CS 420/527

Biologically-Inspired Computation

Bruce MacLennan

http://www.cs.utk.edu/~mclennan/Classes/420

Contact Information

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CS 420 vs. CS 527

- CS 420: Undergraduate credit (but graduate students can count one 400-level course)
- CS 527: Graduate credit, additional work

(CS 527 is approved for the Interdisciplinary Graduate Minor in Computational Science)

Grading

- You will conduct a series of computer experiments, which you will write up
- Some of these will be run on off-the-shelf simulators
- Others will be run on simulators that you will program
- Graduate students will do additional experiments and mathematical exercises
- No exams

Prerequisites

- CS 420 & 527: None per se, but you will be required to write some simulations (in Java, C++, NetLogo, or whatever)
- CS 527: Basic calculus through differential equations, linear algebra, basic probability and statistics

Textbook

Flake, Gary William. *The Computational Beauty of Nature*. MIT Press, 1998

Contents of Flake CBN

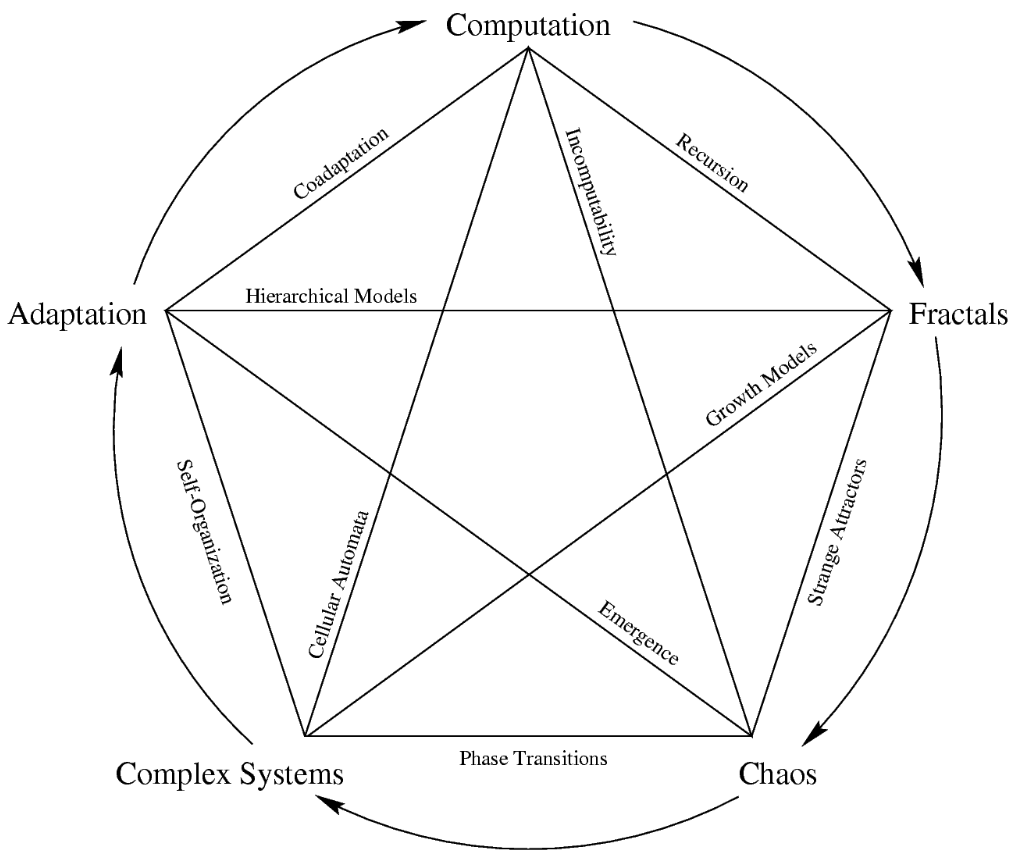


Figure 1.1 An association map of the contents of this book

What We Will Cover

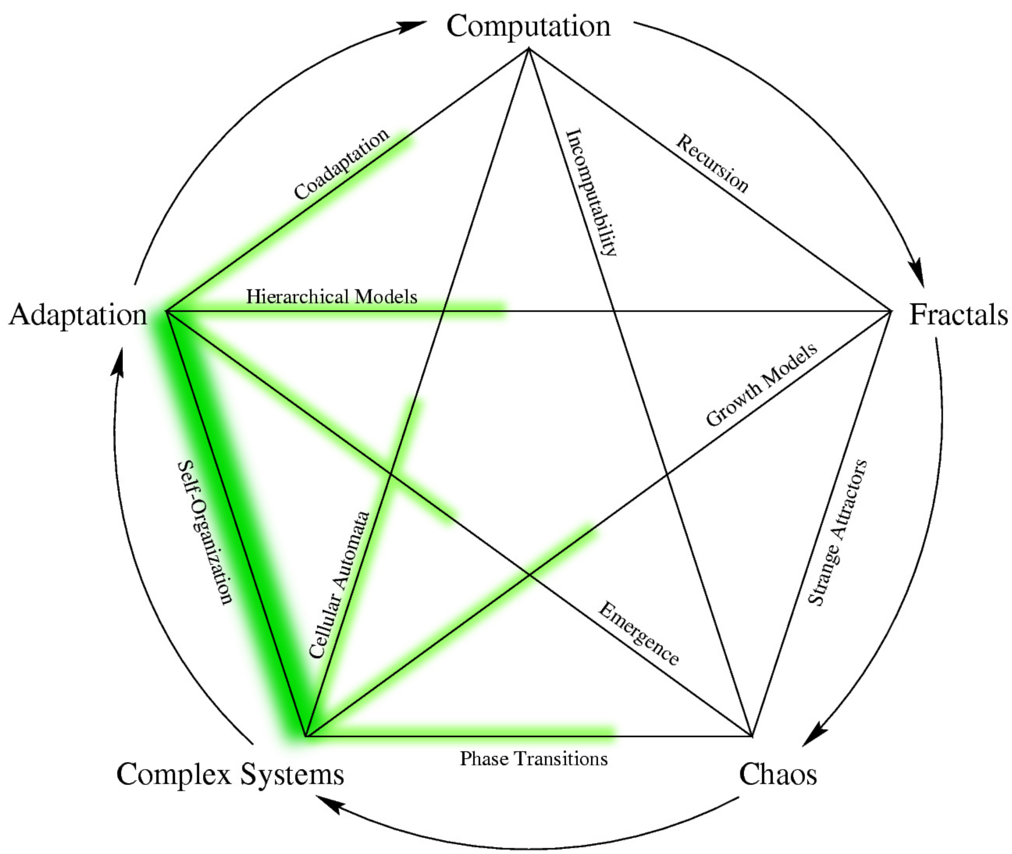


Figure 1.1 An association map of the contents of this book *that we will cover*

Reading for Next Week

- Flake: Ch. 1 (Introduction)
- Flake: Ch. 15 (Cellular Automata)

Course Web Site

- www.cs.utk.edu/~mclennan/Classes/420
- Syllabus
- Link to Flake *CBN* site (with errata, software, etc.)
- Links to other interesting sites
- Handouts:
  - assignments
  - slides in pdf format (revised after class)
- Models (simulation programs)

What is Biologically-Inspired Computation?

- Computer systems, devices, and algorithms based, more or less closely, on biological systems
- *Biomimicry* applied to computing
- Approximately synonymous with: bio-inspired computation, organic computing

Two Kinds of Computation Motivated by Biology

- Computation applied to biology
  - bioinformatics
  - computational biology
  - modeling DNA, cells, organs, populations, etc.
- Biology applied to computation
  - biologically-inspired computation
  - neural networks
  - artificial life
  - etc.

Natural Computation

- "Computation occurring in nature or inspired by that occurring in nature"
- Information processing occurs in natural systems from the DNA-level up through the brain to the social level
- We can learn from these processes and apply them in CS (bio-inspired computing)
- In practice, can't do one without the other

Biological Computation

- Refers to the use of biological materials for computation
  - e.g. DNA, proteins, viruses, bacteria
- Sometimes called "biocomputing"
- Goal: Biocomputers
- Bio-inspired computing need not be done on biocomputers

Why Do Bio-inspired Computation?

- Biological systems are:
  - efficient
  - robust
  - adaptive
  - flexible
  - parallel
  - decentralized
  - self-organizing
  - self-repairing
  - self-optimizing
  - self-protecting
  - self-*
  - etc.

Some of the Natural Systems We Will Study

- adaptive path minimization by ants
- wasp and termite nest building
- army ant raiding
- fish schooling and bird flocking
- pattern formation in animal coats
- coordinated cooperation in slime molds
- synchronized firefly flashing
- soft constraint satisfaction in spin glasses
- evolution by natural selection
- game theory and the evolution of cooperation
- computation at the edge of chaos
- information processing in the brain

Some of the Artificial Systems We Will Study

- artificial neural networks
- simulated annealing
- cellular automata
- ant colony optimization
- artificial immune systems
- particle swarm optimization
- genetic algorithms
- other evolutionary computation systems

Lecture 2

❋

Ants

❋

Emergence and Self-Organization

Ants

Think about the value of having computers, networks, and robots that could do these things.

Why Ants?

- Ants are successful:
  - 30% of Amazon biomass is ants and termites
  - Dry weight of social insects is four times that of other land animals in Amazon
  - Perhaps 10% of Earth's total biomass
  - Comparable to biomass of humans
- Good source: Deborah Gordon: *Ants at Work* (1999)

Intelligent Behavior of Harvester Ants

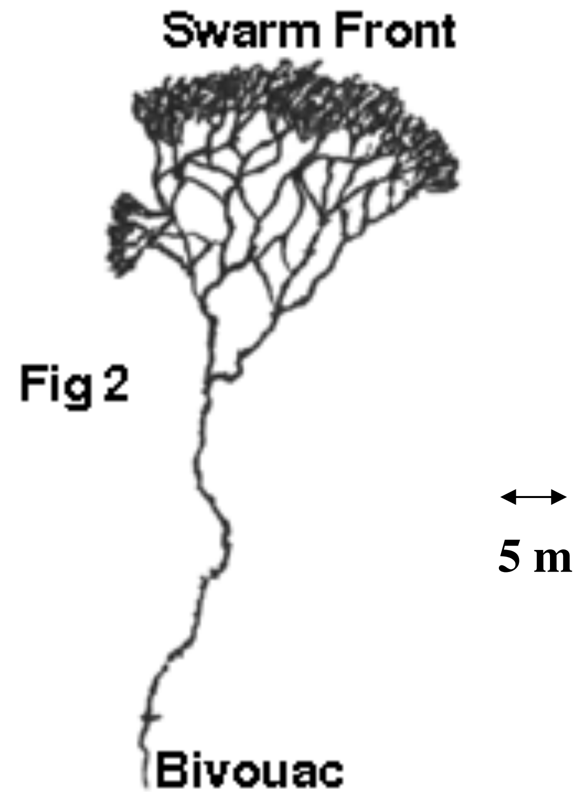
- Find shortest path to food
- Prioritize food sources based on distance & ease of access
- Adjust number involved in foraging based on:
  - colony size
  - amount of food stored
  - amount of food in area
  - presence of other colonies
  - etc.

Army Ants

- No permanent nest
- Create temporary "bivouacs" from bodies of workers
- Raiding parties of up to 200 000
- Act like unified entity

Army Ant Raiding Patterns

Eciton hamatum

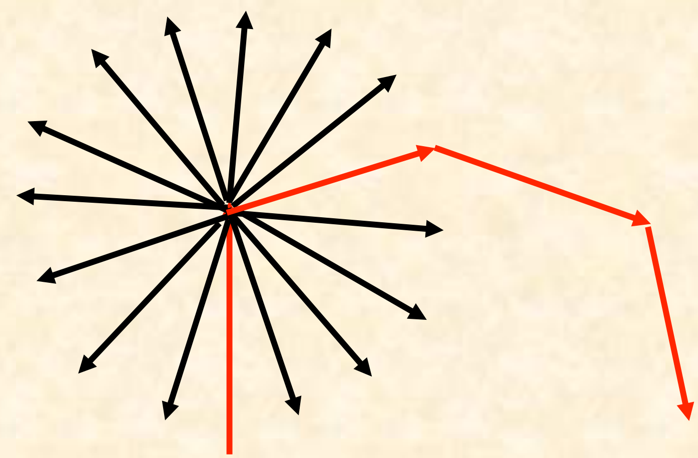


Eciton burchelli

from Solé & Goodwin, *Signs of Life*

Coordination in Army Ant Colonies

- Timing:
  - nomadic phase (15 days)
  - stationary phase (20 days)
- Navigation in stationary phase
  - 14 raids
  - 123° apart

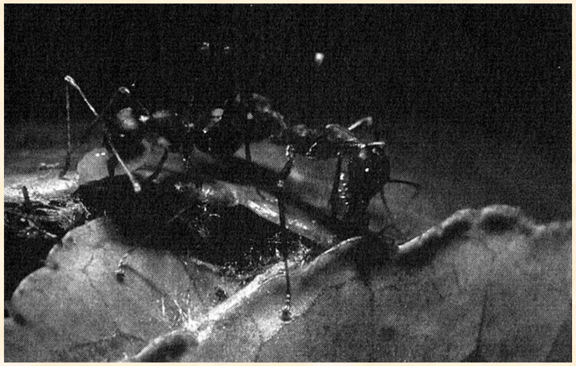


Collective Navigation

- Ants may use polarized sunlight to determine direction
- But army ants have single-facet eyes
  - most insects have multiple facet eyes
- Theory: the two facets of individual ants in group function collectively as a multiple facet eye

Weaver Ants

- Form chains of bodies to bridge gaps
- Others may cross these bridges
- Use chains to pull leaf edges together
- Connect edges with silk from larvae held by workers



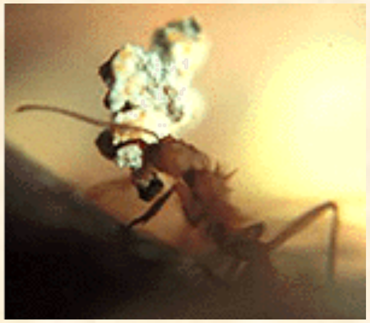
Workers Bridging Gap

Adults Using Larvae as "Glue Guns"

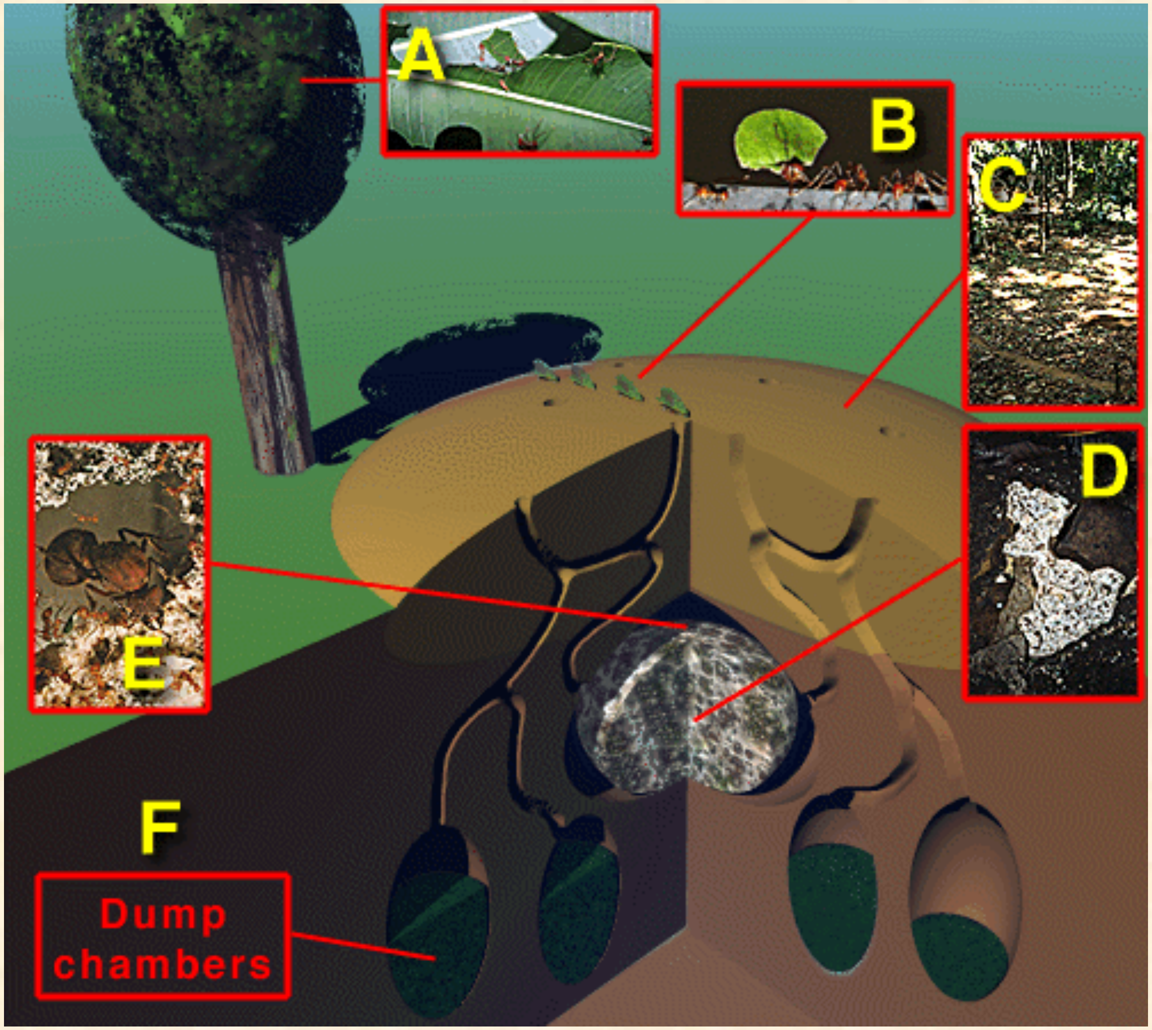
(fig. from *Self-Org. Biol.Sys.*)

Fungus Cultivator Ants

- “Cultivate” fungi underground
- Construct “gardens”
- Plant spores
- Weed out competing fungi
- Fertilize with compost from chewed leaves



Fungus Cultivator Nest



(fig. from AntColony.org)

Leaf Cutting

- Leaves being cut by workers

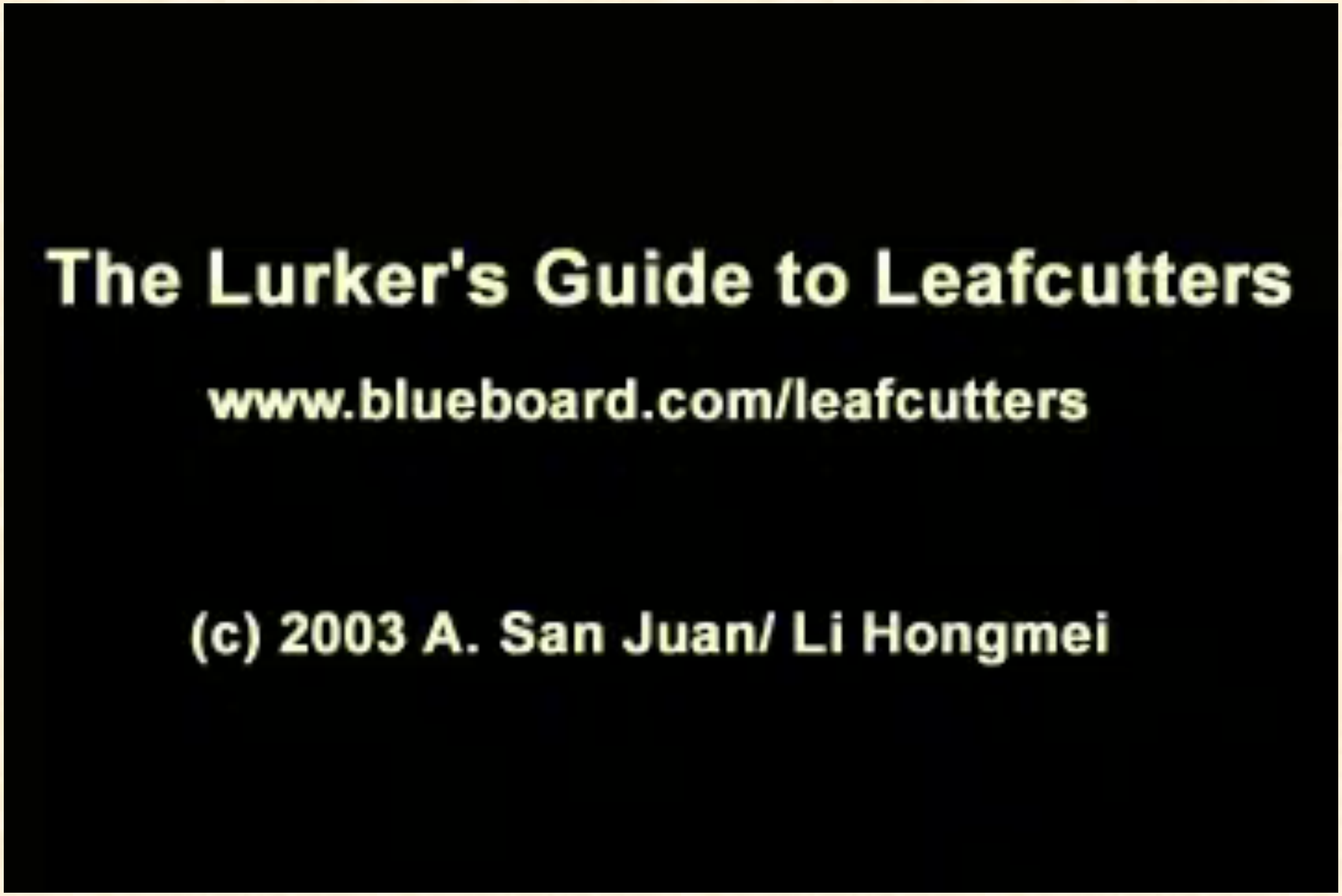
(fig. from AntColony.org)

Transport of Cut Leaves

- Cut leaves are transported from source to nest along trails
- Some temporarily held in caches near the tree

(fig. from AntColony.org)

Transporting Cut Leaves to Nest



(vid. from www.blueboard.com/leafcutters)

Protection by Minims

- Small workers (minims) ride piggy-back
- Protect large workers from parasitic fly trying to lay eggs on head

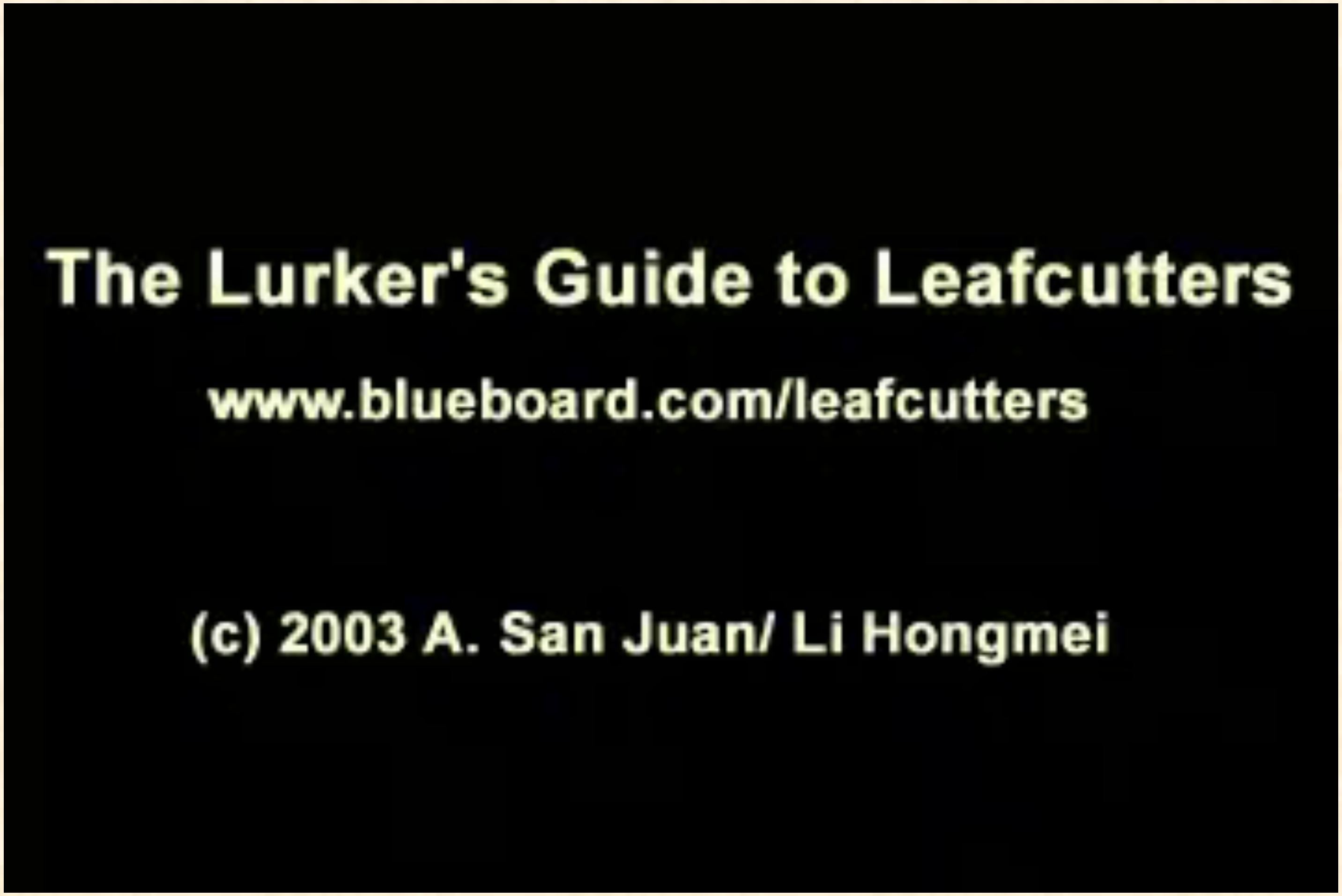
(fig. from AntColony.org)

A Large Nest

- Two mounds, 50 cm in diameter
- Part of a single nest
- Foraging trail visible

(fig. from AntColony.org)

Nest Construction



- Several tons of earth may be removed by large colony

(vid. from www.blueboard.com/leafcutters)

Leaf Brought to Fungus Garden

- Leaf being brought to fungus garden in nest
- Leaf mulch is fed to fungus

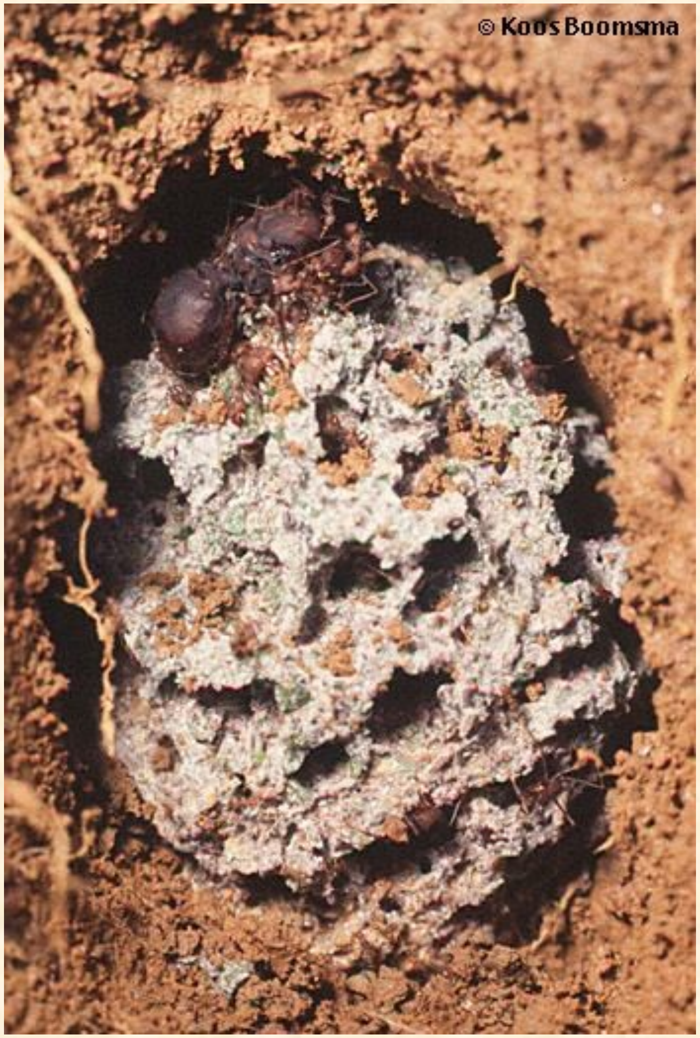
(fig. from AntColony.org)

The Fungus Garden

- Fungus grows special nutritional structures
- Ant larvae and adults can eat these

(fig. from AntColony.org)

Queen in Fungus Garden



- Queen stays in fungus garden
- Lays eggs
- Hatched larvae eat fungus
- Larvae cared for by nurse workers

 (fig. from AntColony.org)

Dump Chambers

- Dump chamber in lab
- In nature, may be 2m underground
- Contain:
  - waste leaf material
  - dead fungus
  - dead ants

(fig. from AntColony.org)

Maeterlinck on Ants

"What is it that governs here? What is it that issues orders, foresees the future, elaborates plans, and preserves equilibrium?"

Emergent Aspects

- Colony size ~ 8×10^6

  but no one is "in charge"!
- Colony lifetime ~ 15 years
- Colonies have a "life cycle"
  - older behave differently from younger
- But ants live no longer than one year
  - Males live one day!

How Do They Do It?

- Communication in Red Harvester Ants
- Good source: Deborah Gordon: *Ants at Work* (1999)

(video from *Stanford Report*, April 2003)

How do they do it?

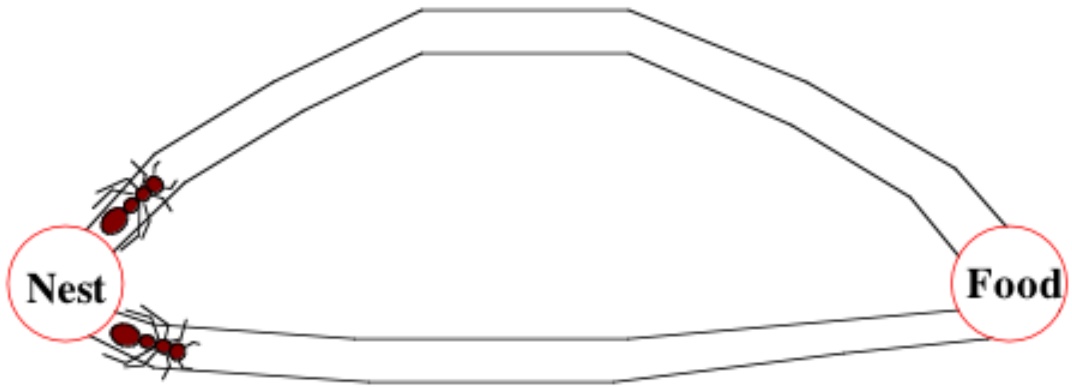
- Semiochemically: deposit pheromones
  - 10-20 signs, many signal tasks
  - ants detect pheromone gradients and frequency of encounter
- Follow trails imperfectly

  ⇒ exploration
- Feedback reinforces successful trails

  ⇒ biased randomness

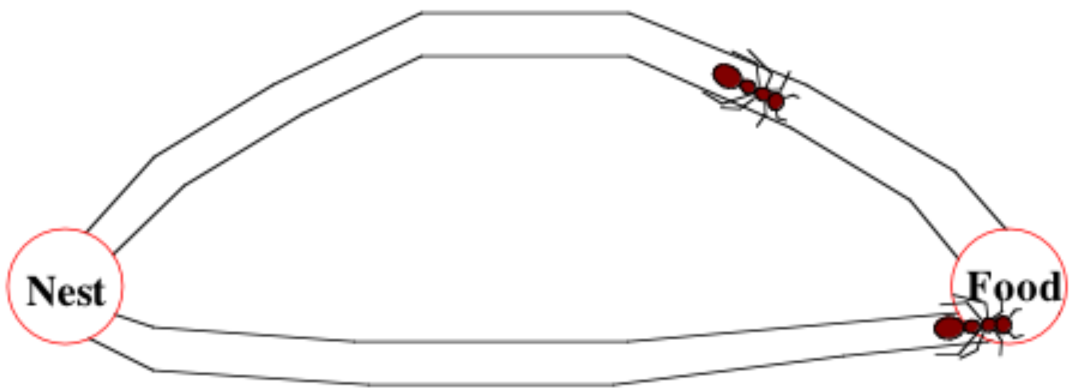
Ant foraging

Cooperative search by pheromone trails



Ant foraging

Cooperative search by pheromone trails



Ant foraging

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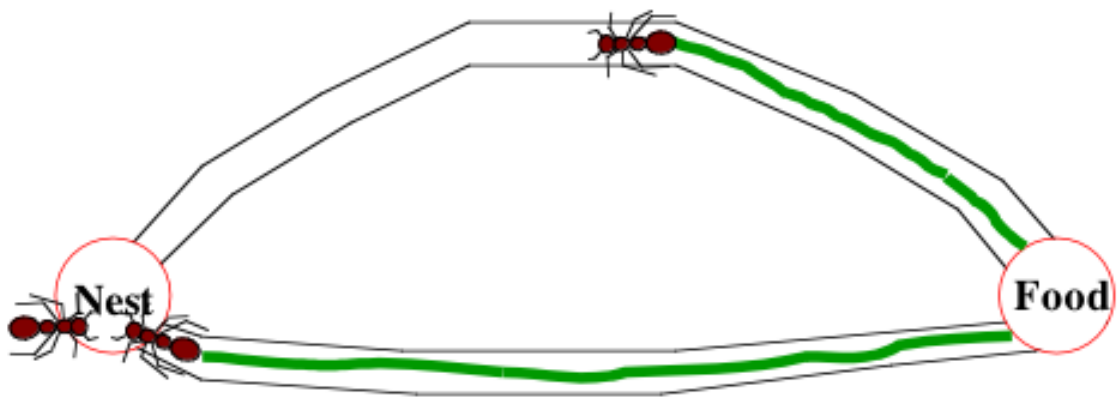

Ant foraging

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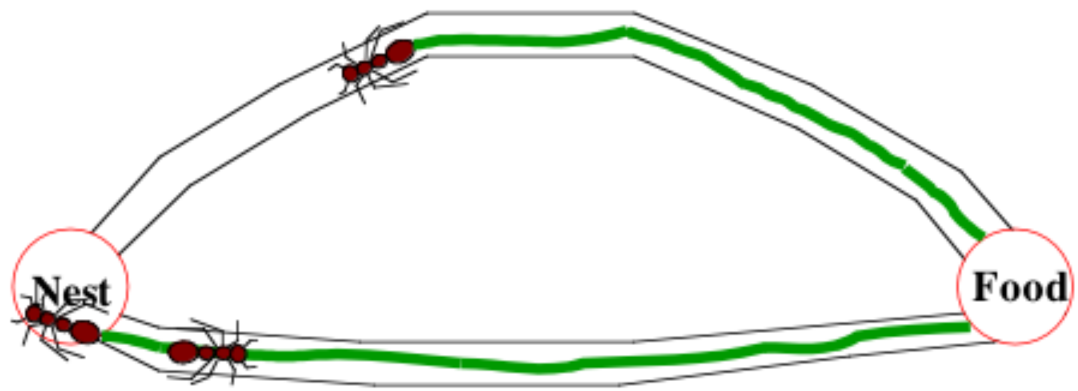
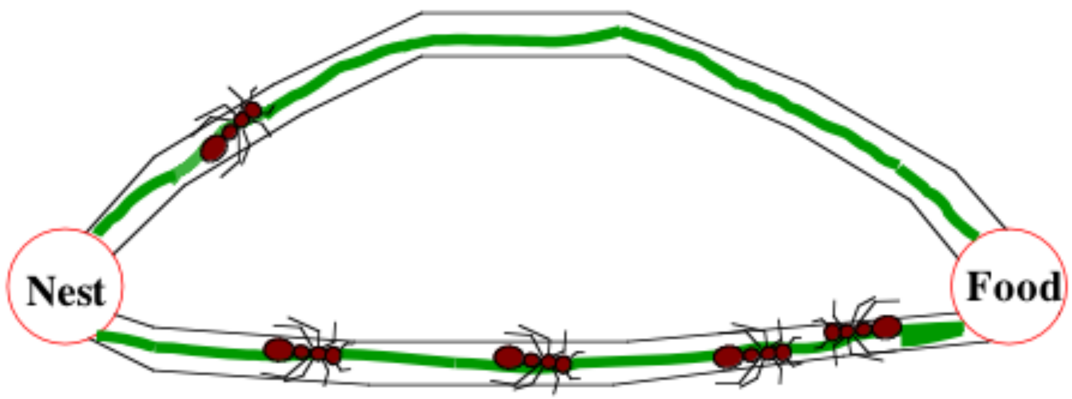


Ant foraging

Cooperative search by pheromone trails



Ant foraging

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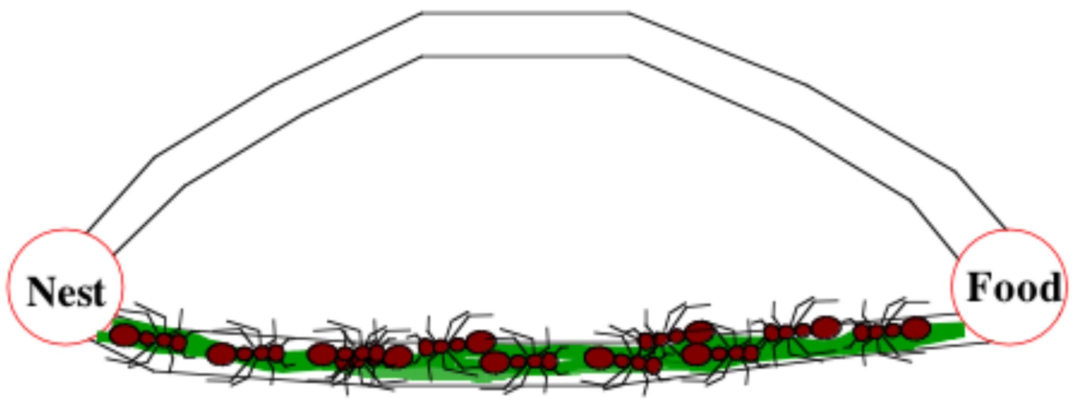

Adaptive Path Optimization

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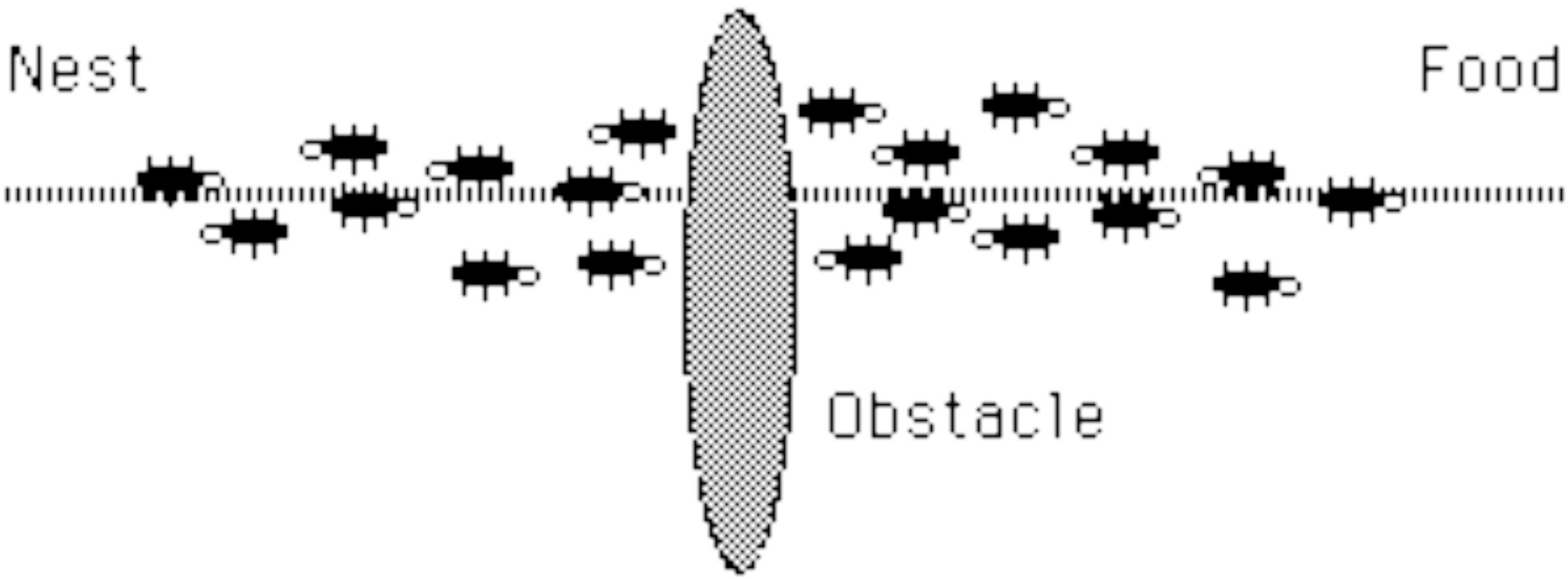
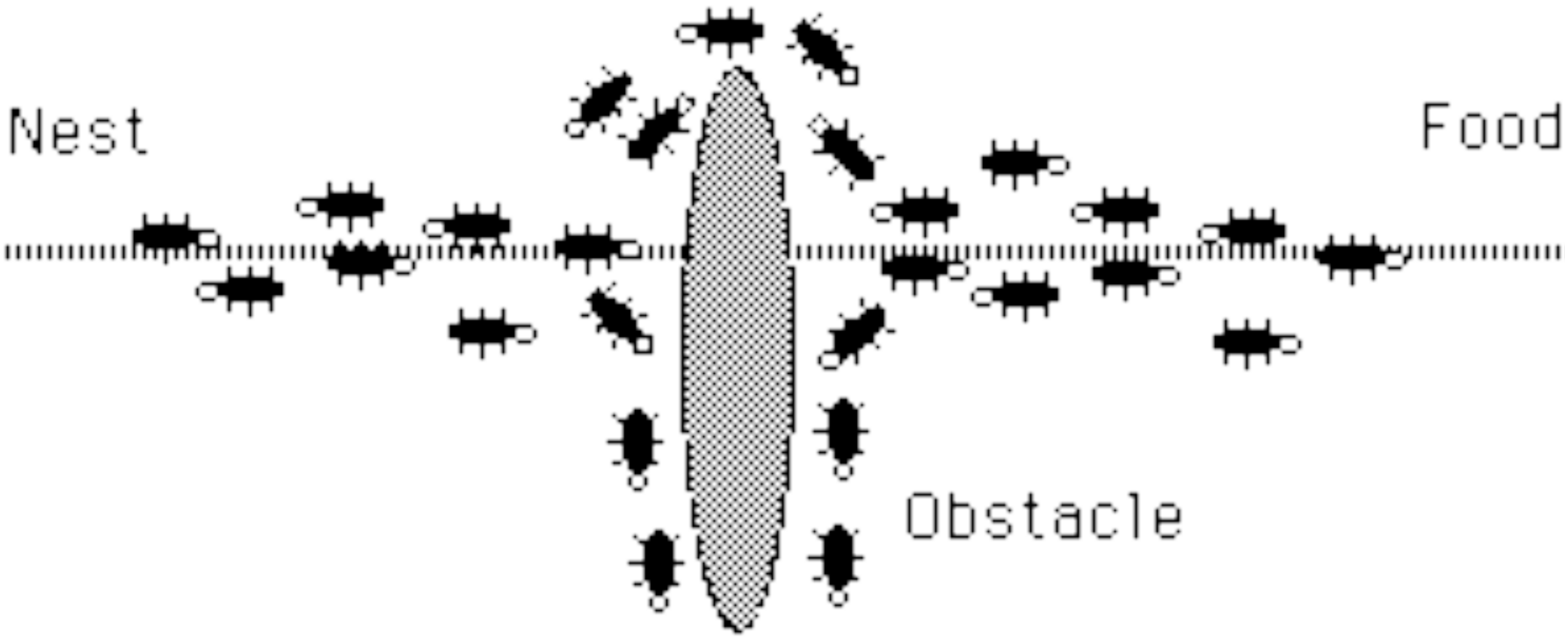
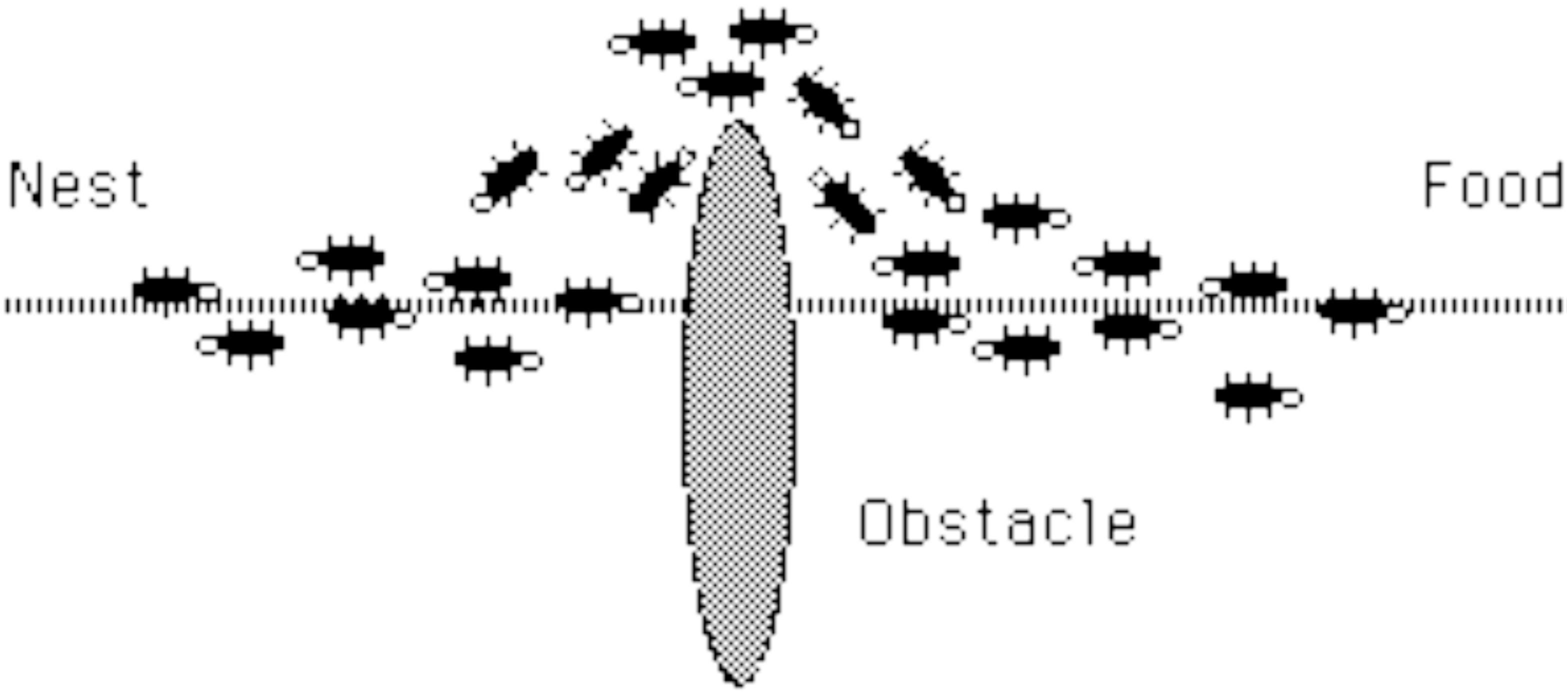


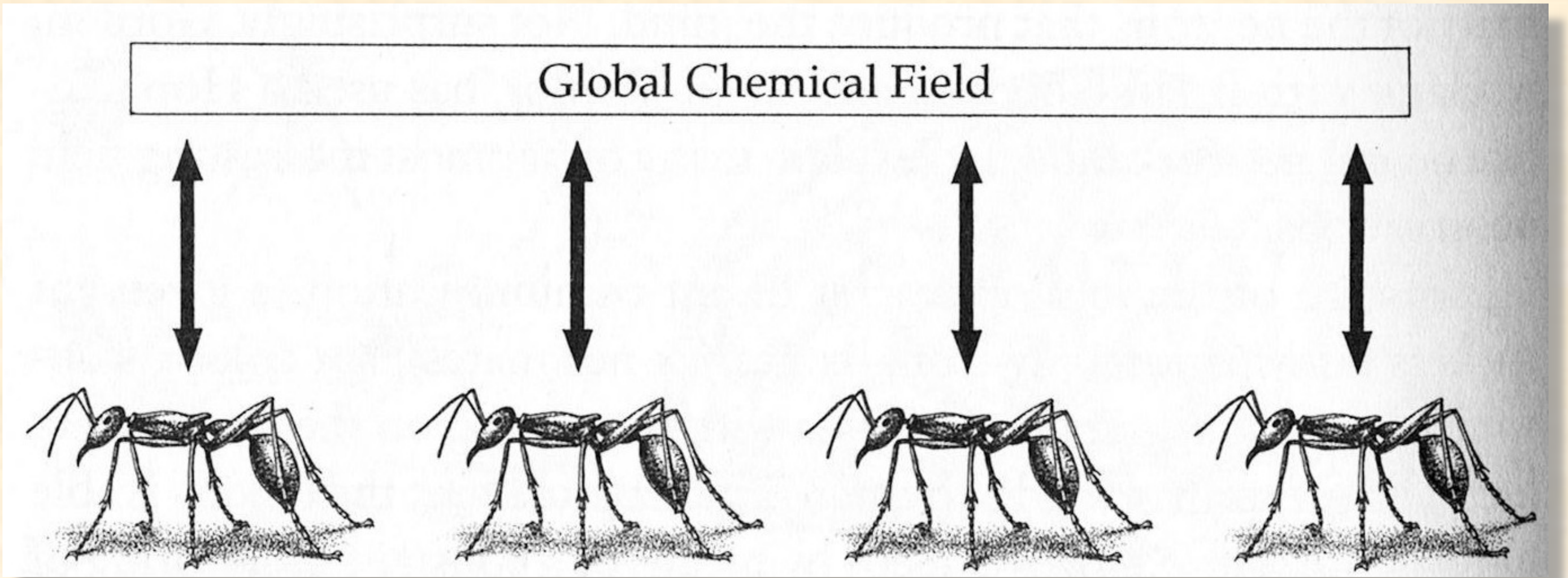
Adaptive Path Optimization



Adaptive Path Optimization



Circular Causality



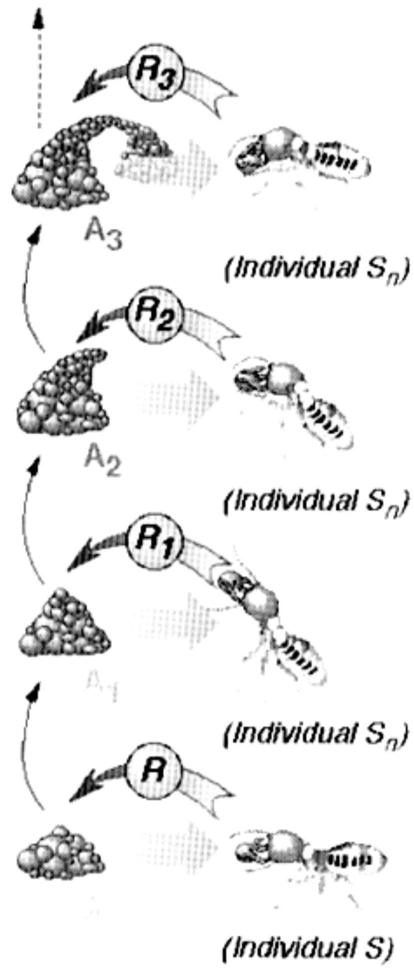
- Global pattern emergent from total system
- Individuals respond to local field

fig. from Solé & Goodwin

Stigmergy

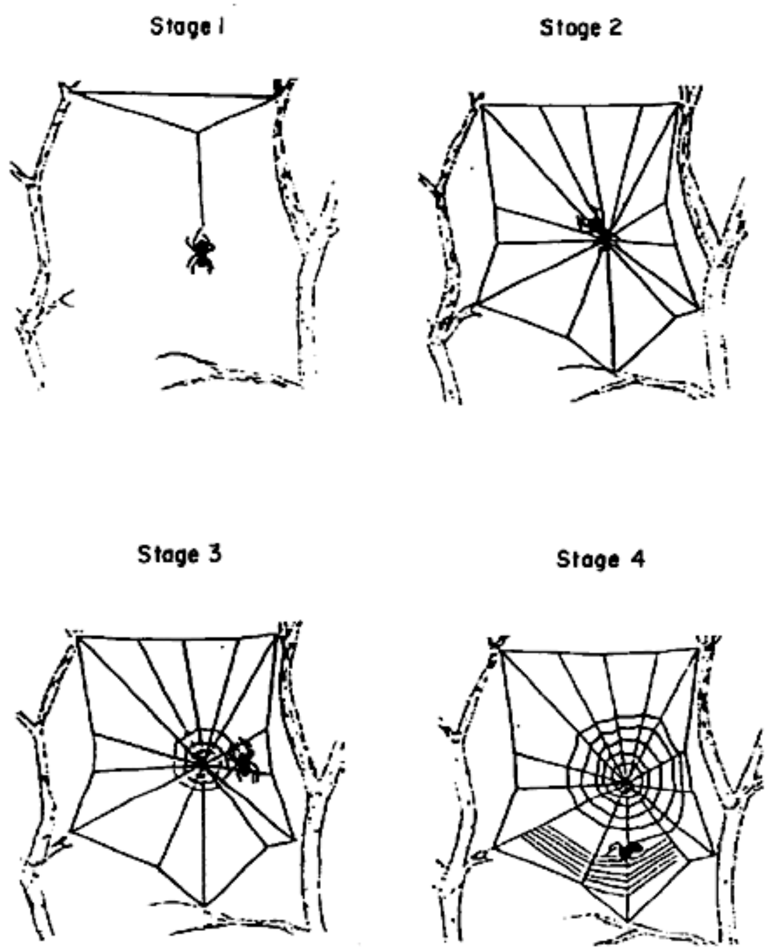
- From στιγμός = pricking + ἔργον = work
- The project (work) in the environment is an instigation
- Agent interactions may be:
  - direct
  - indirect (time-delayed through environment)
- Mediates individual and colony levels

Stigmergy in termite nest building



Fig, from EVALife

Stigmergy in spider webs



Fig, from EVALife

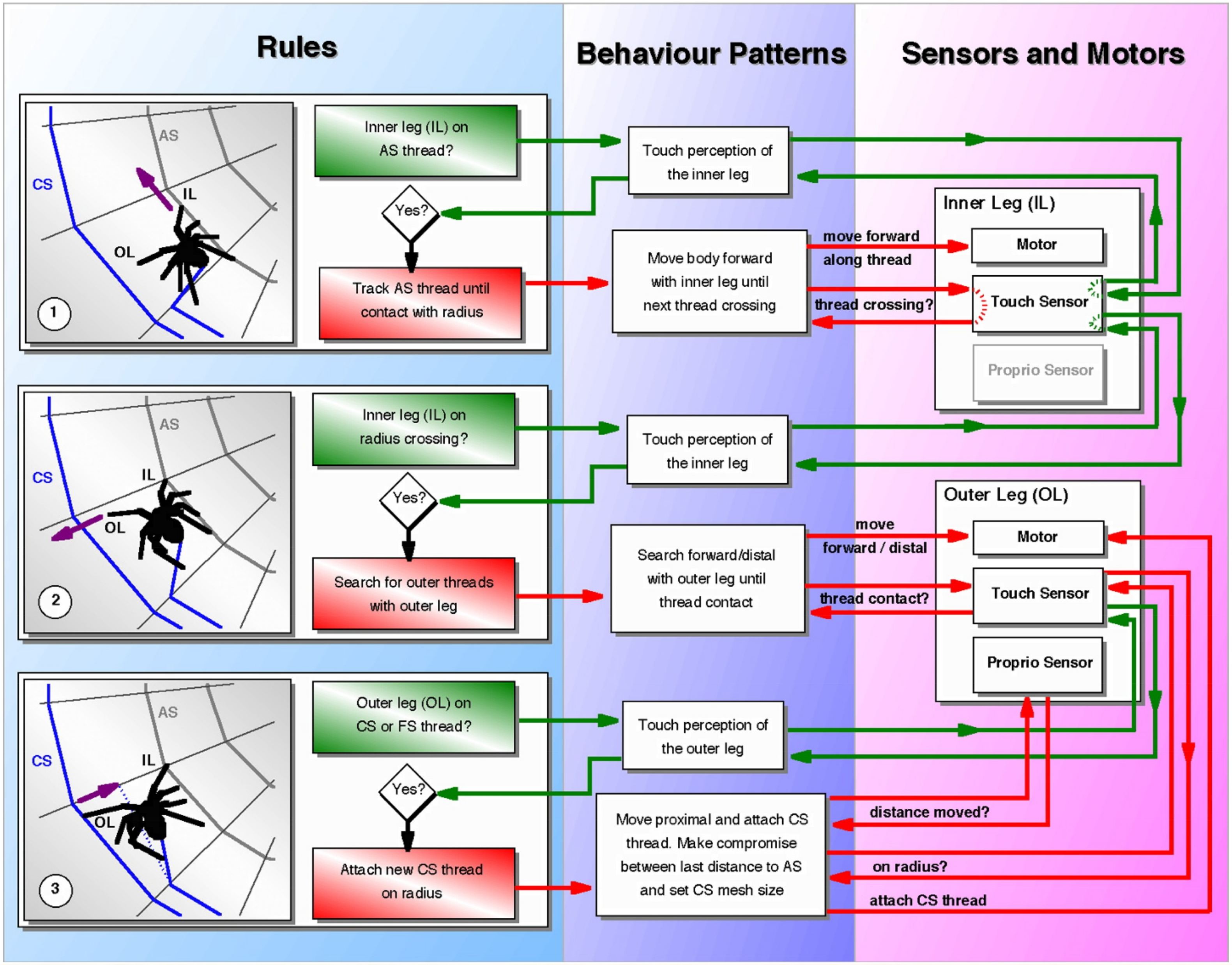
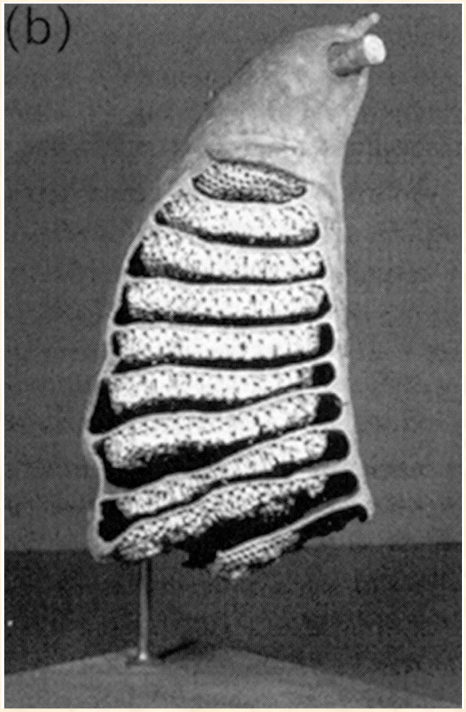


Fig. from EVALife

Advantages of Stigmergy

- Permits simpler agents
- Decreases direct communication between agents
- Incremental improvement
- Flexible, since when environment changes, agents respond appropriately



Emergence

- The appearance of *macroscopic* patterns, properties, or behaviors
- that are not simply the "sum" of the *microscopic* properties or behaviors of the components
  - non-linear but not chaotic
- Macroscopic order often described by fewer & different variables than microscopic order
  - e.g. ant trails vs. individual ants
  - *order parameters*

Self-Organization

- Order may be imposed from outside a system
  - to understand, look at the external source of organization
- In *self-organization*, the order emerges from the system itself
  - must look at interactions within system
- In biological systems, the emergent order often has some adaptive purpose
  - e.g., efficient operation of ant colony

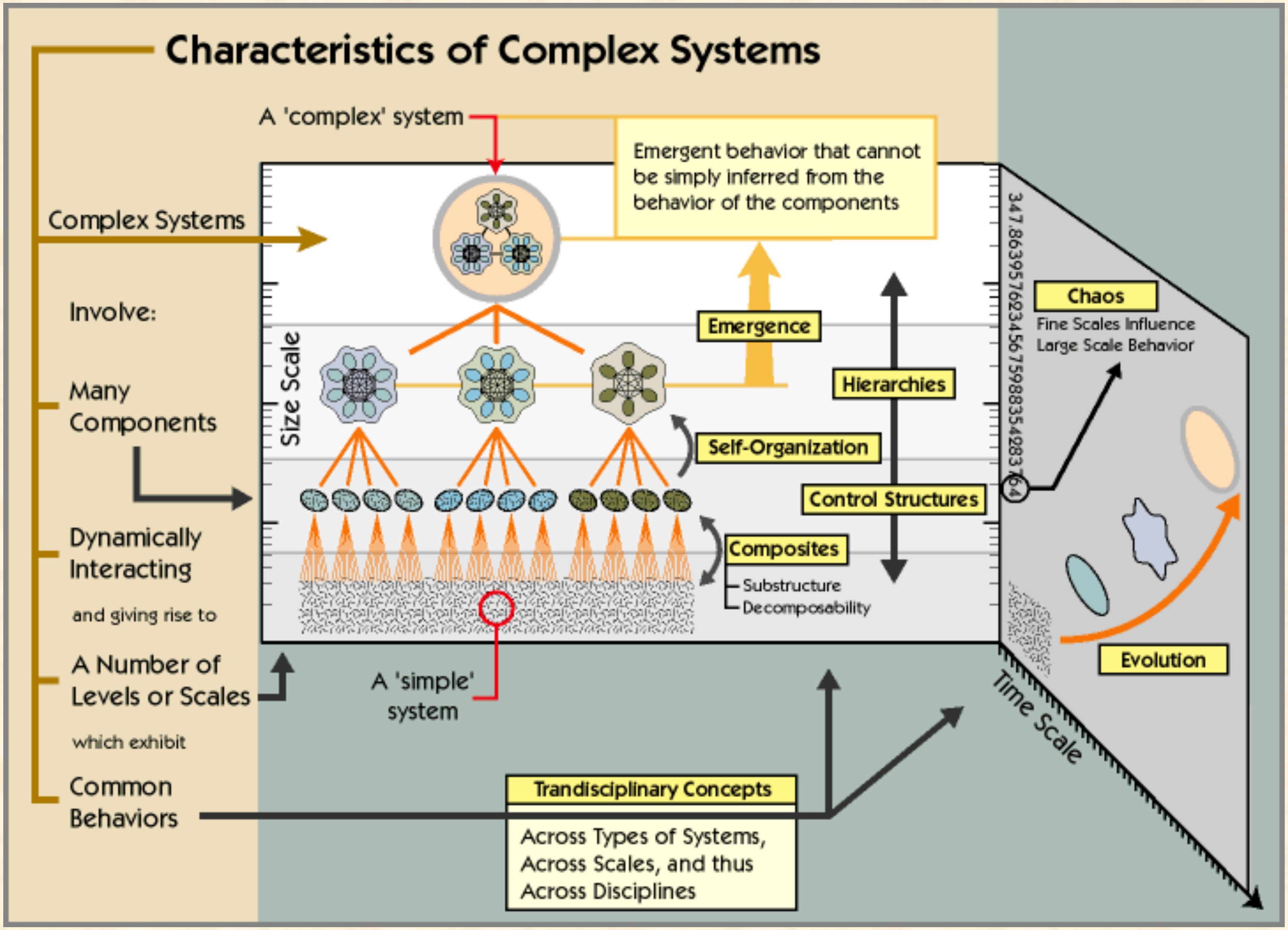


Fig. from NECSI

Why Are Complex Systems & Self-Organization Important for CS?

- Fundamental to theory & implementation of massively parallel, distributed computation systems
- How can millions of independent computational (or robotic) agents cooperate to process information & achieve goals, in a way that is:
  - efficient
  - self-optimizing
  - adaptive
  - robust in the face of damage or attack

Some Principles Underlying Emergent Systems

- “More is different”
- “Ignorance is useful”
- “Encourage random encounters”
- “Look for patterns in signals”
- “Pay attention to your neighbor”
  (“Local information leads to global wisdom”)

— Johnson, *Emergence*, pp. 77-9.

Similar Principles of SO

- Ant colonies
- Development of embryo
- Molecular interactions within cell
- Neural networks

Comparison of Ant Colonies and Neural Networks

	Ant Colonies	*Neural Nets*
No. of units	high	high
Robustness	high	high
Connectivity	local	local
Memory	short-term	short/long term
Connect. stability	weak	high
Global patterns	trails	brain waves
Complex dynamics	observed	common

from Solé & Goodwin: *Signs of Life*, p. 149

Self-Organization

- Concept originated in physics and chemistry
  - emergence of macroscopic patterns
  - out of microscopic processes & interactions
- "Self-organization is a set of dynamical mechanisms whereby structures appear at the global level of a system from interactions among its lower-level components." — Bonabeau, Dorigo & Theraulaz, p. 9

Four Ingredients of Self-Organization

- Activity amplification by positive feedback
- Activity balancing by negative feedback
- Amplification of random fluctuations
- Multiple Interactions

— Bonabeau, Dorigo & Theraulaz, pp. 9-11

Characteristics of Self-Organized System

- Creation of spatiotemporal structures in initially homogeneous medium
- Multistability
- Bifurcations when parameters are varied

— Bonabeau, Dorigo & Theraulaz, *Swarm Intelligence*, pp. 12-14

Two Approaches to the Properties of Complex Systems

Focal Issue: Emergence

- Deals with: elements & interactions
- Based on: relation between parts & whole
- Emergent simplicity
- Emergent complexity
- Importance of scale (level)

Focal Issue: Complexity

- Deals with: information & description
- Based on: relation of system to its descriptions
- Information theory & computation theory are relevant
- Must be sensitive to level of description

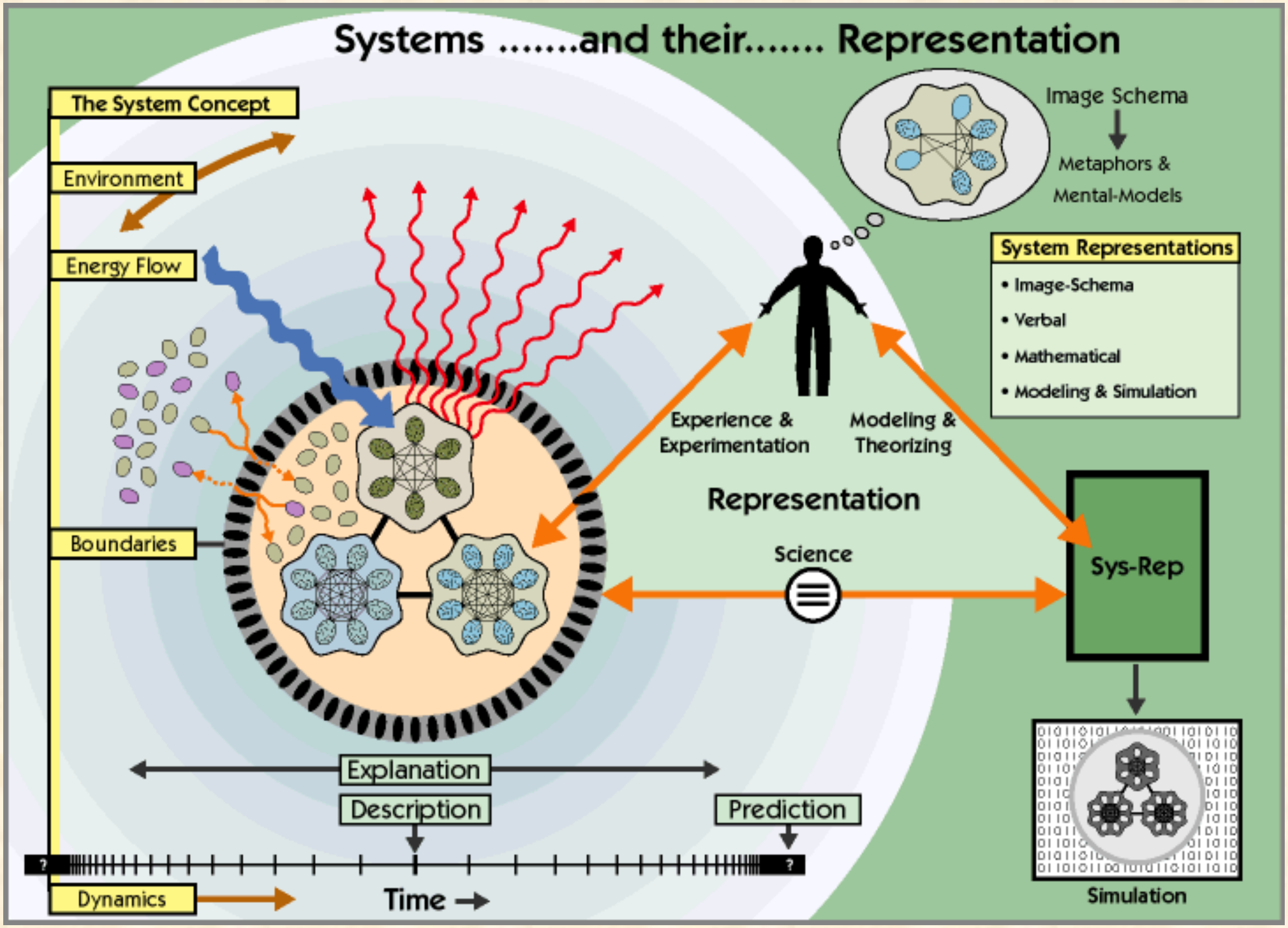


Fig. from NECSI

Additional Bibliography

1. Solé, Ricard, & Goodwin, Brian. *Signs of Life: How Complexity Pervades Biology*. Basic Books, 2000.
2. Bonabeau, Eric, Dorigo, Marco, & Theraulaz, Guy. *Swarm Intelligence: From Natural to Artificial Systems*. Oxford, 1999.
3. Gordon, Deborah. *Ants at Work: How an Insect Society Is Organized*. Free Press, 1999.
4. Johnson, Steven. *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*. Scribner, 2001. A popular book, but with many good insights.

Part II