# COSC 420/427/527

# Biologically-Inspired Computation

Bruce MacLennan

# Contact Information

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# COSC 420 vs. COSC 527

- COSC 420:  Undergraduate credit (but graduate students can count one 400-level course)
- COSC 427 (Honors) = COSC 527
- COSC 527: Graduate credit, additional work
  - Approved for the Interdisciplinary Graduate Minor in Computational Science
  - You cannot take 527 if you have already taken 420/7

# 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
- There may be some written homework
- COSC 427/527 students will do additional experiments and mathematical exercises
- Occasional pop quizzes
- No other exams

# Prerequisites

- COSC 420/427/527:  None per se, but you will be required to write some simulations (in Java, C++, python, or whatever)

- I will assume you know the things any senior or grad student in CS should know

- COSC 527: Basic calculus through differential equations, linear algebra, basic probability and statistics

# Non-CS Majors

- I welcome non-CS majors in this class to broaden the interdisciplinary discussion
- If you are a non-CS major and think your programming skills might not be adequate, we can arrange alternative projects for you

# Textbook

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

- You are expected to do readings before class
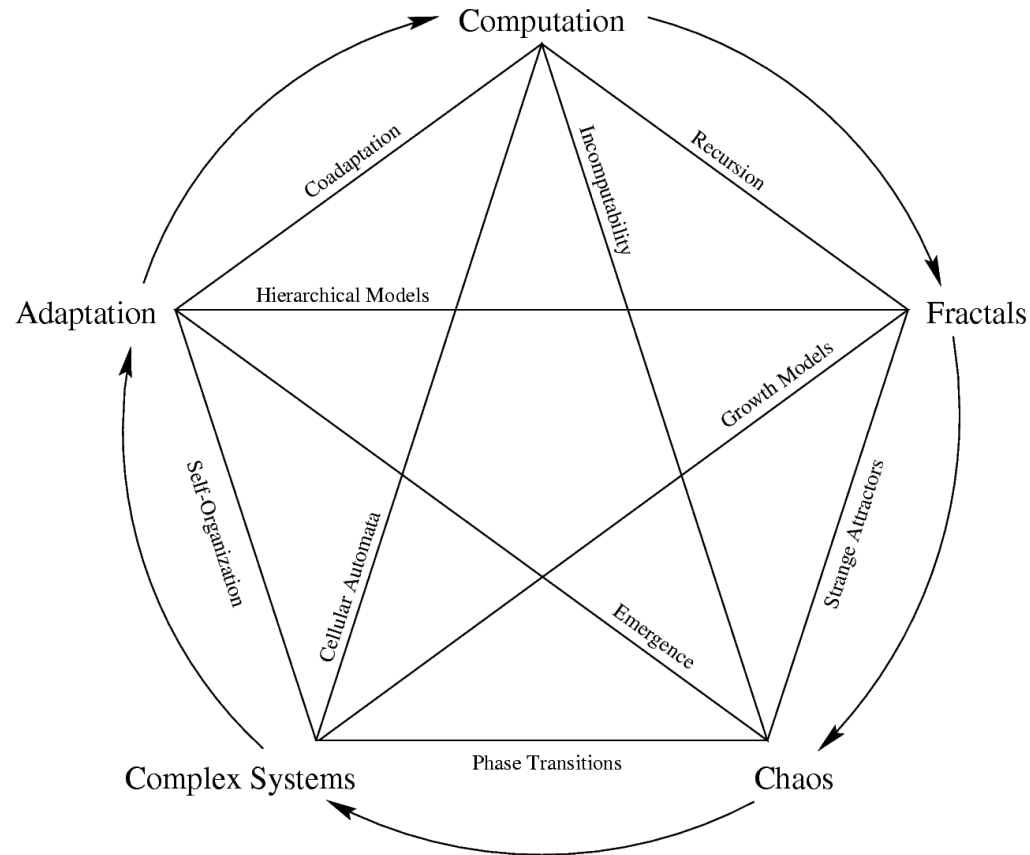- I will not necessarily cover them in class

# Contents of Flake CBN



**Figure 1.1**  An association map of the contents of this book
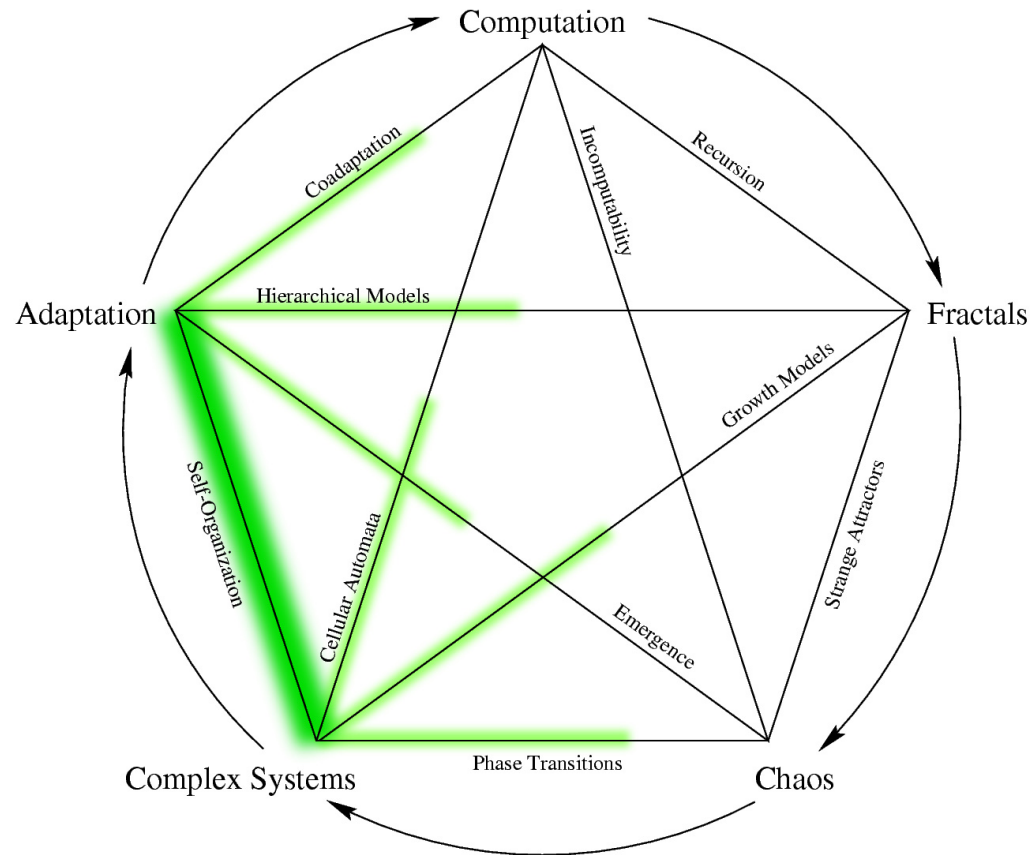
# What We Will Cover



**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

- web.eecs.utk.edu/~bmaclenn/Classes/420-527
- Syllabus
- Link to Flake *CBN* site (with errata, software, etc.)
- Links to other interesting sites
- Models (simulation programs)
- Canvas for handouts:
  - assignments
  - slides in pdf format (revised after class)
- Piazza for questions, answers, discussions,…

# B. Biologically-Inspired Computation

# 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: natural 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
- particle swarm optimization
- artificial immune systems
- genetic algorithms
- other evolutionary computation systems

# C. 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 sources:
  - Deborah Gordon: *Ants at Work* (1999)
  - B. Hölldobler & E. O. Wilson: *The Superorganism* (2009)

# Intelligent Behavior of Harvester Ants

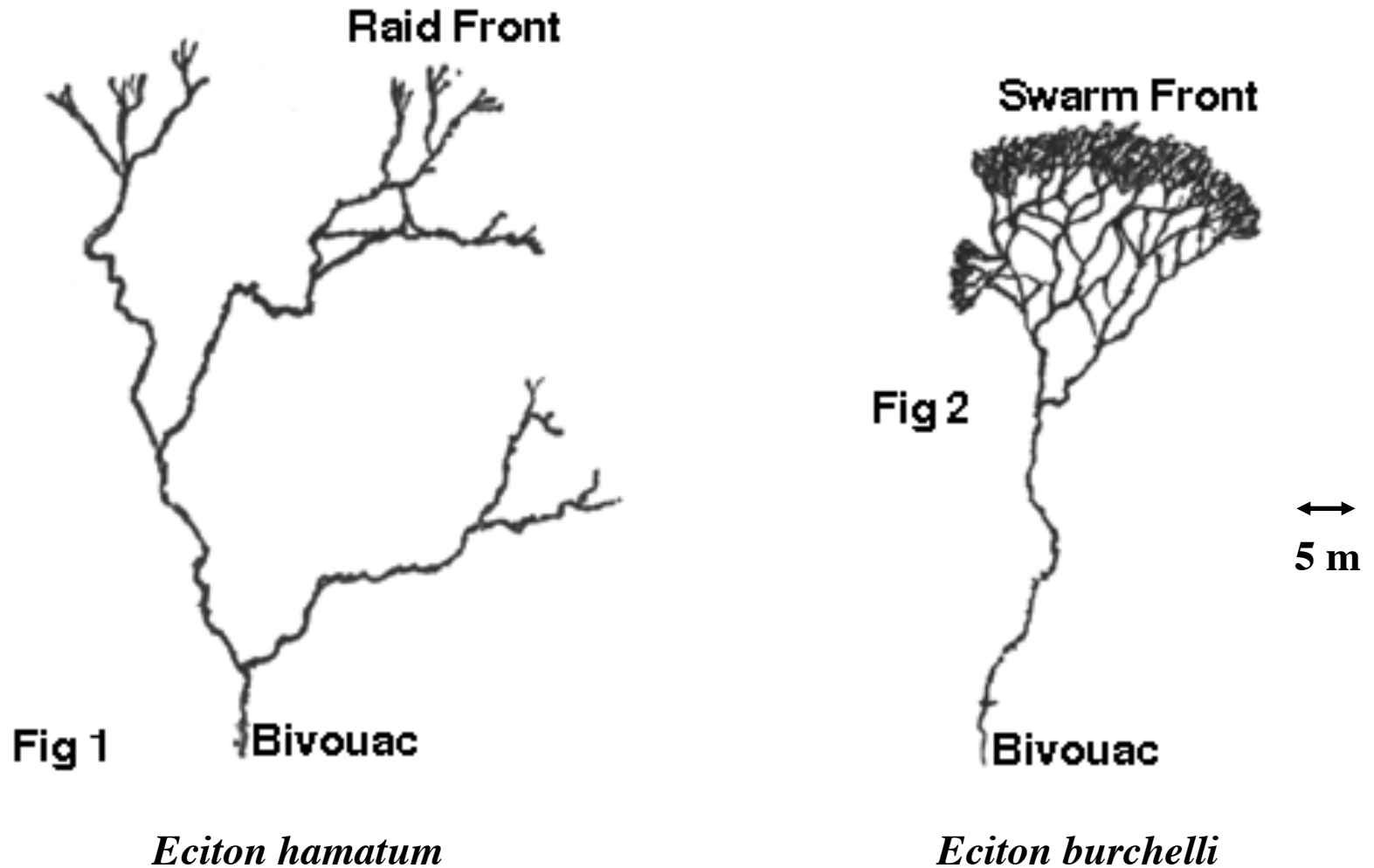- Find shortest path to food
- Prioritize food sources based on distance & ease of access
- Adjust number involved in foraging based on:
  - colony size
  - amount of food stored
  - amount of food in area
  - presence of other colonies
  - etc.

# 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

**Raid Front**

**Swarm Front**

Fig 1

Fig 2

**Bivouac**

**Bivouac**

5 m

*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
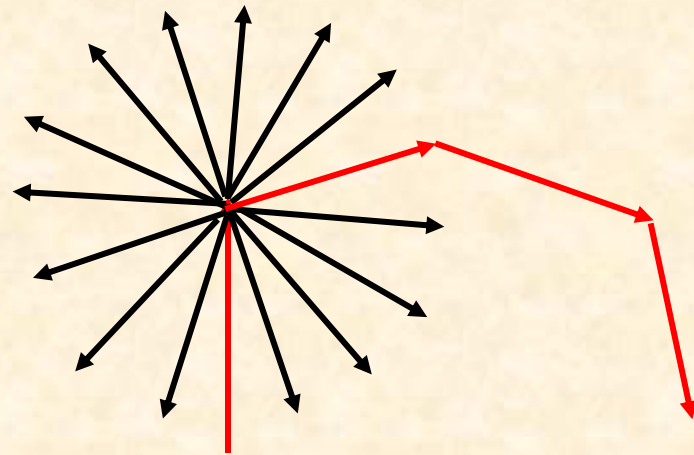
# Collective Navigation

- 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



A

B

C

D

E

F

Dump chambers

(fig. from AntColony.org)

# Leaf Cutting



© Palle Villesen
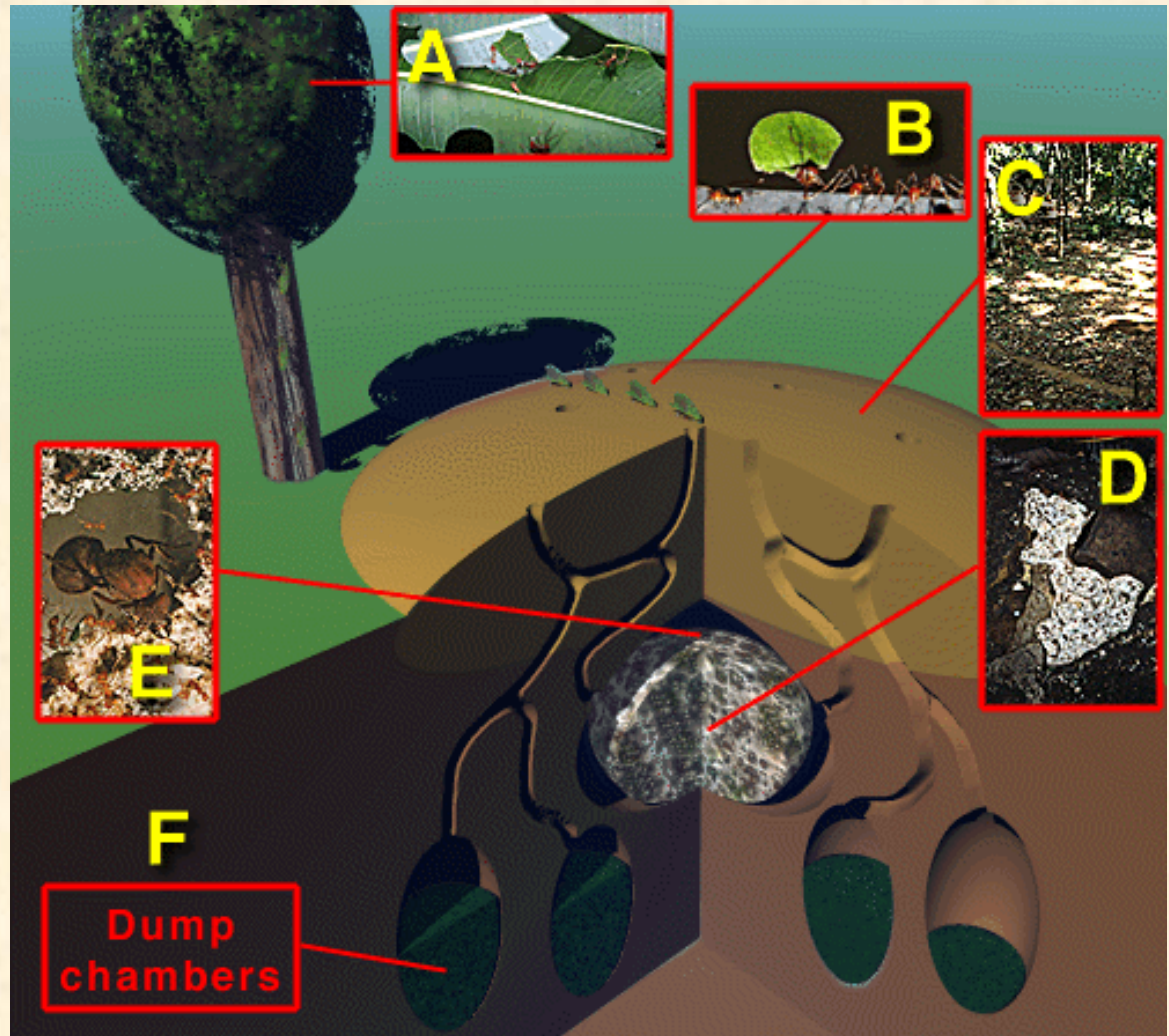
- Leaves being cut by workers

(fig. from AntColony.org)

# Transport of Cut Leaves


© David Nash

- 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

(c) 2003 A. San Juan/ Li Hongmei

# Protection by Minims


© David Nash

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

# A Large Nest


© Koos Boomsma

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

(fig. from AntColony.org)

# Nest Construction



The Lurker's Guide to Leafcutters

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



© Klaus Lechner

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

(fig. from AntColony.org)

# The Fungus Garden



© Palle Villesen

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

# Queen in Fungus Garden



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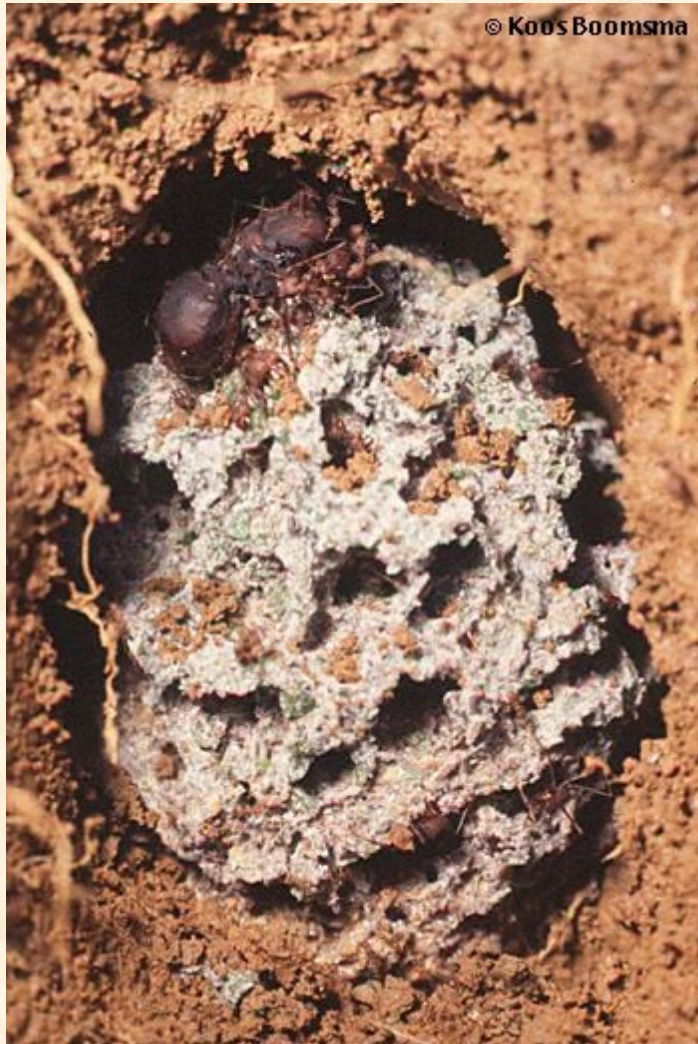
- Queen stays in fungus garden
- Lays eggs
- Hatched larvae eat fungus
- Larvae cared for by nurse workers

# Dump Chambers

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



© David Nash

(fig. from AntColony.org)

(fig < Hölldobler & Wilson, *Superorganism*)

(fig < Hölldobler & Wilson, *Superorganism*)
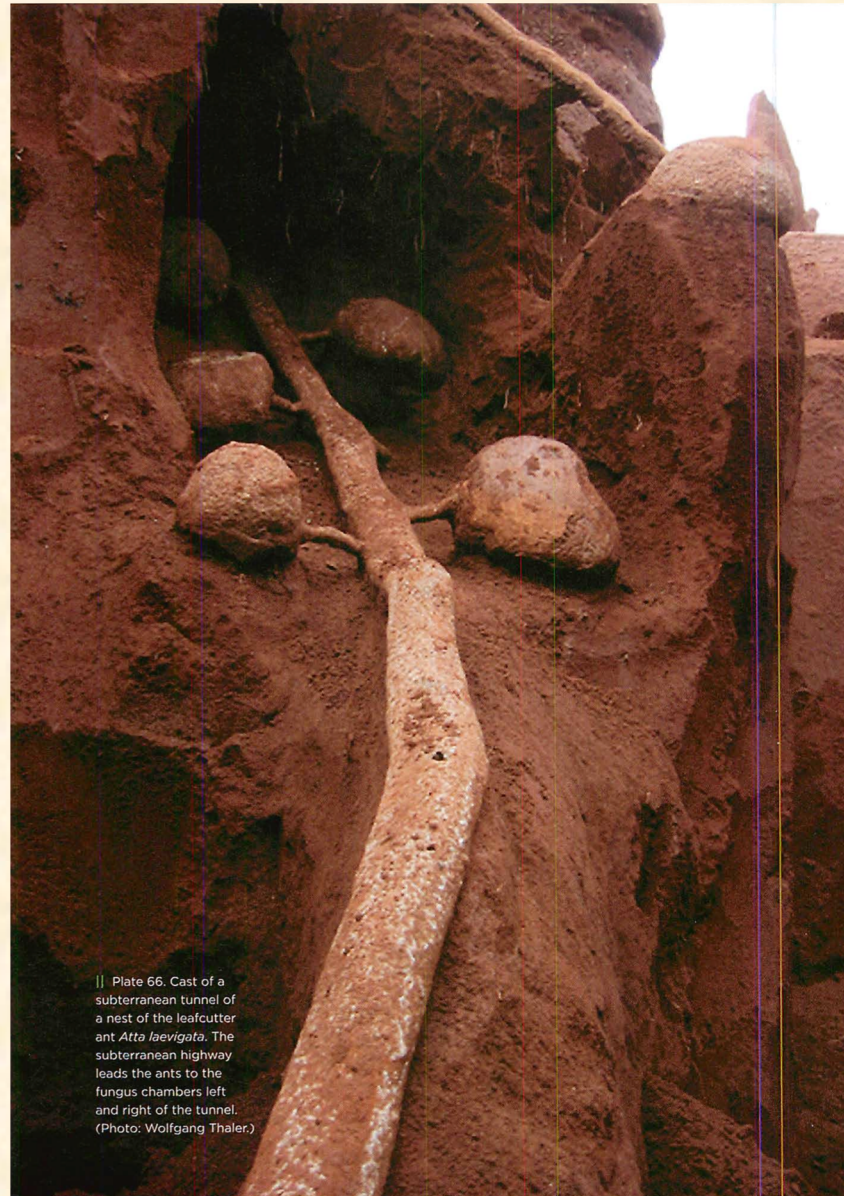
(fig < Hölldobler & Wilson, *Superorganism*)

|| Plate 66. Cast of a subterranean tunnel of a nest of the leafcutter ant *Atta laevigata*. The subterranean highway leads the ants to the fungus chambers left and right of the tunnel. (Photo: Wolfgang Thaler.)

(fig < Hölldobler & Wilson, *Superorganism*)

Trail III

W
S — N
E

Trail II

● Cutting location
■ Nest entrance
— Foraging trail
◠ Foraging area (based on crown projections)

Trail IV

Trail I

0                    50 m

(fig < Hölldobler & Wilson, *Superorganism*)
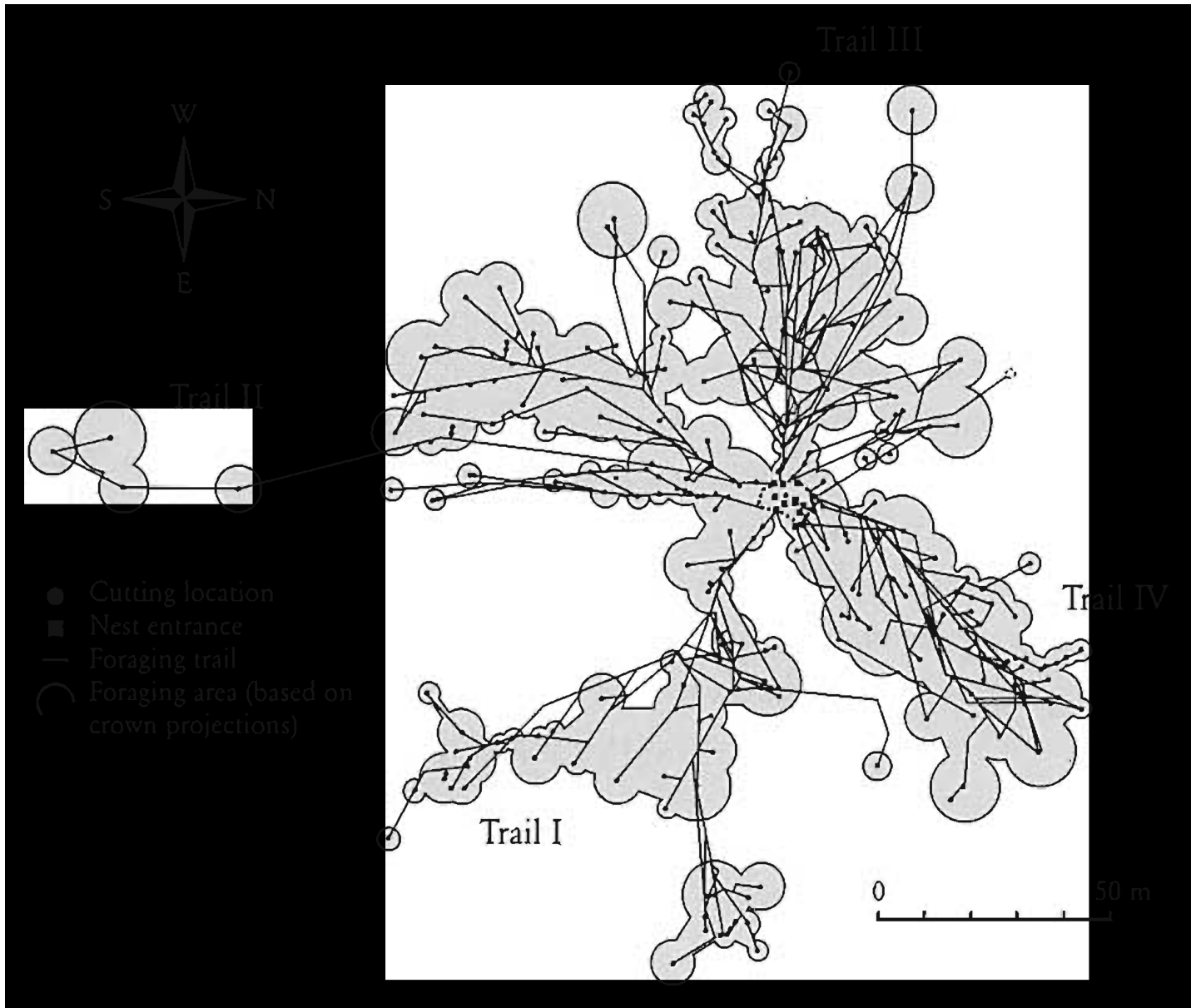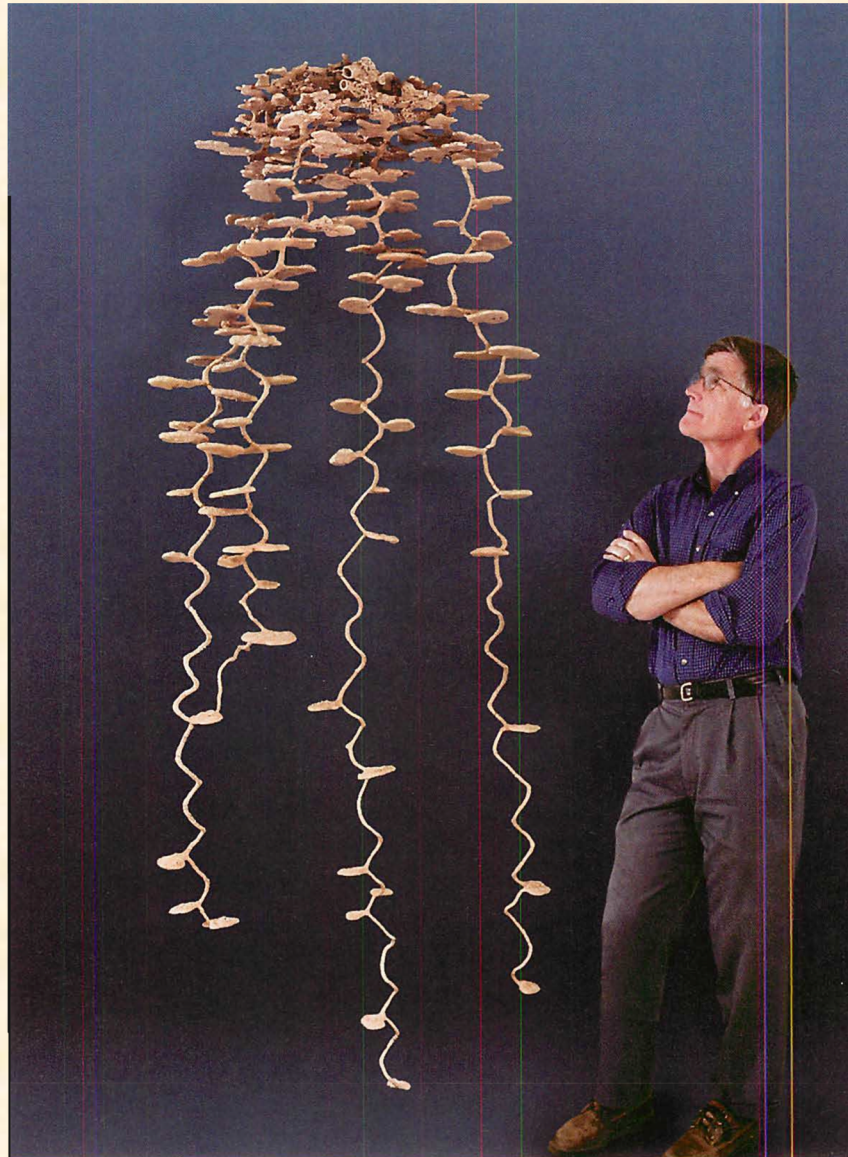
(fig < Hölldobler & Wilson, *Superorganism*)

# Maeterlinck on
# "White Ants" (Termites)

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

# Emergent Aspects

- Colony size ~ $8 \times 10^6$

  *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
  
  $\Rightarrow$ exploration
- Feedback reinforces successful trails
  
  $\Rightarrow$ biased randomness

# Demonstration:
# Simulation of Ant Foraging

Run NetLogo Ant-Foraging

# Macro-Micro Feedback



Global Chemical Field
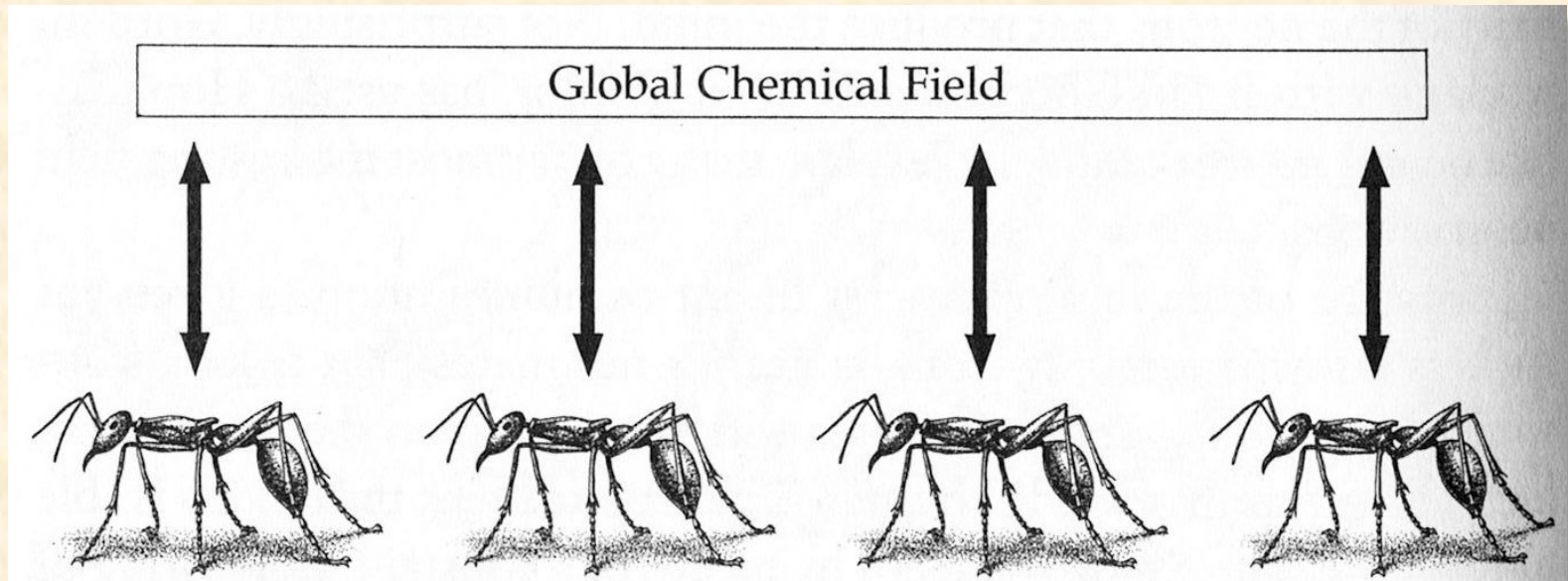
- Global pattern emergent from total system
- Individuals respond to local field
- Also called <u>circular causality</u>

fig. from Solé & Goodwin

# Stigmergy

- From στίγμα = mark, sign + ἔργον = work, action
- The mark left by an action is a sign for the next action
- Agent interactions may be:
  - direct
  - indirect (time-delayed through environment)
- Mediates individual and colony levels

# Stigmergy in termite nest building



Fig, from EVALife
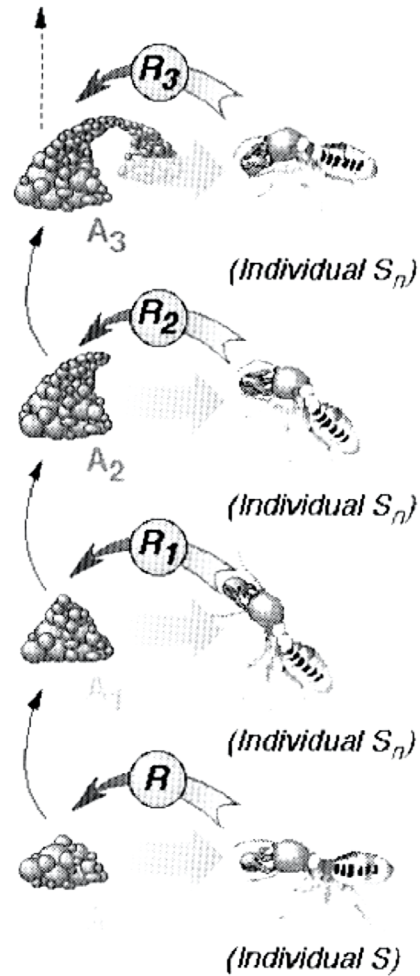
# Stigmergy in spider webs

Stage 1          Stage 2

Stage 3          Stage 4

Fig, from EVALife

**Rules**

**Behaviour Patterns**

**Sensors and Motors**

1.
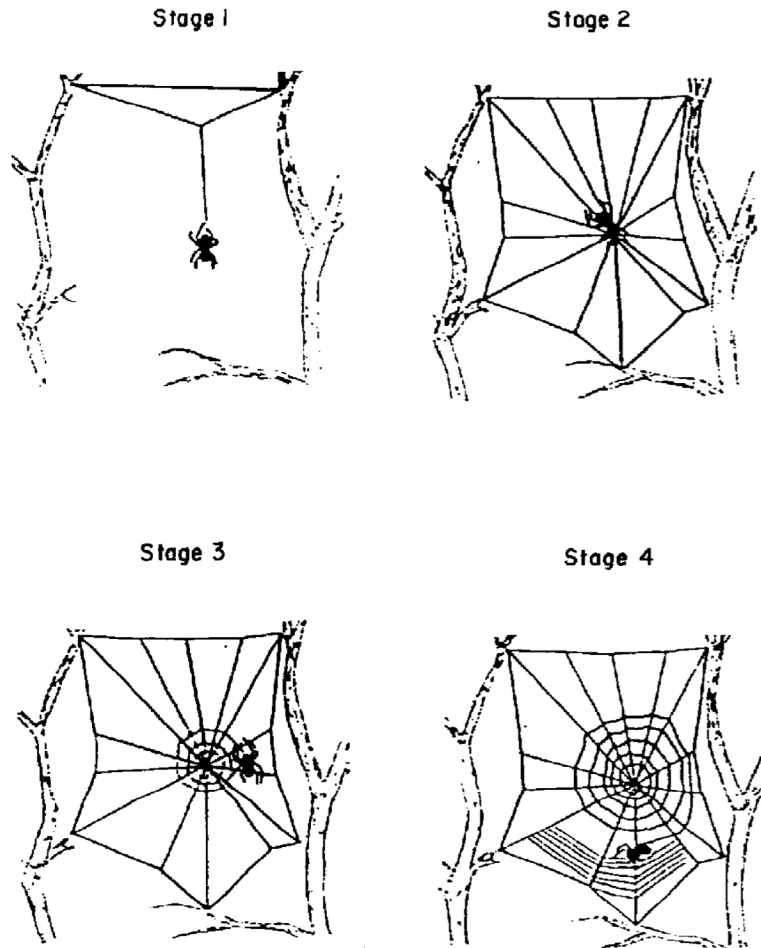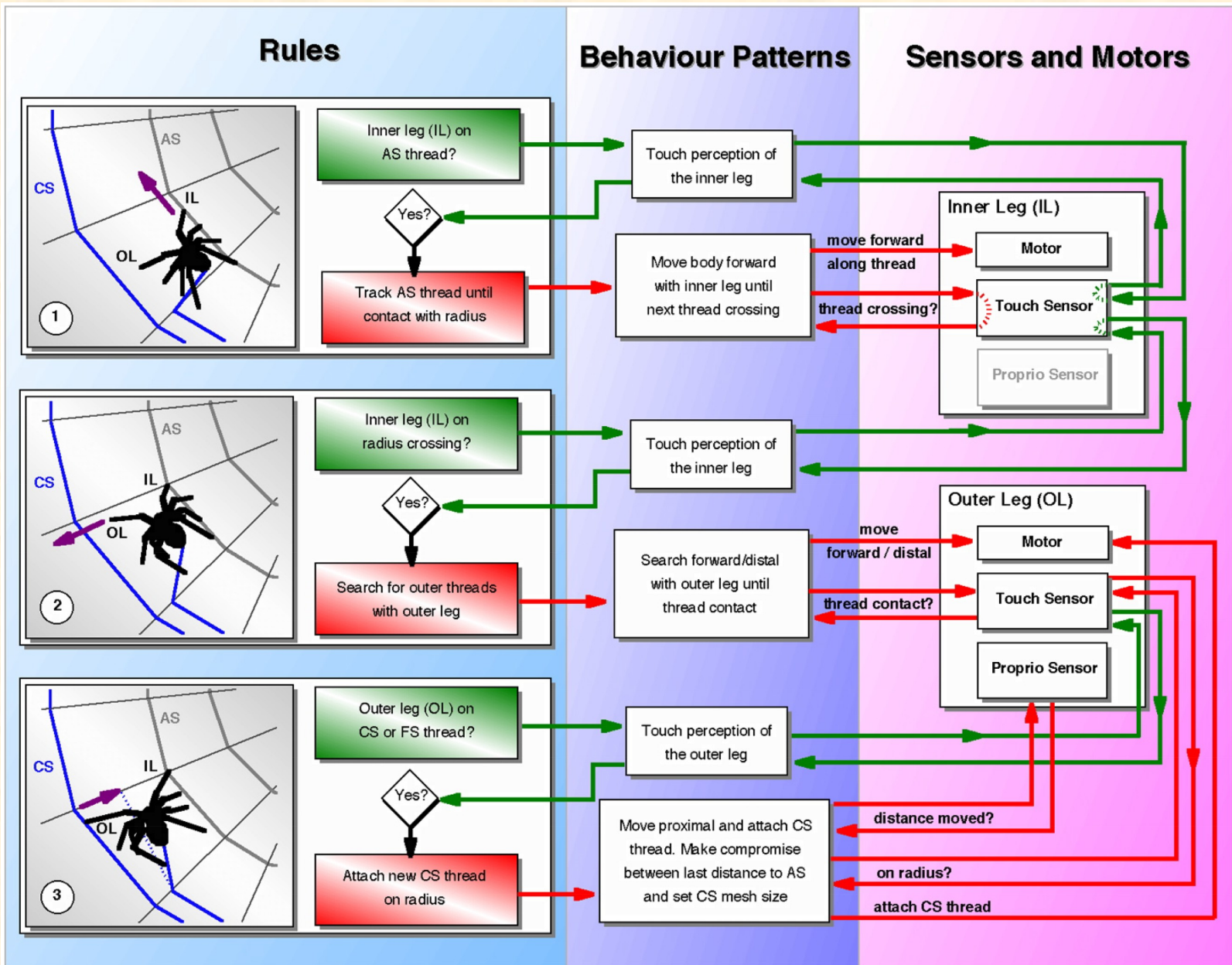- Inner leg (IL) on AS thread?
- Yes?
- Track AS thread until contact with radius

- Touch perception of the inner leg
- Move body forward with inner leg until next thread crossing

2.
- Inner leg (IL) on radius crossing?
- Yes?
- Search for outer threads with outer leg

- Touch perception of the inner leg
- Search forward/distal with outer leg until thread contact

3.
- Outer leg (OL) on CS or FS thread?
- Yes?
- Attach new CS thread on radius

- Touch perception of the outer leg
- Move proximal and attach CS thread. Make compromise between last distance to AS and set CS mesh size

**Inner Leg (IL)**
- Motor
- Touch Sensor
- Proprio Sensor

move forward along thread
thread crossing?

**Outer Leg (OL)**
- Motor
- Touch Sensor
- Proprio Sensor

move forward / distal
thread contact?

distance moved?
on radius?
attach CS thread
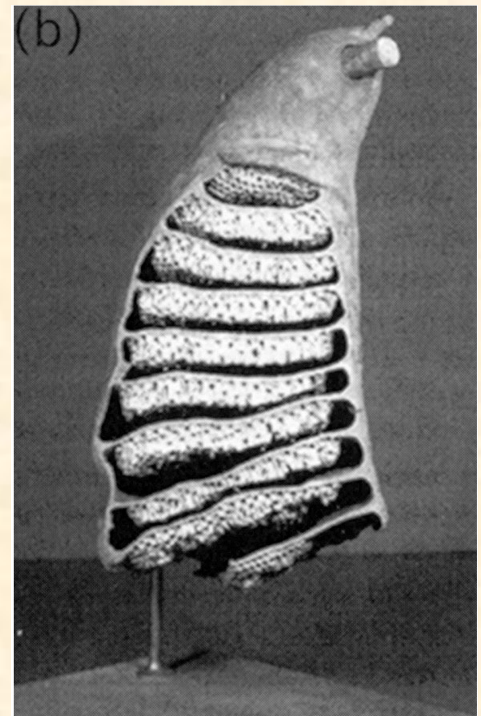
# Advantages of Stigmergy

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



(b)

# 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*

# D. 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

# Why Self-Organization
# is 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

Part II

# 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.  Hölldobler, B., & Wilson, E. O. *The Superorganism* (2009)

5.  Johnson, Steven. *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*. Scribner, 2001. A popular book, but with many good insights.