

# CS 420/594

(Advanced Topics in Machine Intelligence)

## Biologically-Inspired Computation

Bruce MacLennan

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

# Contact Information

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# CS 420 vs. CS 594

- CS 420: Undergraduate credit (but graduate students can count one 400-level course)
- CS 594: Graduate credit, additional work

(CS 594 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

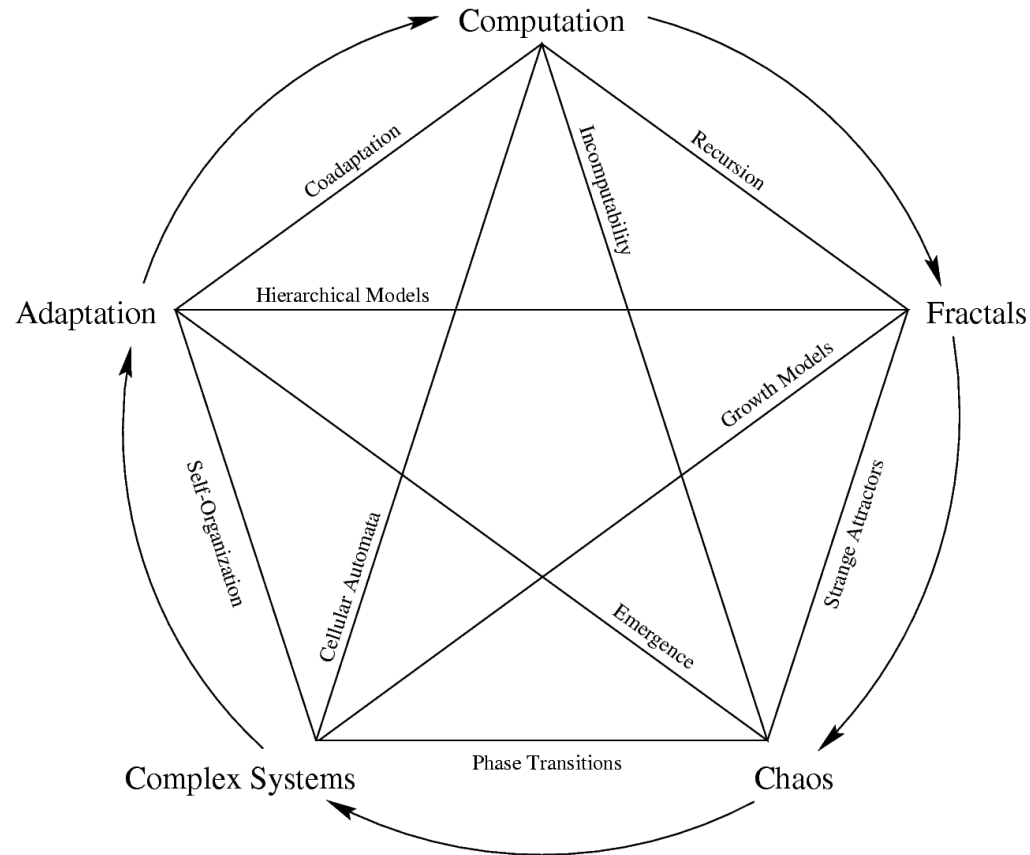
# Prerequisites

- CS 420 & 594: None per se, but you will be required to write some simulations (in Java, C++, NetLogo, or whatever)
- CS 594: Basic calculus through differential equations, linear algebra, basic probability and statistics

# Textbook

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

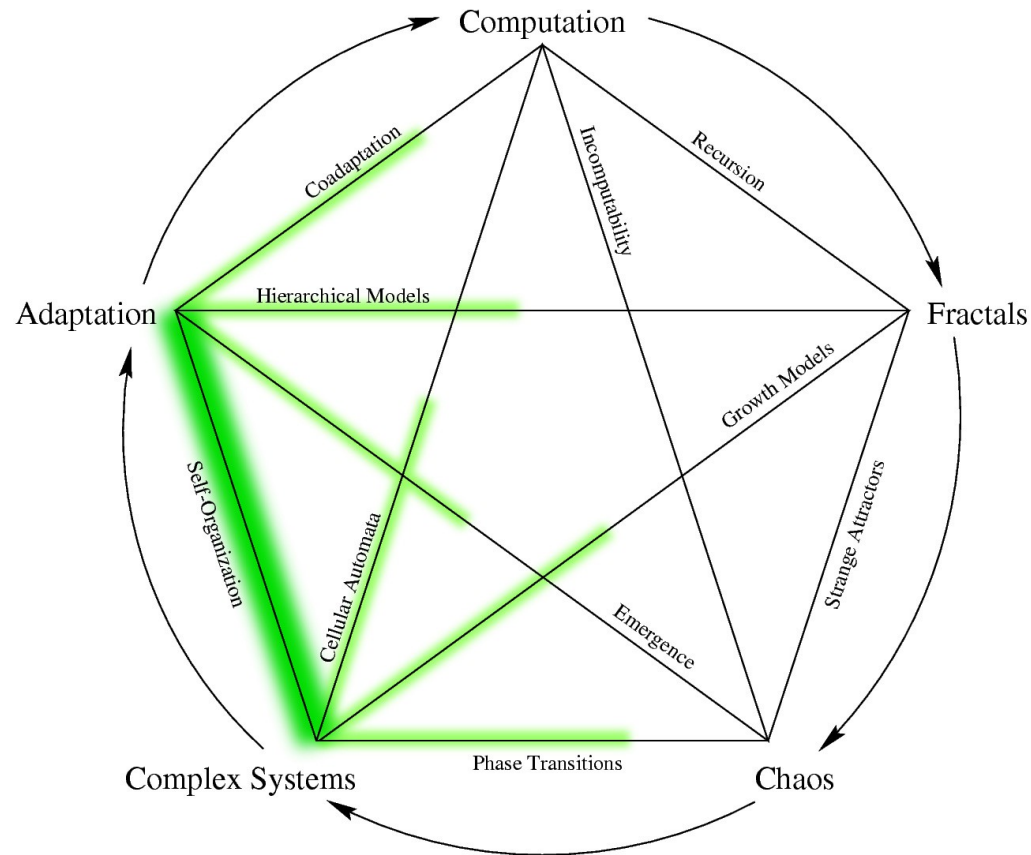
# Contents of Flake CBN



**Figure 1.1** An association map of the contents of this book

Figure from *The Computational Beauty of Nature: Computer Explorations of Fractals, Chaos, Complex Systems, and Adaptation*. Copyright © 1998–2000 by Gary William Flake. All rights reserved. Permission granted for educational, scholarly, and personal use provided that this notice remains intact and unaltered. No part of this work may be reproduced for commercial purposes without prior written permission from the MIT Press.

# What We Will Cover



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

Figure from *The Computational Beauty of Nature: Computer Explorations of Fractals, Chaos, Complex Systems, and Adaptation*. Copyright © 1998–2000 by Gary William Flake. All rights reserved. Permission granted for educational, scholarly, and personal use provided that this notice remains intact and unaltered. No part of this work may be reproduced for commercial purposes without prior written permission from the MIT Press.



# Reading for Next Week

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

# Course Web Site

- [www.cs.utk.edu/~mclennan/Classes/420](http://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 formats (revised after class)

# 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
  - 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

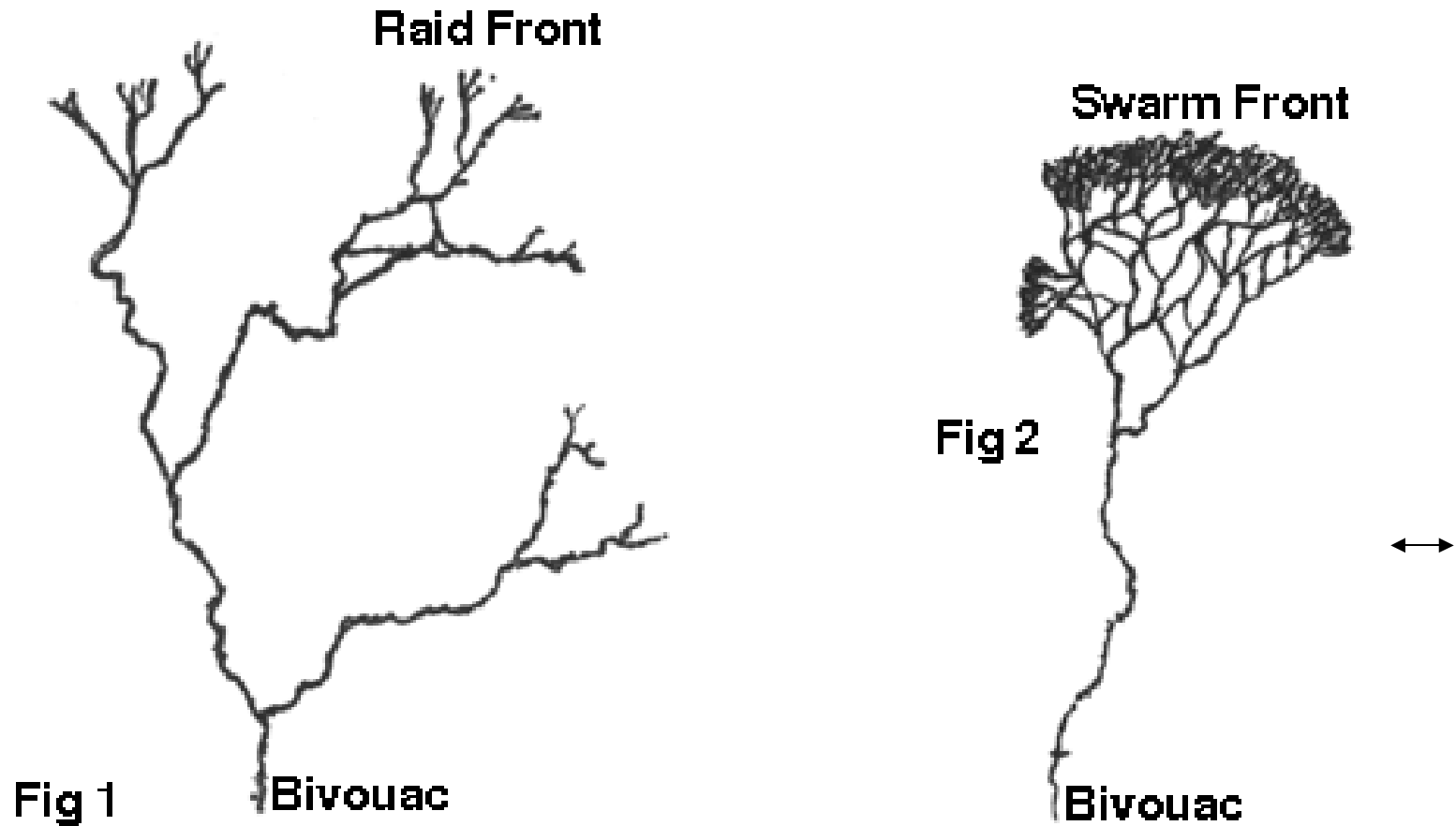
- Find shortest path to food
- Prioritize food sources based on distance & ease of access
- Adjust number involved in foraging based on:
  - colony size
  - amount of food stored
  - amount of food in area
  - presence of other colonies
  - etc.

# Army Ants



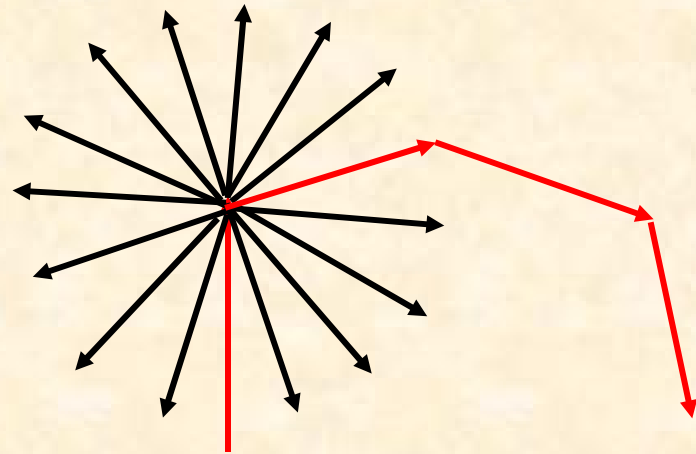
- No permanent nest
- Create temporary “bivouacs” from bodies of workers
- Raiding parties of up to 200 000
- Act like unified entity

# Army Ant Raiding Patterns



# Coordination in Army Ant Colonies

- Timing:
  - nomadic phase (15 days)
  - stationary phase (20 days)
- Navigation in stationary phase
  - 14 raids
  - $123^\circ$  apart





# Collective Navigation

- Ant 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”

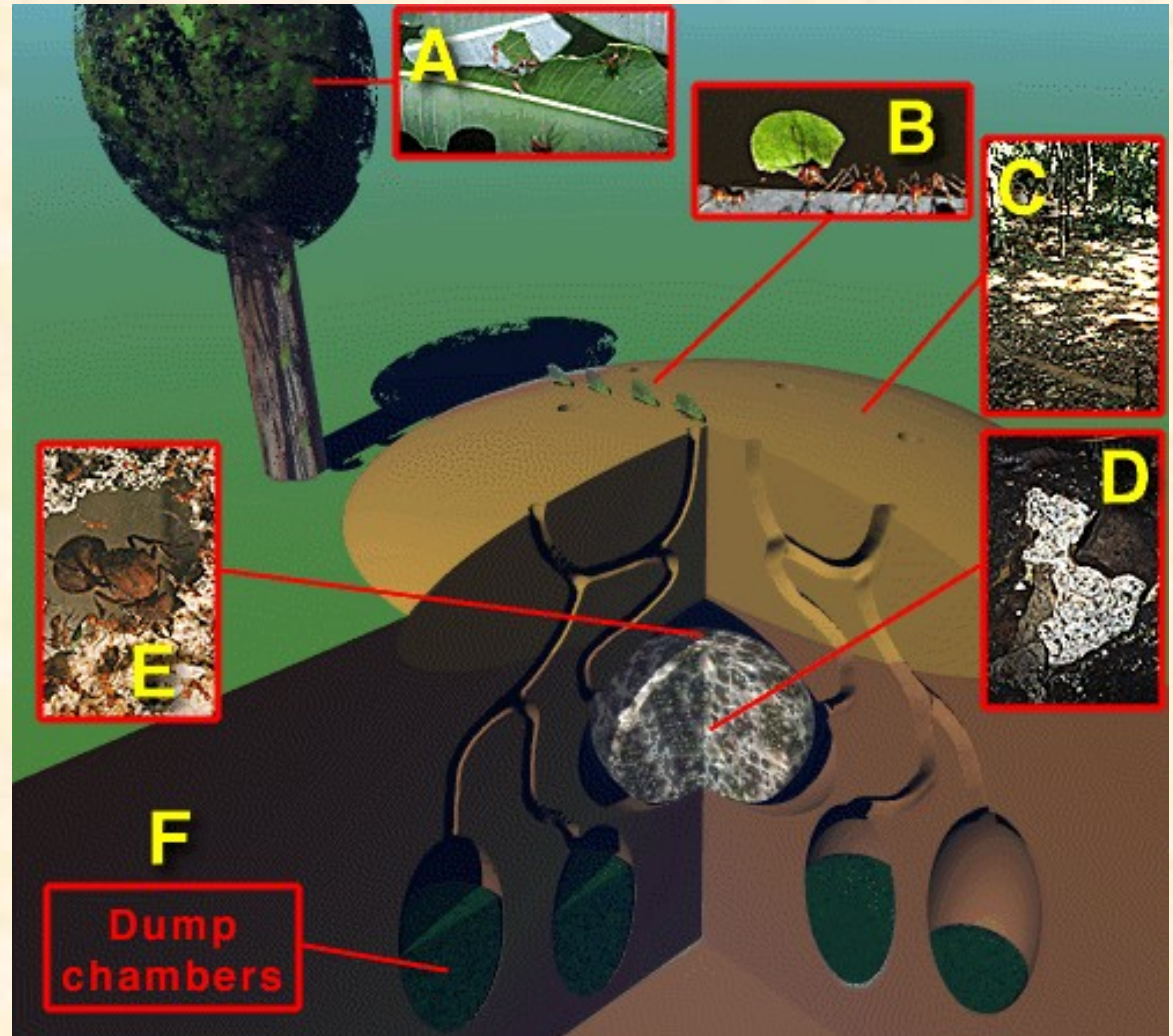


# Fungus Cultivator Ants

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



# Fungus Cultivator Nest



# Leaf Cutting



- Leaves being cut by workers

# Transport of Cut Leaves



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



# Transporting Cut Leaves to Nest

**The Lurker's Guide to Leafcutters**

**[www.blueboard.com/leafcutters](http://www.blueboard.com/leafcutters)**

**(c) 2003 A. San Juan/ Li Hongmei**

# Protection by Minims



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

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# A Large Nest

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

# Nest Construction

## **The Lurker's Guide to Leafcutters**

**[www.blueboard.com/leafcutters](http://www.blueboard.com/leafcutters)**

**(c) 2003 A. San Juan/ Li Hongmei**

- Several tons of earth may be removed by large colony

# Leaf Brought to Fungus Garden



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

# The Fungus Garden



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

# Queen in Fungus Garden



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

# Dump Chambers

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





# 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  $\sim 8 \times 10^6$   
*but no one is “in charge”!*
- Colony lifetime  $\sim 15$  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)

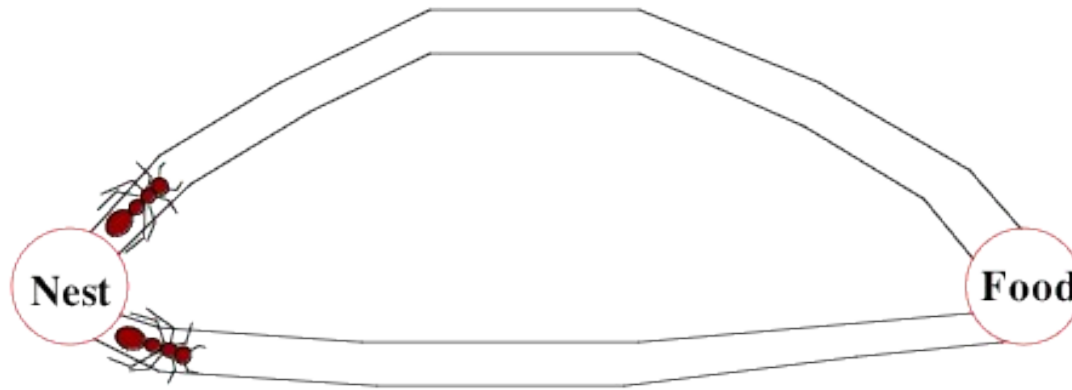


# How do they do it?

- 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

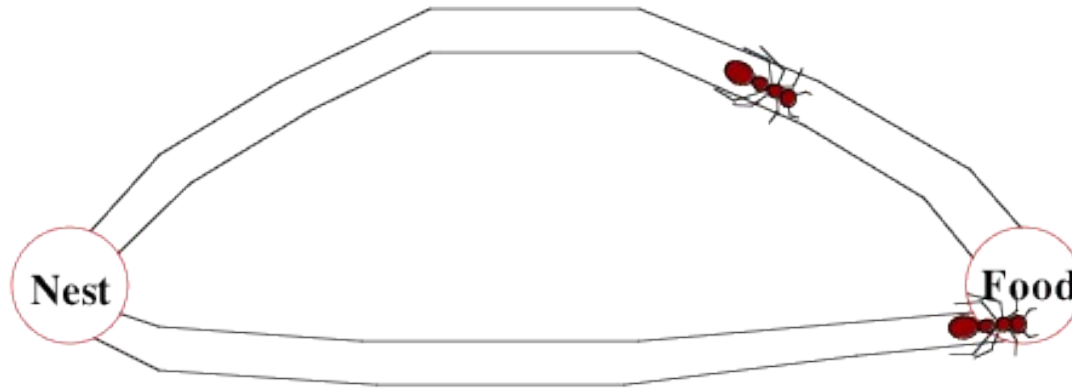
# Ant foraging

## Cooperative search by pheromone trails



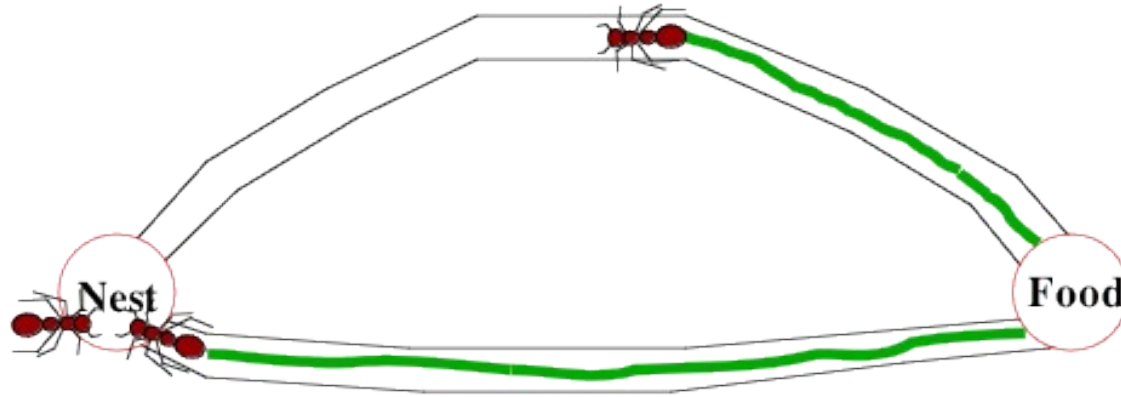
# Ant foraging

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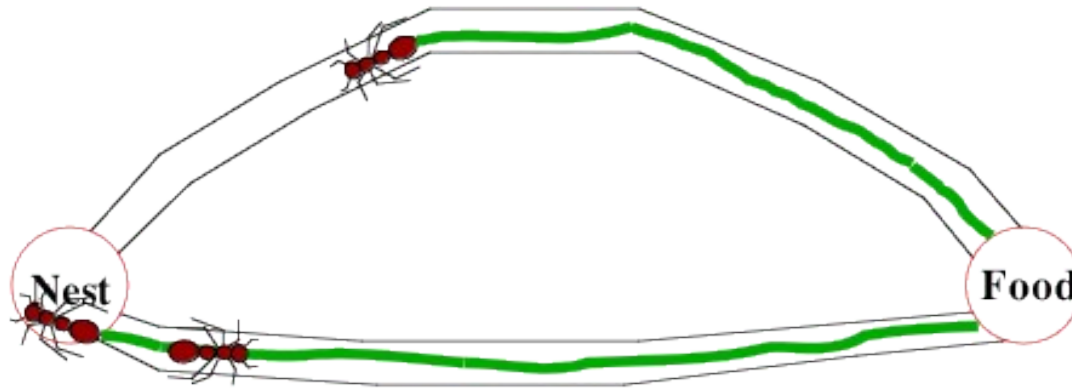
# Ant foraging

## Cooperative search by pheromone trails



# Ant foraging

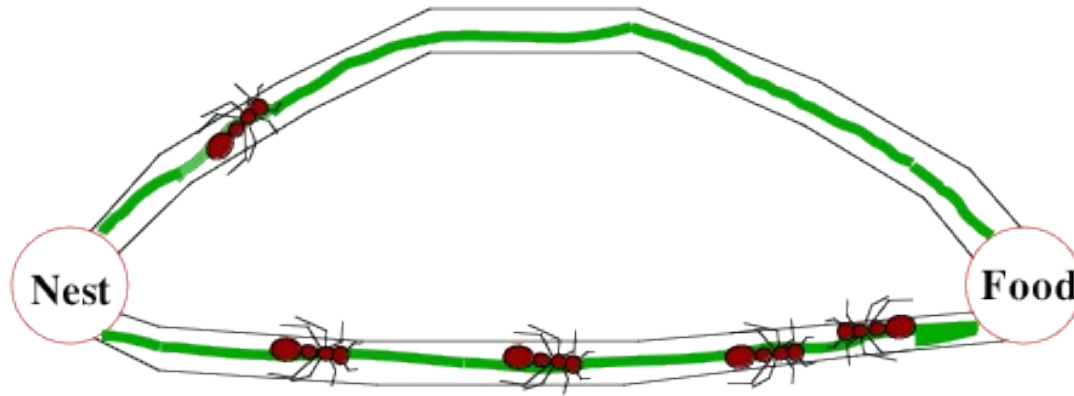
Cooperative search by pheromone trails





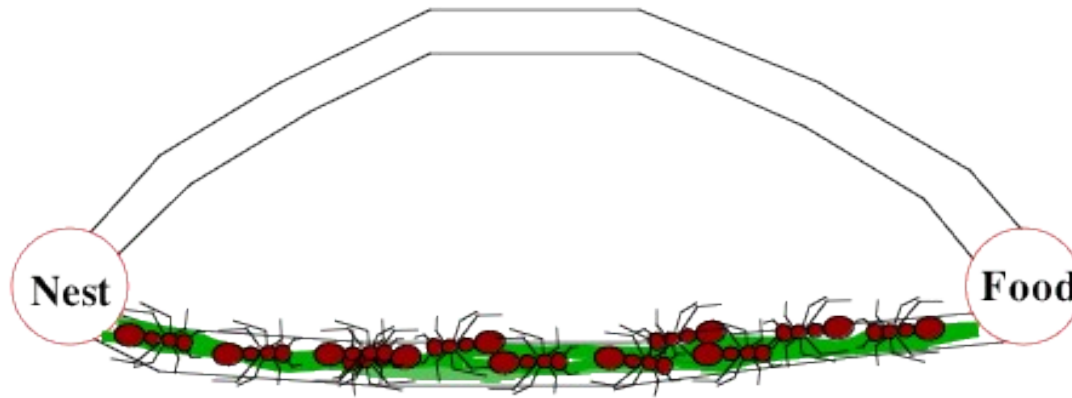
# Ant foraging

## Cooperative search by pheromone trails

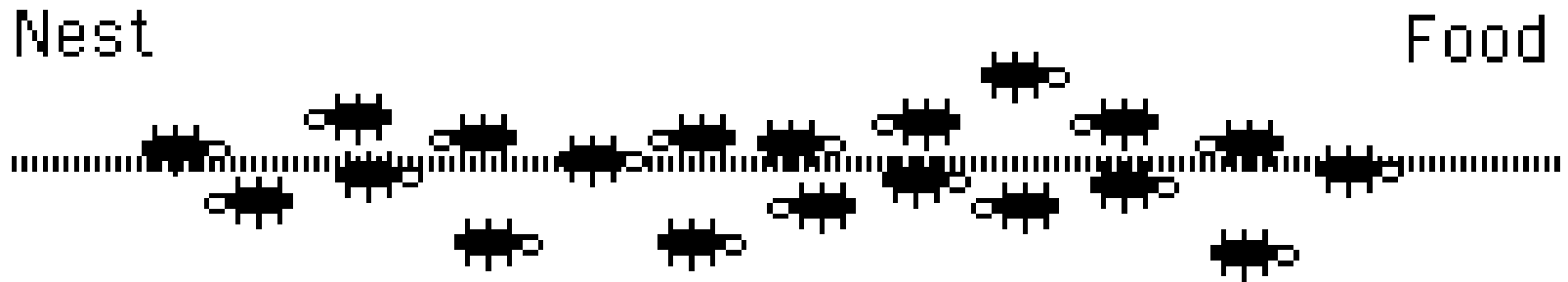


# Ant foraging

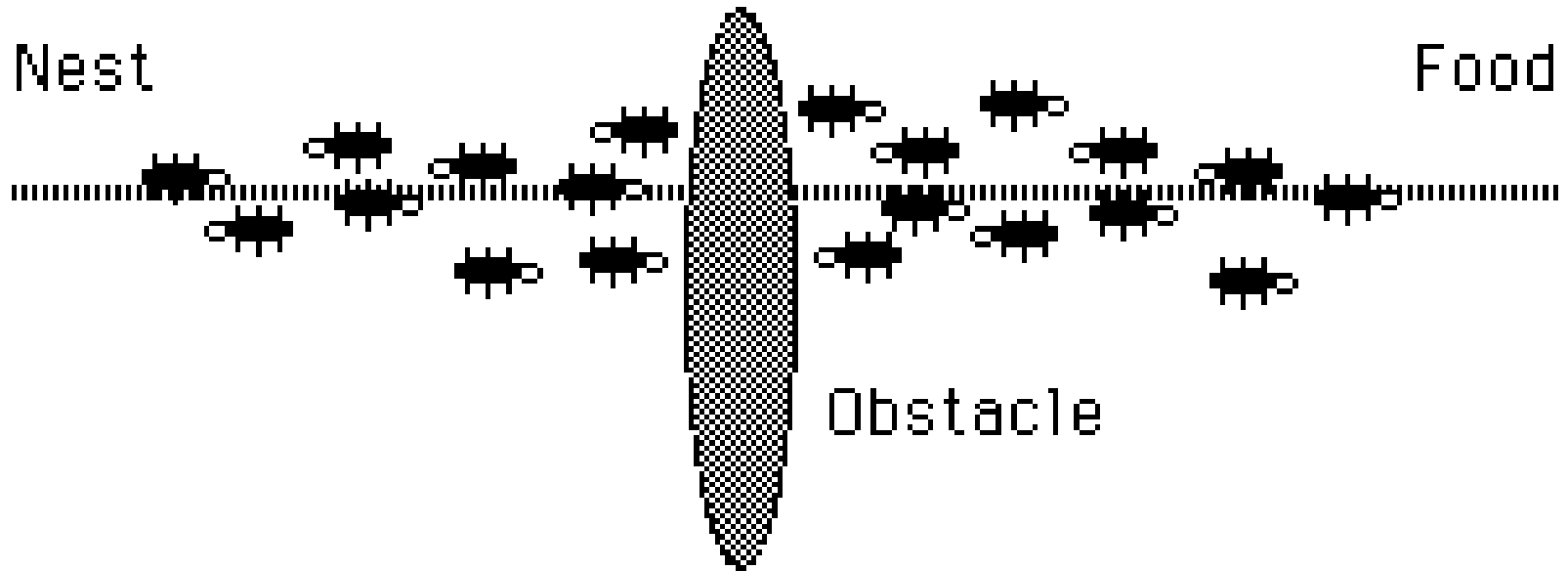
## Cooperative search by pheromone trails



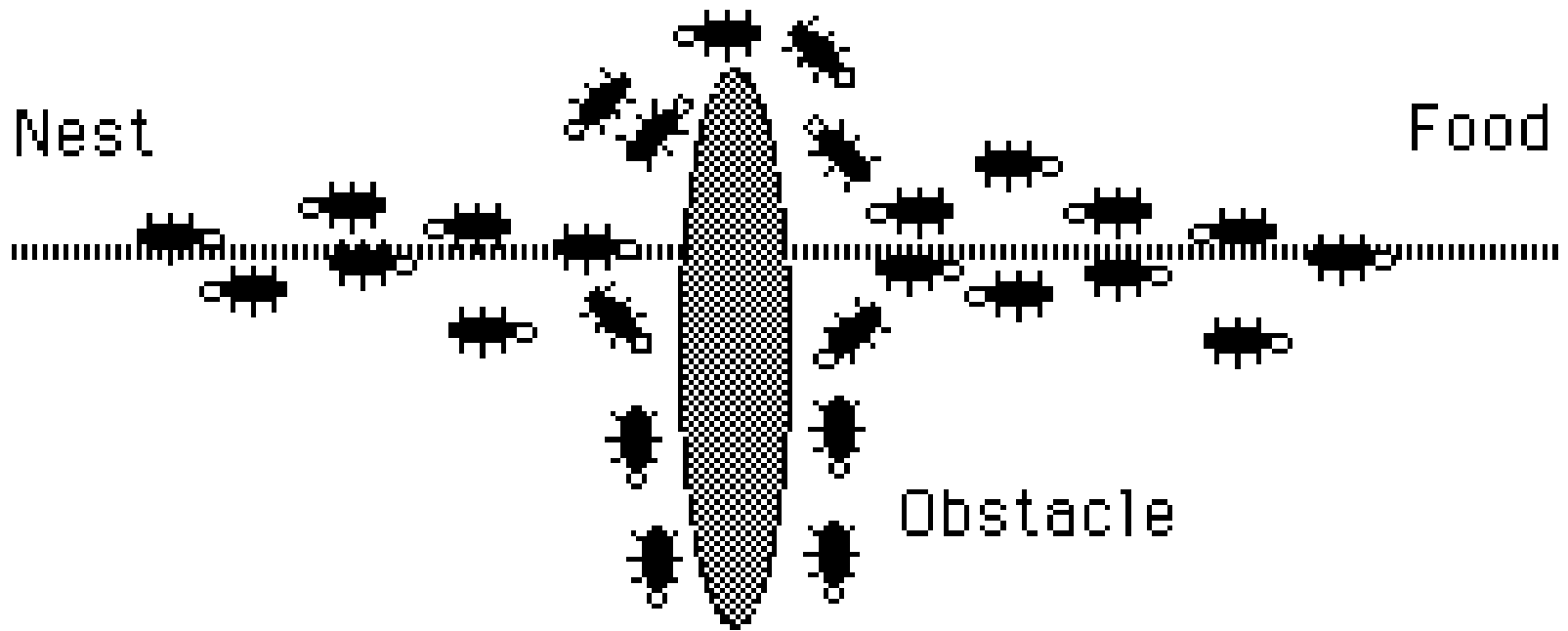
# Adaptive Path Optimization



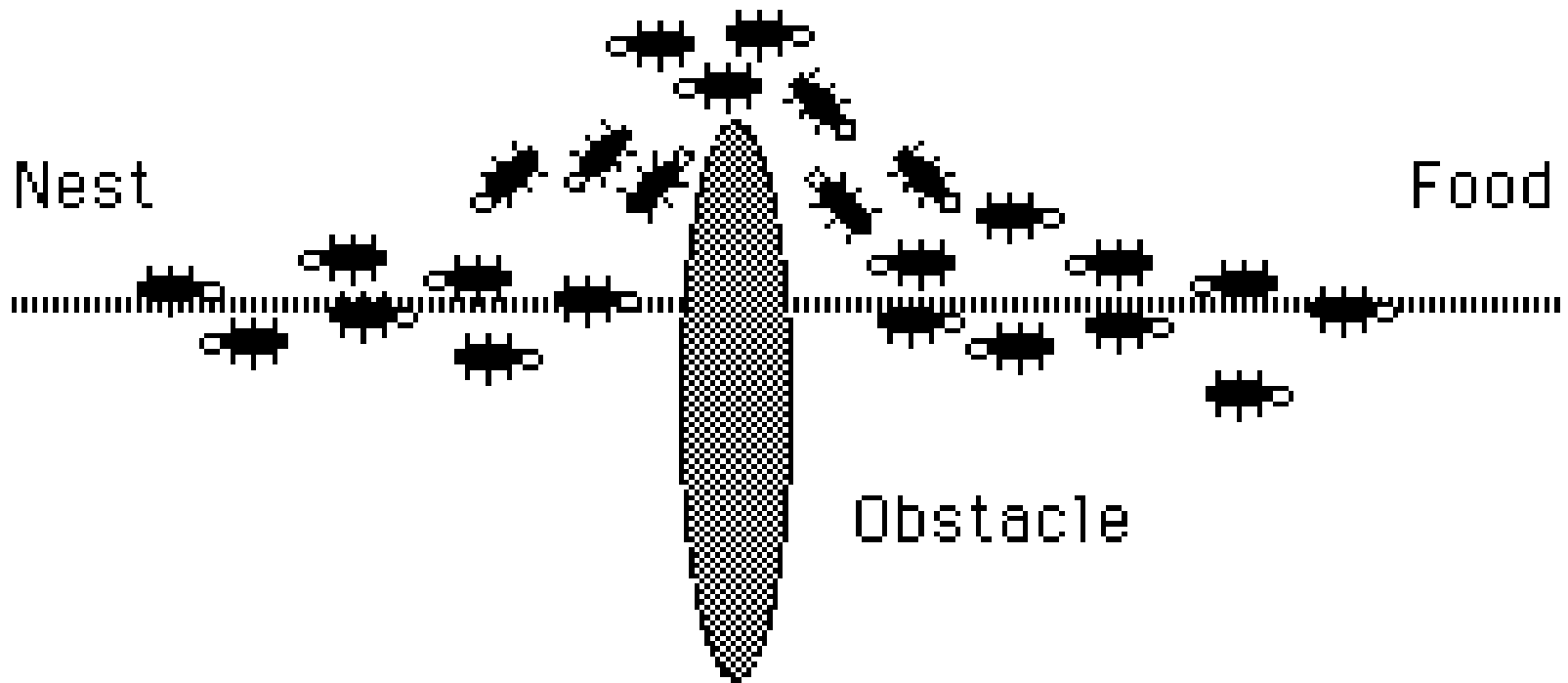
# Adaptive Path Optimization



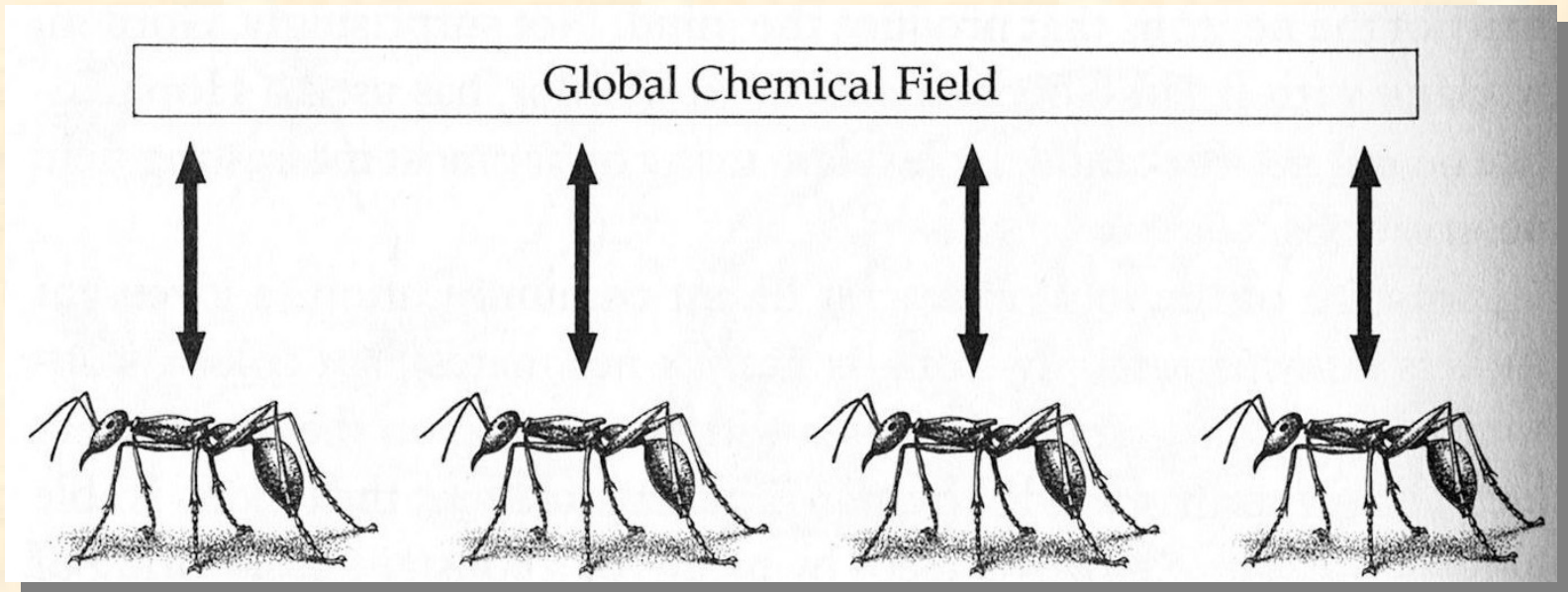
# Adaptive Path Optimization



# Adaptive Path Optimization



# Circular Causality



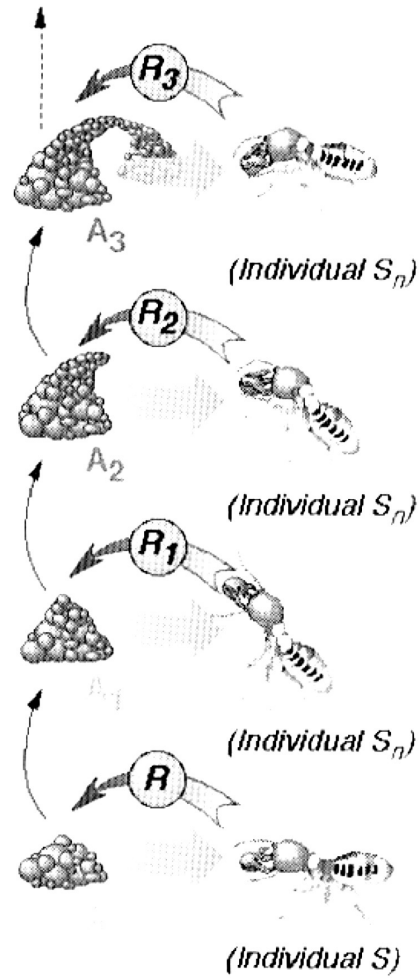
- Global pattern emergent from total system
- Individuals respond to local field

# 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

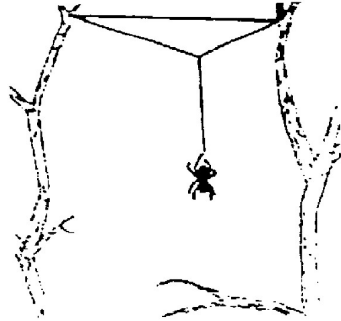


# Stigmergy in termite nest building

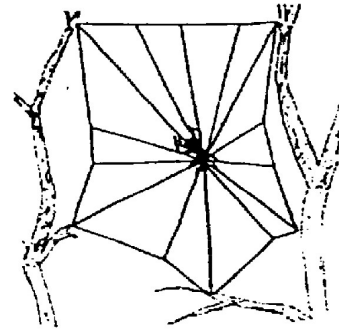


# Stigmergy in spider webs

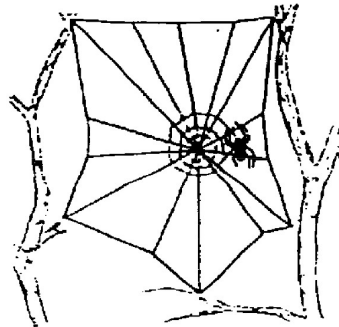
Stage 1



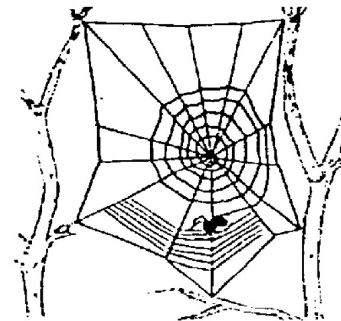
Stage 2



Stage 3



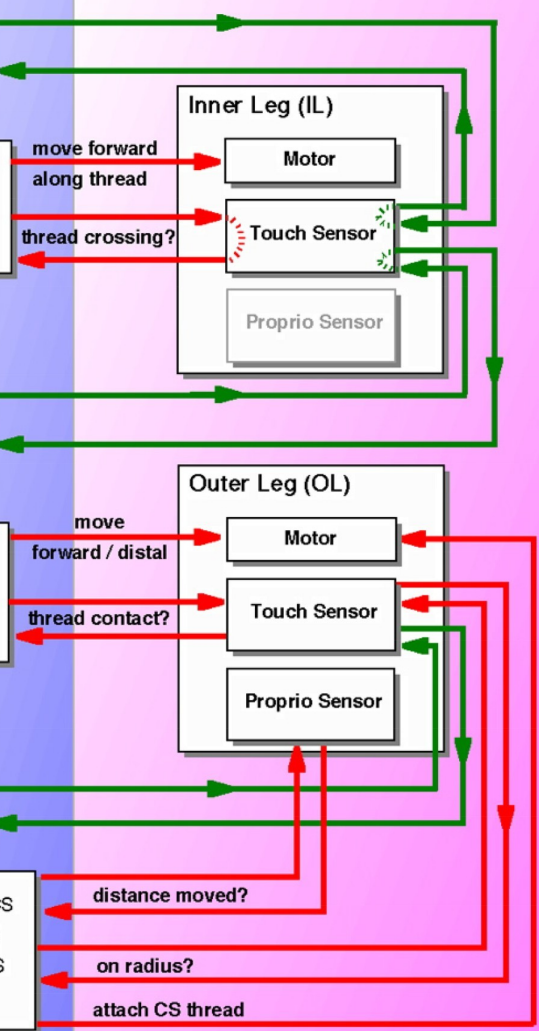
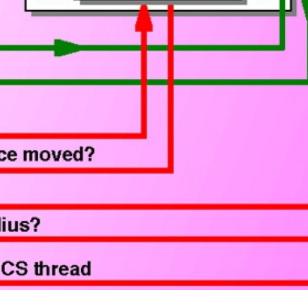
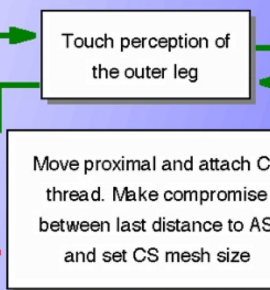
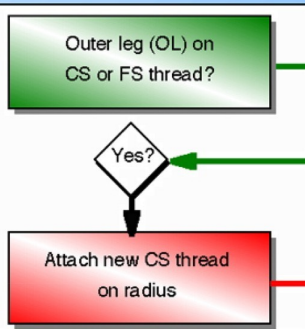
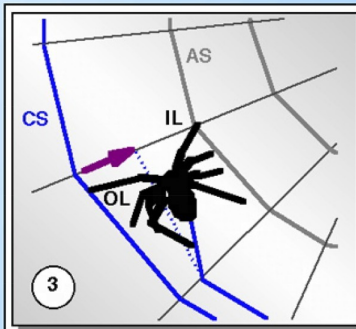
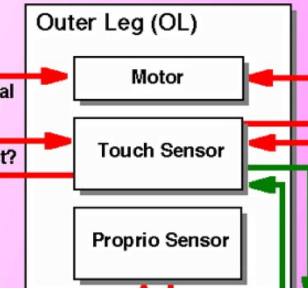
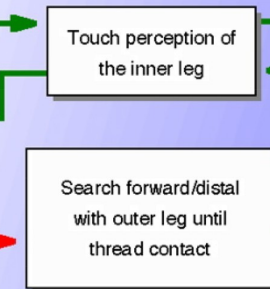
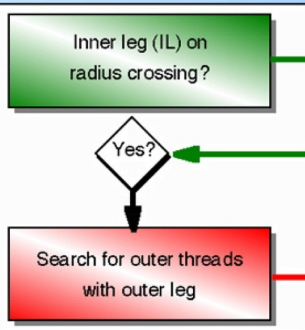
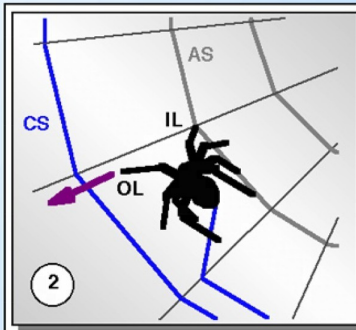
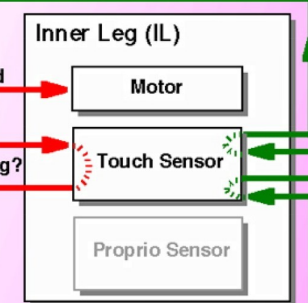
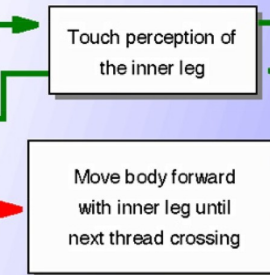
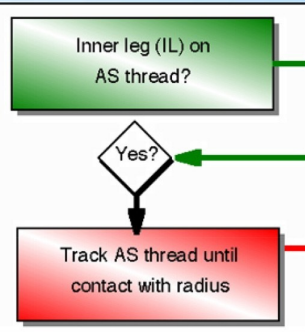
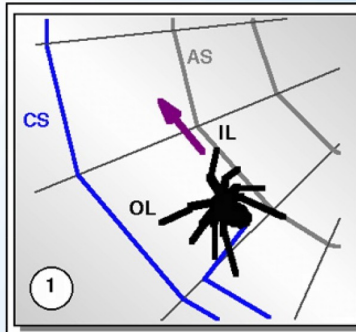
Stage 4



## Rules

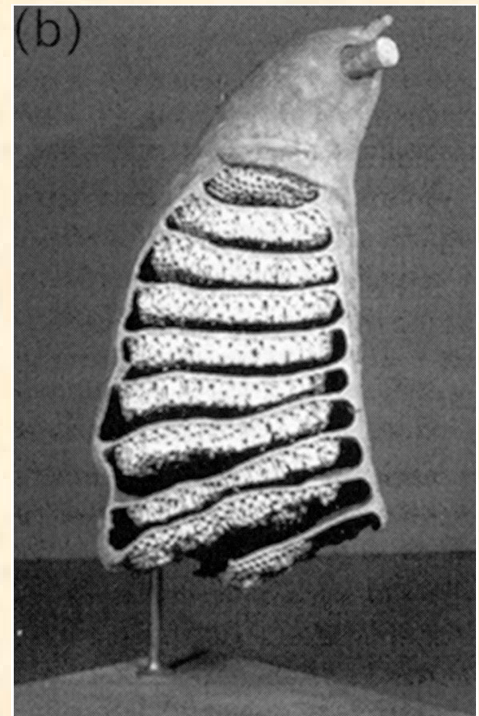
## Behaviour Patterns

## Sensors and Motors



# Advantages of Stigmergy

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



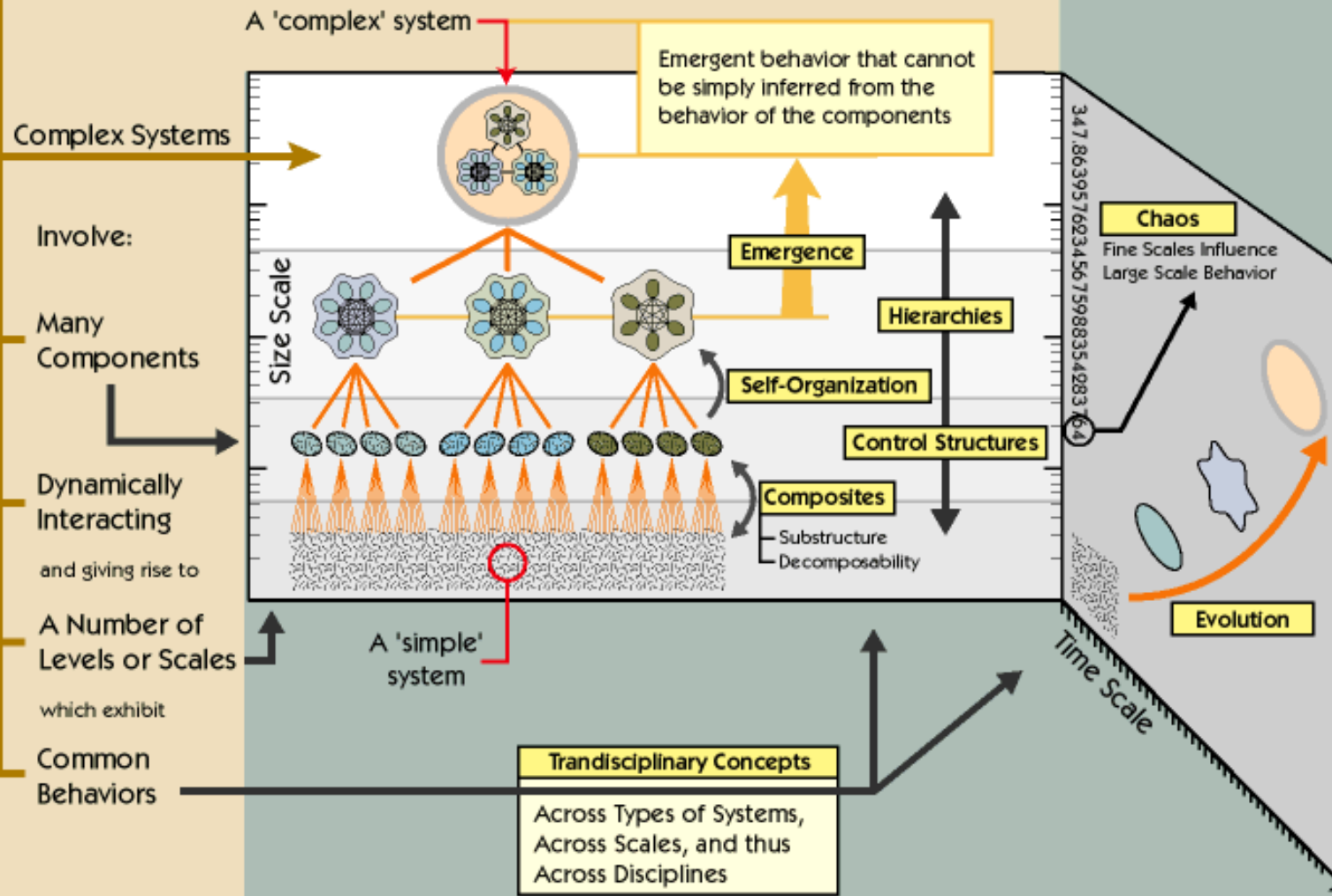
# Emergence

- 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

# Characteristics of Complex Systems



# 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”)

# Similar Principles of SO

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



# 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

# Characteristics of Self-Organized System

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

# Two Approaches to the Properties of Complex Systems

# Focal Issue: Emergence

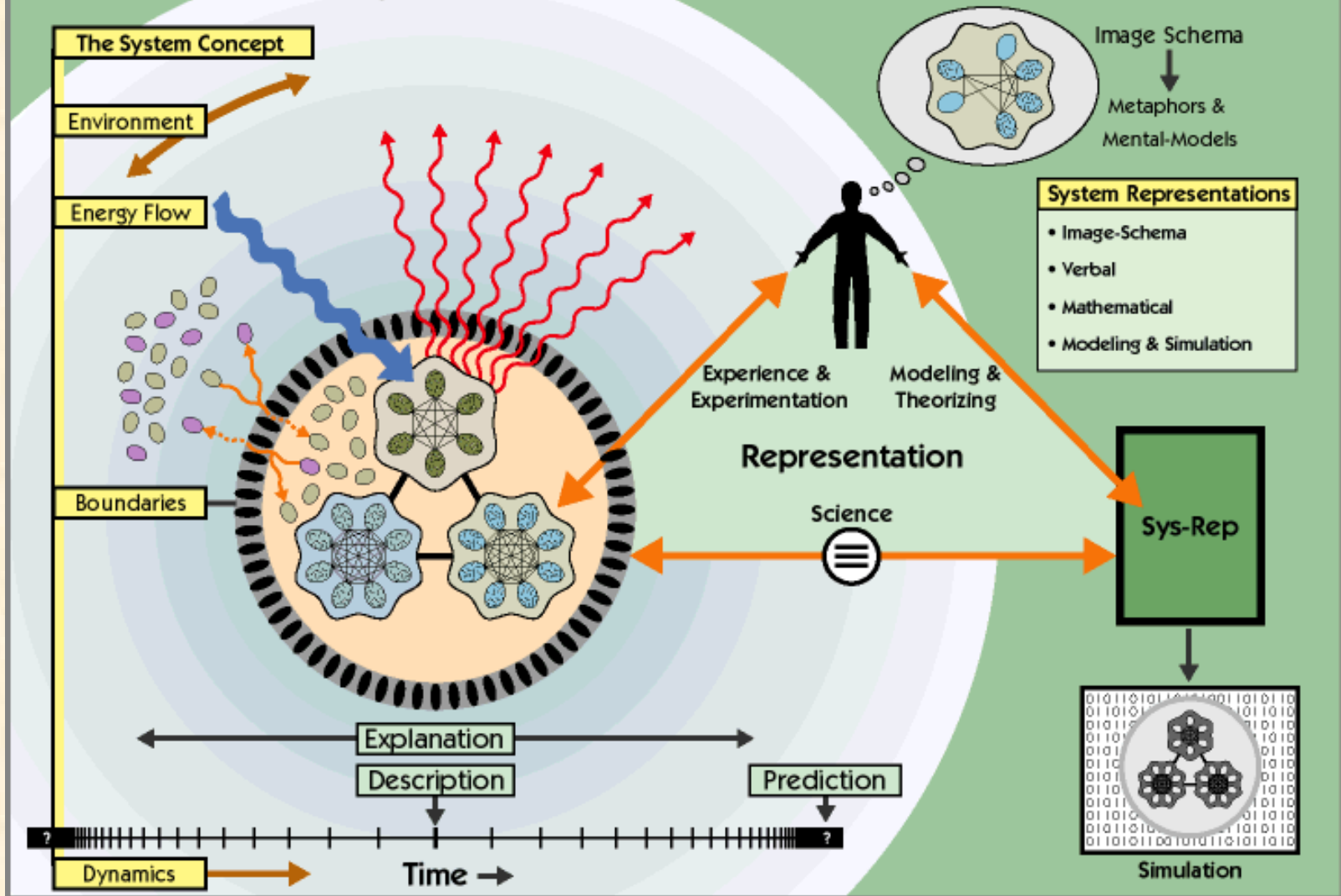
- Deals with: elements & interactions
- Based on: relation between parts & whole
- Emergent simplicity
- Emergent complexity
- Importance of scale (level)



# 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

# Systems .....and their..... Representation



# 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.

