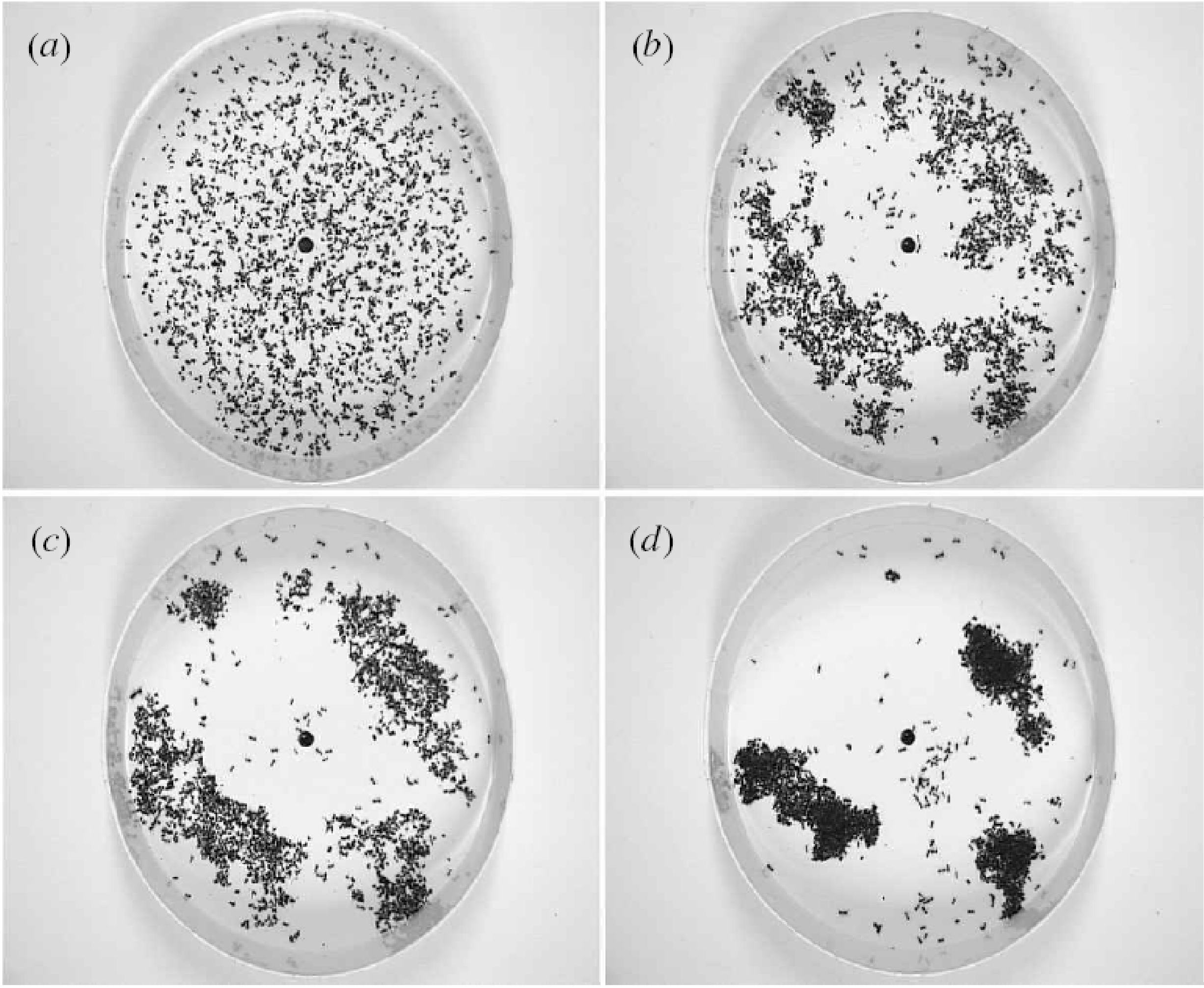


Figure 3. An example of corpse-aggregation dynamics in the ant *M. sancta* observed for an arena of $\varnothing = 30$ cm and with 1500 corpses. (a) The initial state, (b) after 3 h, (c) 6 h and (d) 36 h.

Sorting Behavior in Ants

Any ideas?

Sorting Behavior of Ants

Model by Deneubourg and colleagues (3 behavioral rules):

- If object is far from other objects: probability of "pick-up" is high
- If object is close to other objects: probability of "pick-up" is low
- If ant is carrying an object and similar objects are close-by: probability of "put-down" is high

Formulae anyone?

Sorting Behavior in Ants

(a) (b)

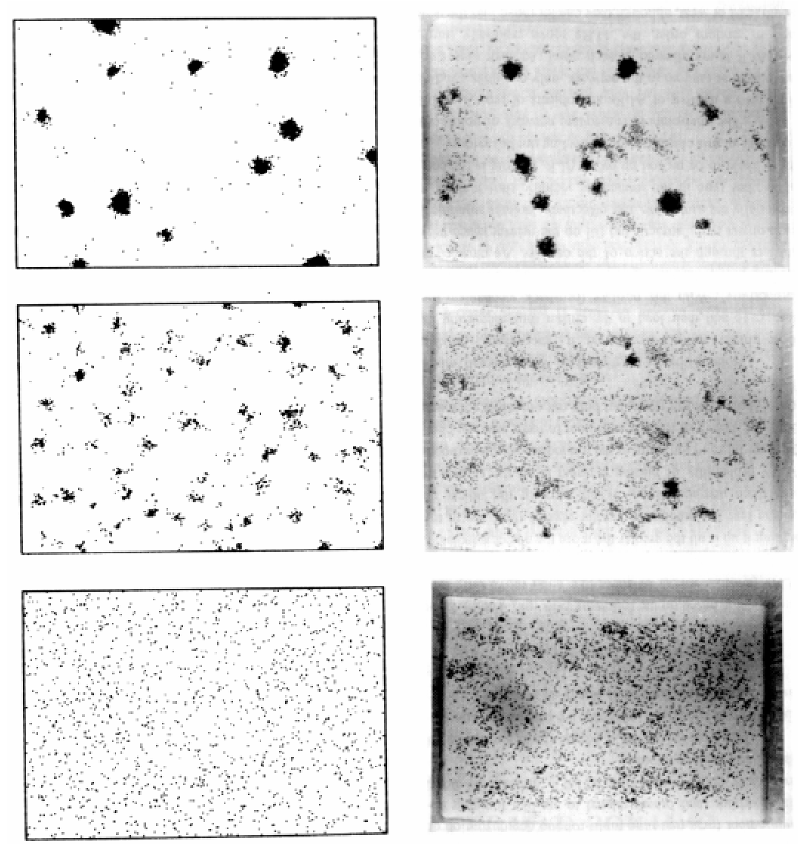


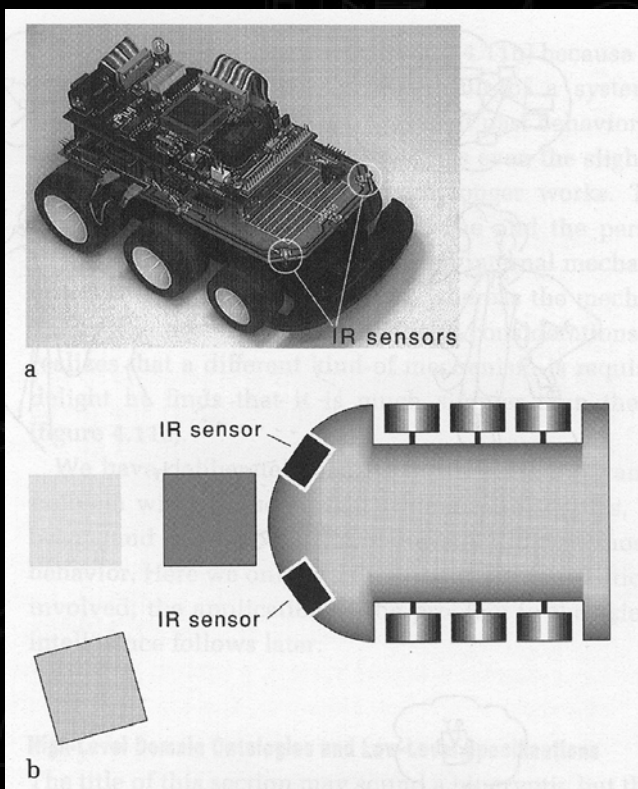
Figure 3.4: *Development of clusters of objects in a society of ants. (a) Simulation. (b) Real ants. The simulation is based on local rules only. The simulated ants can only recognize objects if they are immediately in front of them. If an object is far from other objects, the probability of the ant picking it up is high. If there are other objects present the probability is low. If the ant is carrying an object, the probability of putting it down increases as there are similar objects in its environment. This leads to the clustering behavior shown.*

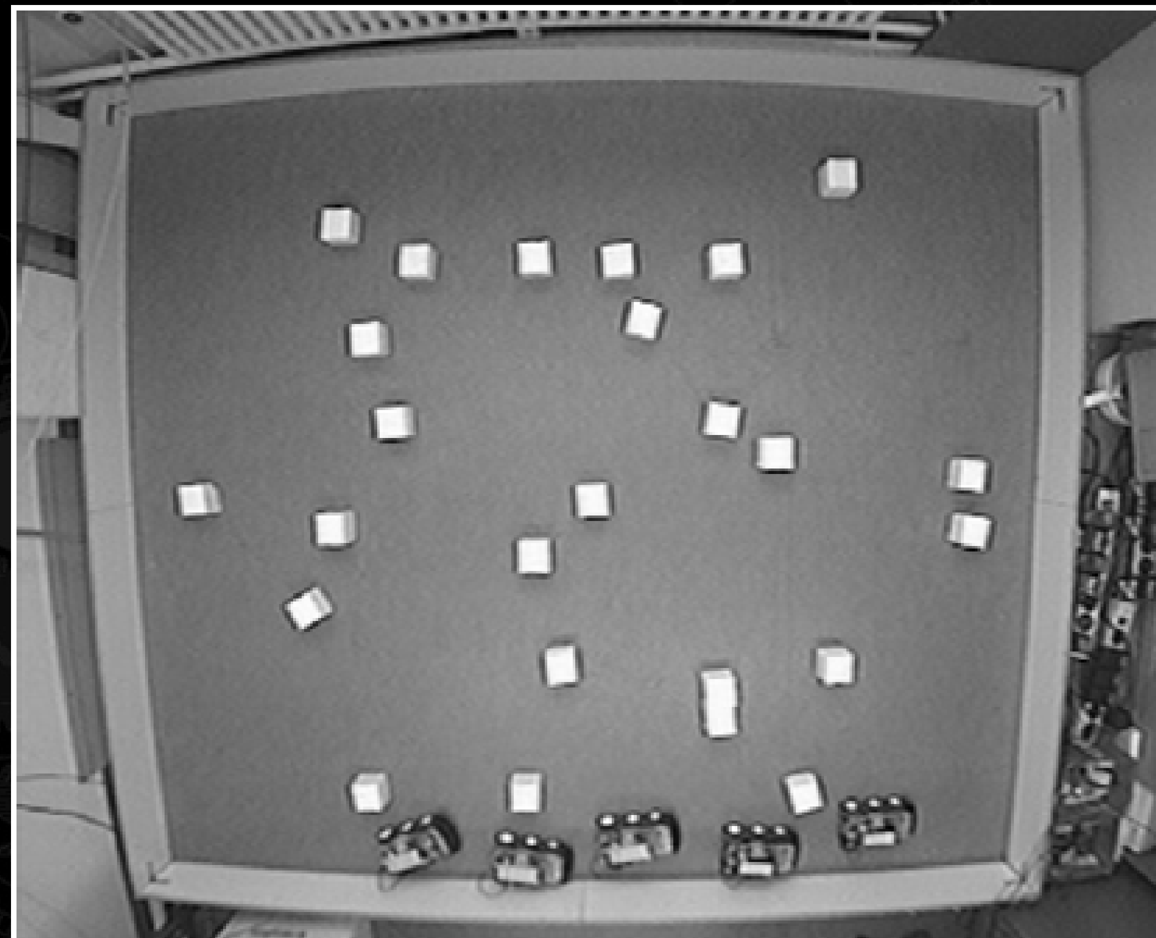
Heap Building with Didabots

Show videos first ...

Heap Building with Didabots

Didabots in their arena. There is an arena with a number of Didabots, typically 3 to 5. All they can do is avoid obstacles





Heap Building with Didabots

Example of heap building by Didabots. Initially the cubes are randomly distributed. Over time, a number of clusters start to form. In the end, there are only two clusters and a number of cubes along the walls of the arena.

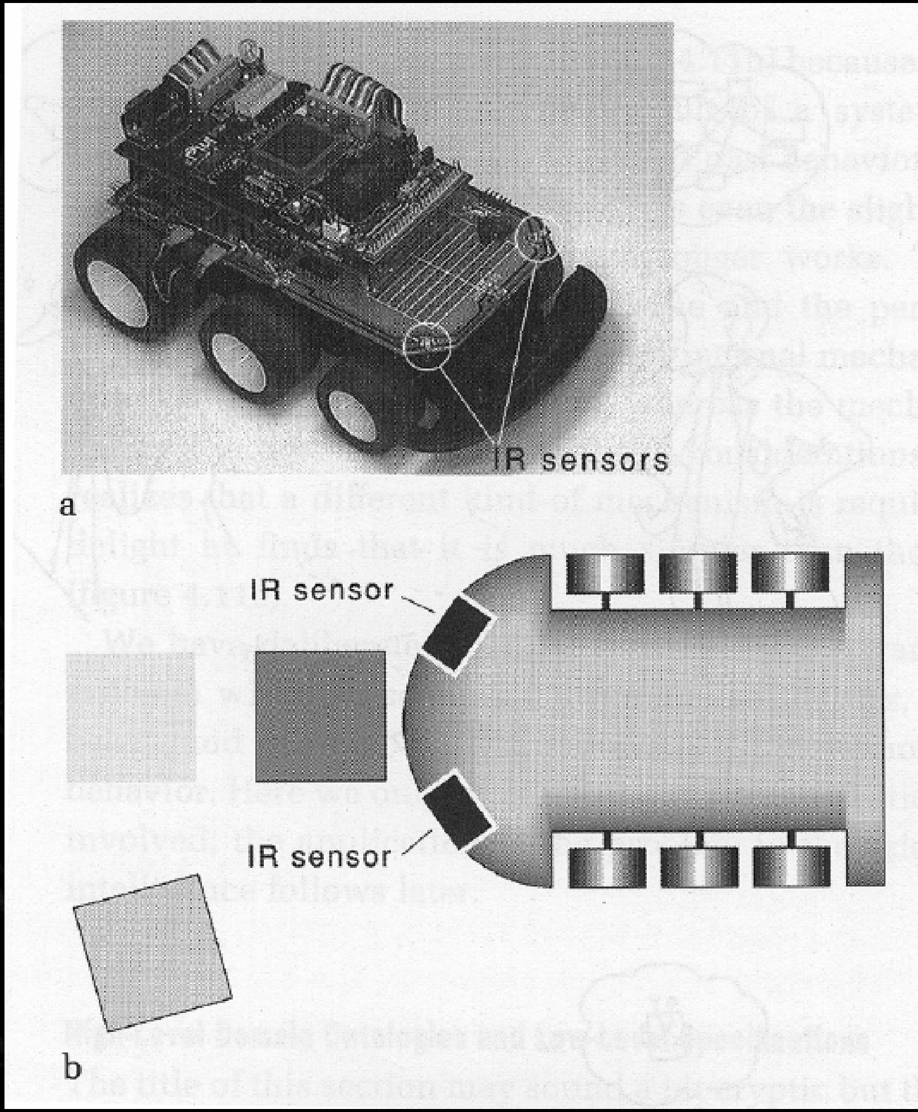
Self-organization without structural changes

Heap Building with the Didabots

The rules are simple!! ☺

Any suggestions?

Heap Building with the Didabots

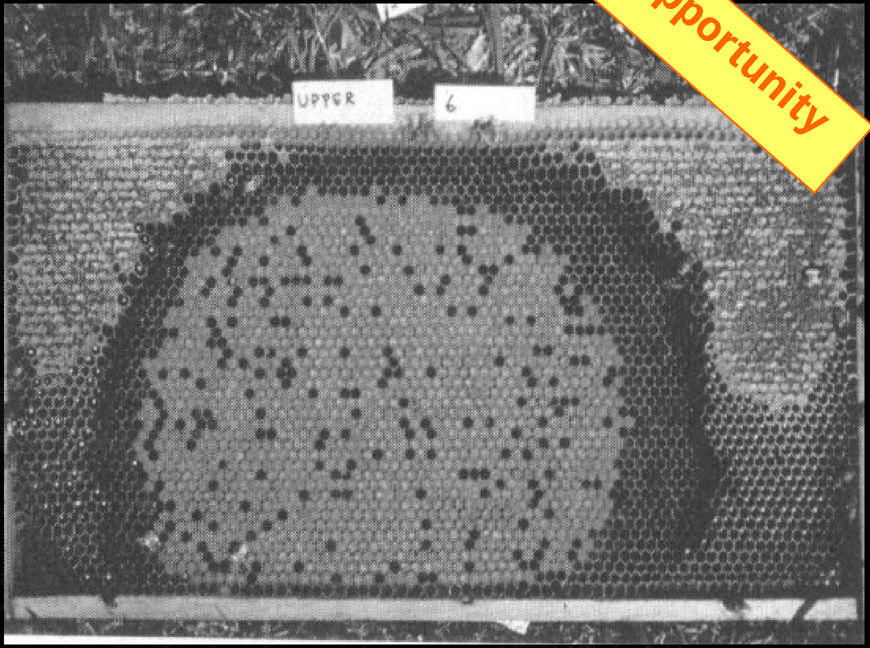


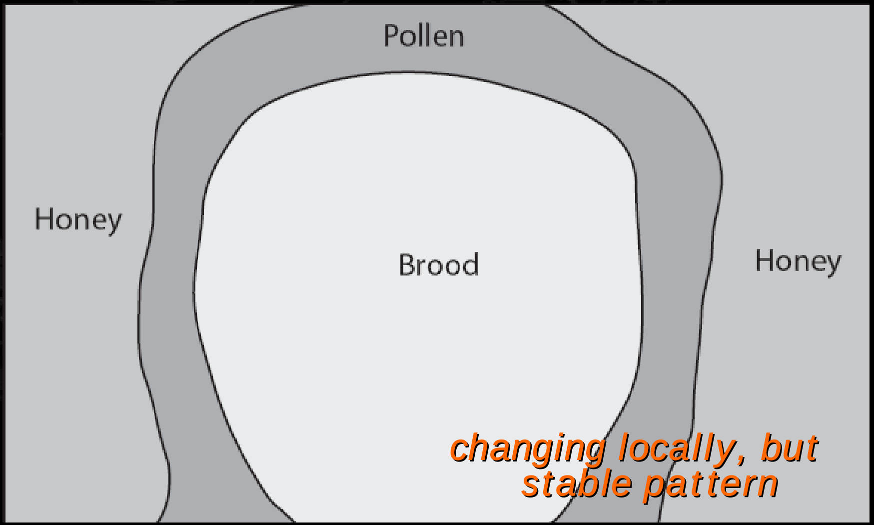
Comb Formation in Honey Bees

Project opportunity

Phenomenon

- Facts about typical honey bee colony
  - 25’000 female worker bees
  - Few thousand drones
  - One queen (lays 1000-2000 eggs/day)
  - Also: immature brood (eggs, larvae, pupae), honey and pollen
  - Comb ca. 100’000 hexagonal cells
  - Temperature: AC 33-34 C.
  - Colony collects 60kg of honey/season
  - 40mg nectar/load → 3’000’000 trips
  - 15mg pollen/load → 1’300’000 trips
- Comb displays regular patterns





changing locally, but stable pattern

Comb Formation in Honey Bees

Project opportunity

Model & Simulation

Behavioral rules:

- Brood is deposited in cells next to cells already containing brood
- Honey and pollen cells close to brood are emptied first
- Extract 4x more honey than pollen (typical removal input ratios for honey and pollen are: 0.6 and 0.95)
- Removal of honey and pollen is proportional to number of surrounding cells containing brood

Literature

- Camazine et al. (2001) (Chapter 16)

Take-Home-Message

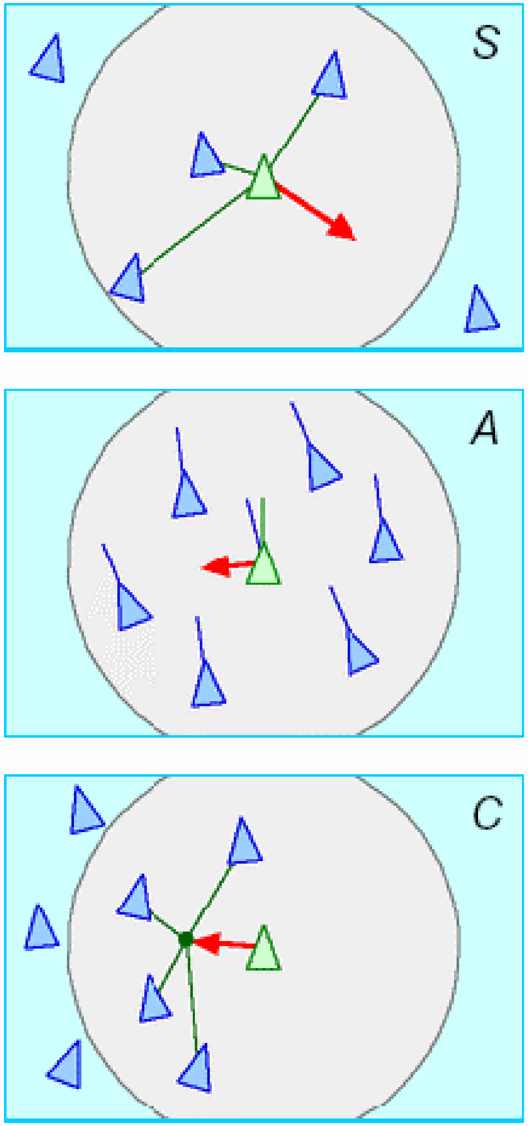
- Complexity from simplicity
- Examples of self-reinforced (autocatalytic) processes (particular instance of self-organization)
- Autocatalytic effects form an alternative view to the idea that patterns are controlled centrally by a blueprint or higher cognitive capabilities of the individuals

Group Motion: Boids

Phenomenon

- Coordinated collective movement of dozens or thousands of individuals
- Adaptive significance:
  - Prey groups confuse predators
  - Predators groups close in on prey
  - Increased aero/hydrodynamic efficiency

Boids

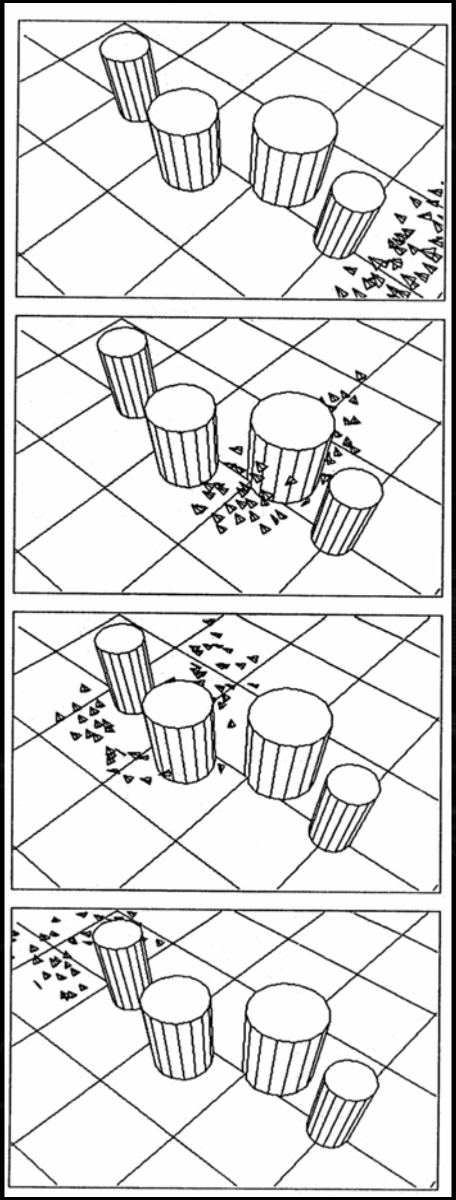


Separation, alignment and cohesion

- Craig Reynolds "Boid" model (1986)
- Among most famous creatures in Artificial Life
- Mechanism:
  - Each individual adjusts its position, orientation and speed according to its nearest neighbors
  - Steering rules:
    - Separation: avoid collisions with local flockmates (and any other obstacles)
    - Alignment: steer towards the average heading of local flockmates
    - Cohesion: move toward average position of local flockmates

http://www.red3d.com/cwr/boids/

Boids: Splitting Behavior



Craig Reynolds's "boids" engage in flocking behavior:

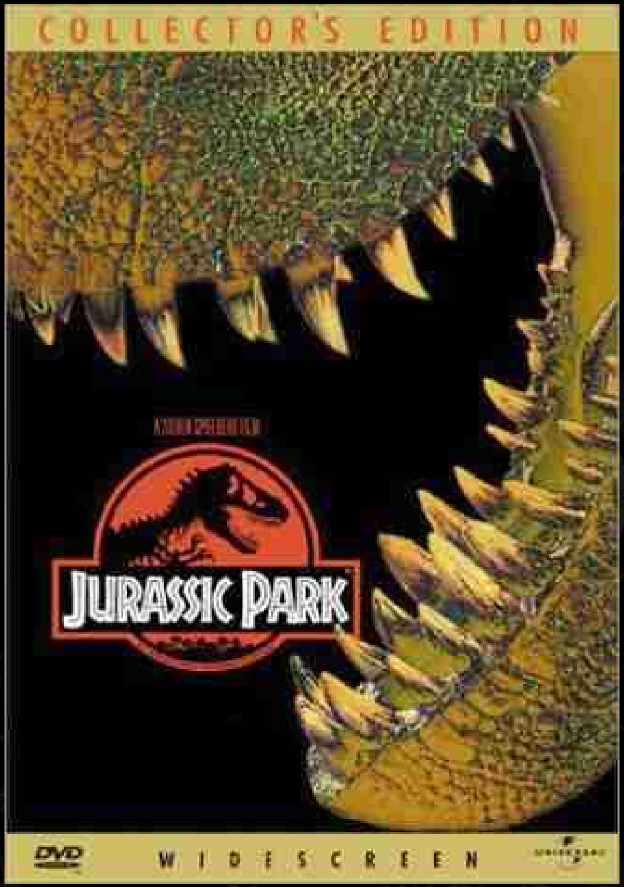
- When the boids encounter a cluster of pillars the flock simply splits and rejoins after it has passed the pillars
- Note that "splitting" is not contained in the set of rules; it is truly emergent: the result of several parallel processes while the boids are interacting with their environment
- Even Reynolds was surprised by this remarkable and beautiful (although fully explainable) behavior

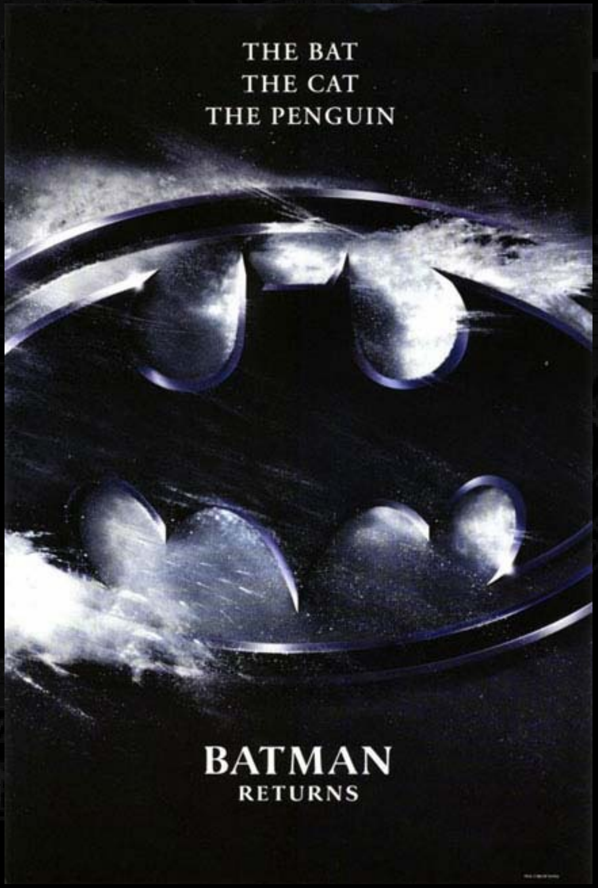
Boids: Properties

Life-like group behavior:

- Unpredictability over moderate time scales (predictable at very short time scales)

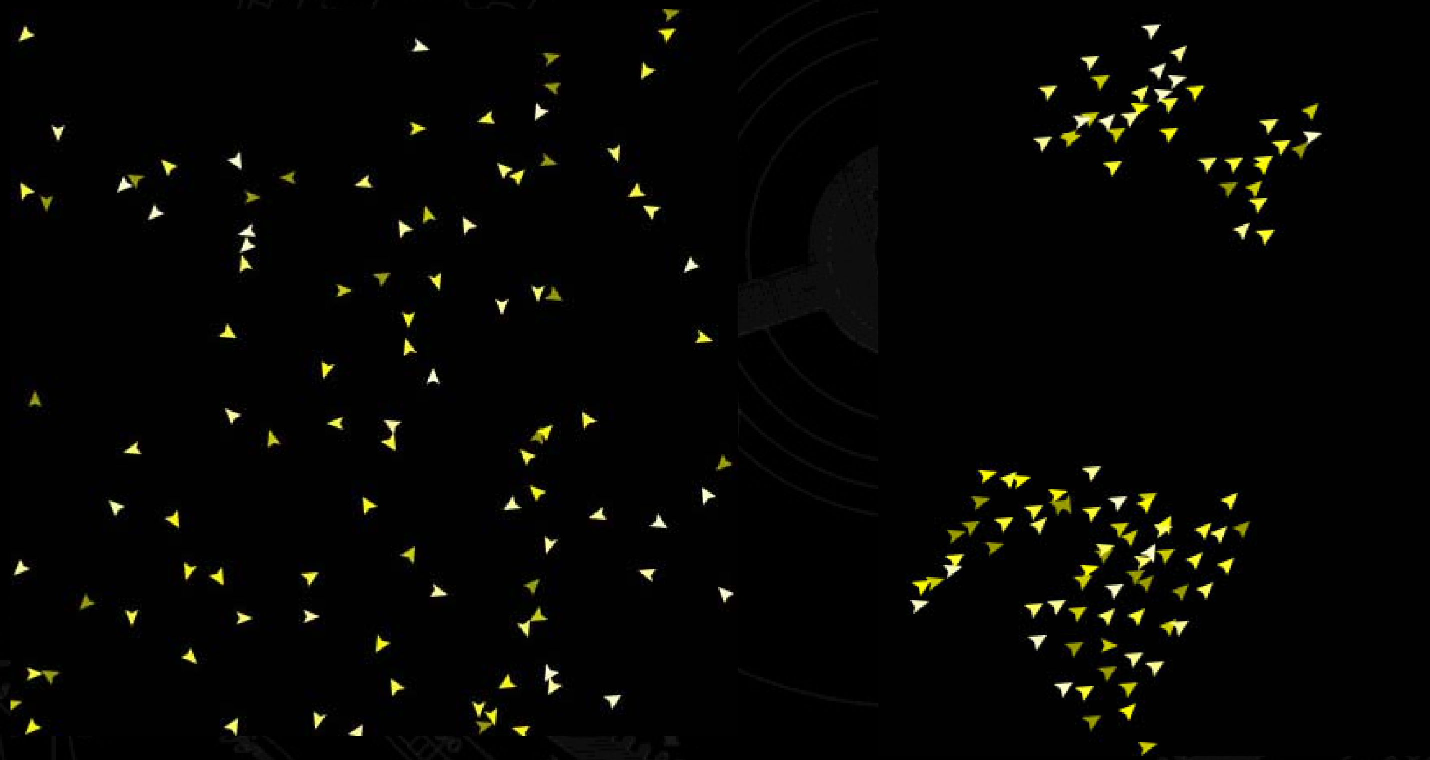
Boids in Movies





Boids in Movies

Boids



NetLogo flocking simulation, after Craig Reynolds "boids" model – http://www.red3d.com/cwrlboids

Boids

Concepts collected from this example:

- Simple individual rules
- Emergence of coordinated collective motion (even "splitting")
- No leader, no external reference point (decentralization)
- Situated view of the world
- Local interactions (animal ↔ animal)
- Cooperation

Guiding Heuristics for Decentralized Thinking

Positive feedback isn't always negative

- Negative image: screeching sound that results when a microphone is placed near a speaker
- Population growth
- Vicious circle ("Teufelskreis")
- Emergence of Silicon Valley
- Winning of standards/computers
- Formation of ant trails

Guiding Heuristics for Decentralized Thinking

Randomness can help create order

- Important role in self-organizing systems
- In traffic jams: small fluctuations in traffic density serve as “seeds”; positive feedback accentuates these density fluctuations, making the seeds sprout into full-fledged traffic jams
- Randomness is required to achieve adaptivity in pheromone trails
- Clapping of an audience often develops into rhythmic clapping

Guiding Heuristics for Decentralized Thinking

A flock isn't a big bird

- Levels should not be confused: often people confuse the behaviors of individuals with the behaviors of the groups; e.g. interactions among individual birds give rise to flocks
- In many cases, the individuals on one level behave differently from objects on another level: traffic jams tend to move backwards, even though the cars within the jams are moving forward
- In the Sugarscape model, there are diagonal migration patterns even though the agents can only move up/down and left/right
- The leader in a flock is always changing

Guiding Heuristics for Decentralized Thinking

A traffic jam isn’t just a collection of cars

- It is important to realize that some objects (“emergent objects”) have an ever-changing position
- Over an individual’s life-time cells are always dying and new cells are being created, but the individual remains the same individual
- The ants that make up a bridge change continuously
- The water making up the shape of a fountain is always different, but the shape remains

Guiding Heuristics for Decentralized Thinking

The hills are alive (the environment has an independent dynamics)

- People often focus on the behaviors of individual agents, overlooking the environment that surrounds the objects
- Resources are exploited, pollution diffuses to other patches, etc

(adapted from Resnick, 1997)