

COSC 420/427/527

Biologically-Inspired  
Computation

Bruce MacLennan

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Contact Information

- Instructor: Bruce MacLennan  
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Min Kao 550  
Office Hours: 1:30–2:30 MWF (or make appt.)
- Teaching Assistant:  
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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

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### 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
- Graduate students will do additional experiments and mathematical exercises
- Occasional pop quizzes
- No other exams

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### Prerequisites

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

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### 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

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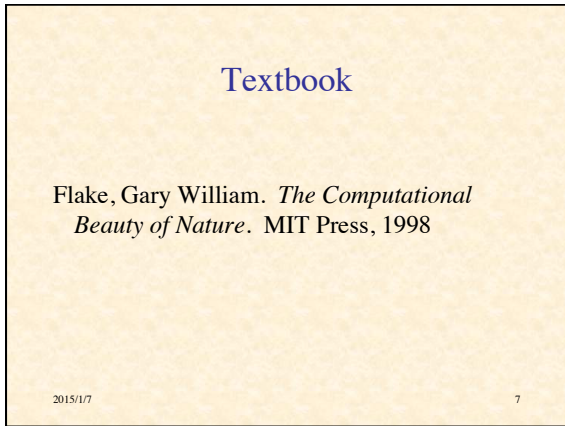
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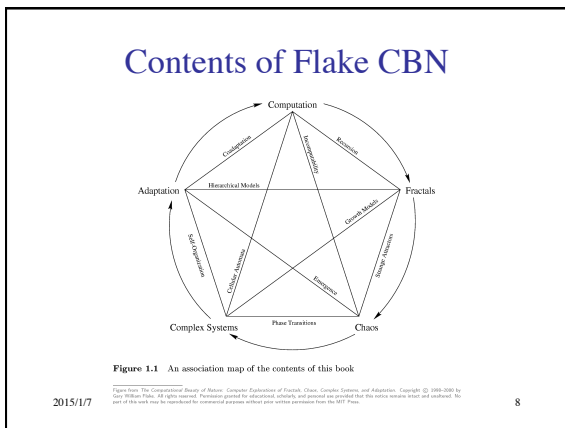
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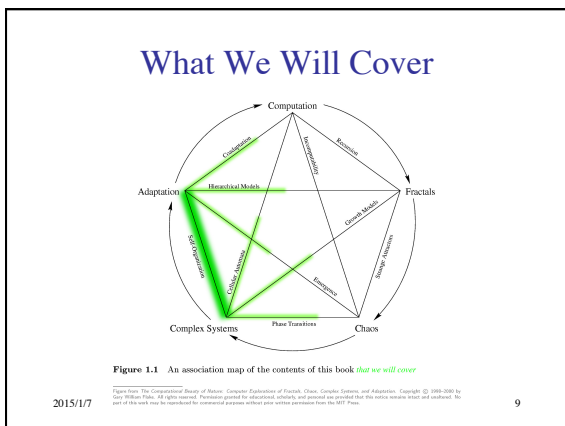
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**Reading for Next Week**

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

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**Course Web Site**

- [web.eecs.utk.edu/~mclennan/Classes/420](http://web.eecs.utk.edu/~mclennan/Classes/420) or [527](http://web.eecs.utk.edu/~mclennan/Classes/527)
- 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)
- Piazza for questions, answers, discussions,...

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**B. Biologically-Inspired  
Computation**

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### 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

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### 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.

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### 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

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## 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

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## Why Do Bio-Inspired Computation?

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

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## 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

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**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

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**C. Ants**

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

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**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)

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### 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.

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### Army Ants



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

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### Army Ant Raiding Patterns

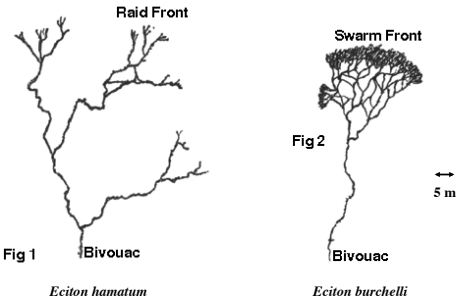


Fig 1 *Eciton hamatum*      Fig 2 *Eciton burchelli*

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from Solé & Goodwin, Signs of Life

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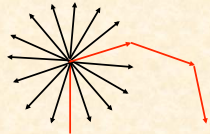
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### Coordination in Army Ant Colonies

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



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### 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

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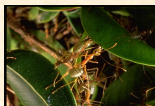
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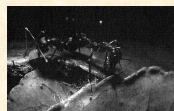
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### Weaver Ants



- 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



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### Workers Bridging Gap



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### Adults Using Larvae as “Glue Guns”



2015/1/7 (fig. from *Self-Org. Biol.Sys.*) 29

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### Fungus Cultivator Ants

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



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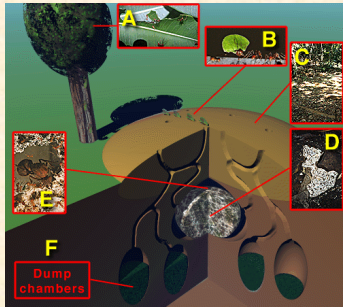
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### Fungus Cultivator Nest



The diagram illustrates the internal structure of a fungus cultivator nest. It shows a cross-section of the nest with various chambers and tunnels. Labels A through F point to specific features: A is a tree trunk, B is a chamber containing a fungus, C is a chamber with a fungus, D is a chamber with a fungus, E is a chamber with a fungus, and F is a chamber labeled 'Dump chambers'.

2015/1/7 (fig. from AntColony.org) 31

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### Leaf Cutting



A close-up photograph shows several ants working on a large green leaf. They are using their mandibles to cut and tear pieces of the leaf. The ants are positioned along the edge of the leaf, and some are actively cutting.

- Leaves being cut by workers

2015/1/7 (fig. from AntColony.org) 32

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### Transport of Cut Leaves



A photograph shows a line of ants on a dark surface. One ant is carrying a large, flat, green leaf fragment on its back. The ants are moving in a line, suggesting a trail.

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

2015/1/7 (fig. from AntColony.org) 33

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### 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

2015/1/7 (vid. from [www.blueboard.com/leafcutters](http://www.blueboard.com/leafcutters)) 34

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### Protection by Minims



© David Nash

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

2015/1/7 (fig. from [AntColony.org](http://AntColony.org)) 35

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### A Large Nest



© Klaus Bonitz

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

2015/1/7 (fig. from [AntColony.org](http://AntColony.org)) 36

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## 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

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

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## Leaf Brought to Fungus Garden



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

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(fig. from [AntColony.org](http://AntColony.org))

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## The Fungus Garden



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

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(fig. from [AntColony.org](http://AntColony.org))

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### Queen in Fungus Garden



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

2015/1/7 (fig. from AntColony.org) 40

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### Dump Chambers

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



2015/1/7 (fig. from AntColony.org) 41

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2015/1/7 (fig < Hölldobler & Wilson, *Superorganism*) 42

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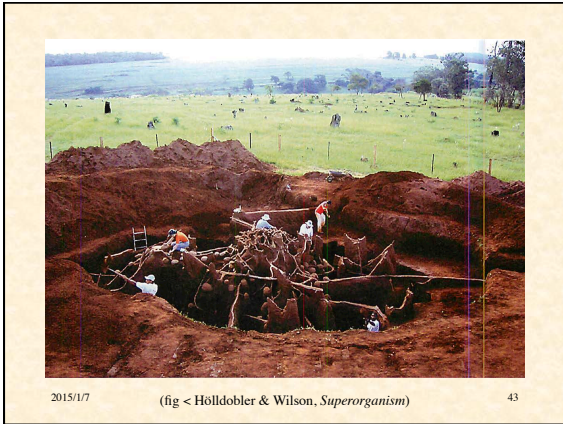
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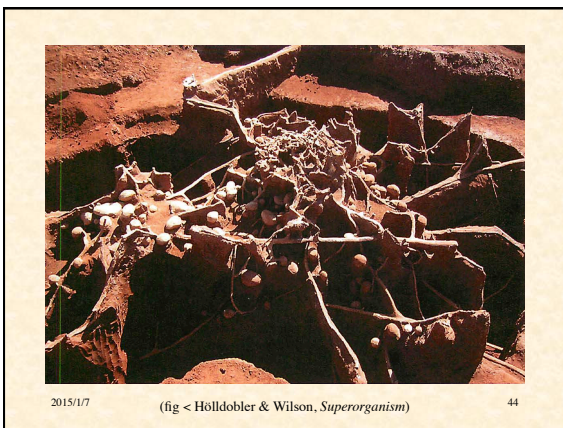
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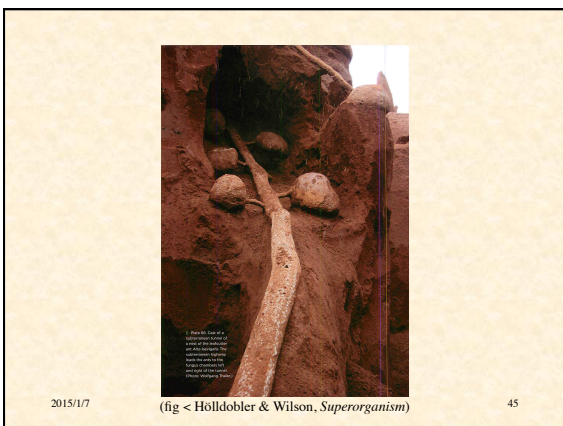
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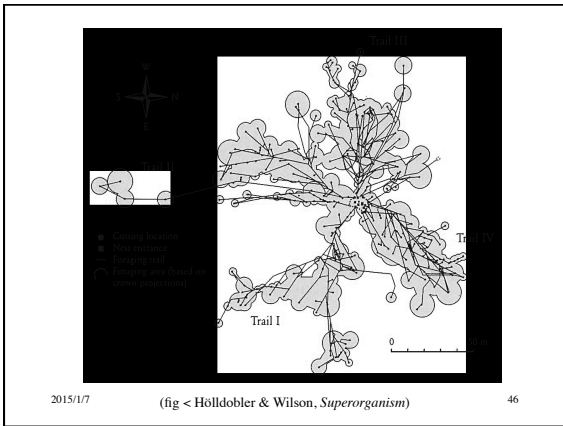
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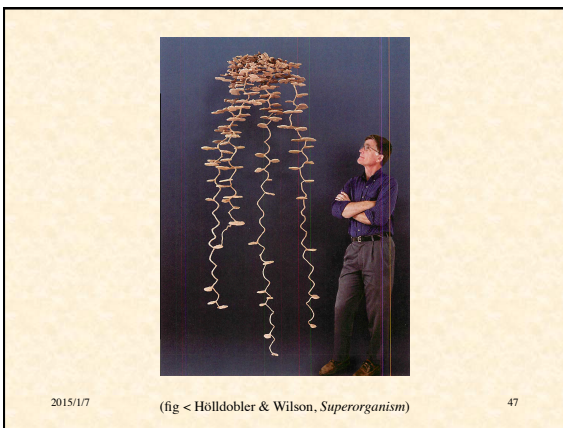
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**Maeterlinck on  
“White Ants” (Termites)**

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

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### 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!

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### How Do They Do It?

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



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(video from *Stanford Report*, April 2003) 50

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### 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

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**Demonstration:  
Simulation of Ant Foraging**

[Run NetLogo Ant-Foraging](#)

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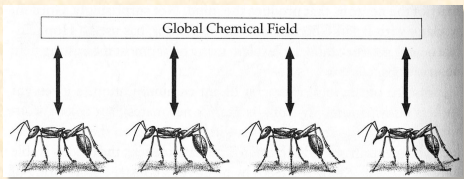
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**Macro-Micro Feedback**



- Global pattern emergent from total system
- Individuals respond to local field
- Also called circular causality

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fig. from Solé & Goodwin

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**Stigmergy**

- From στίγμας = 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

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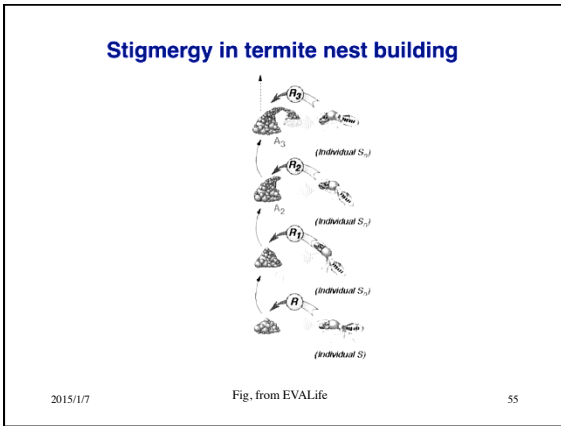
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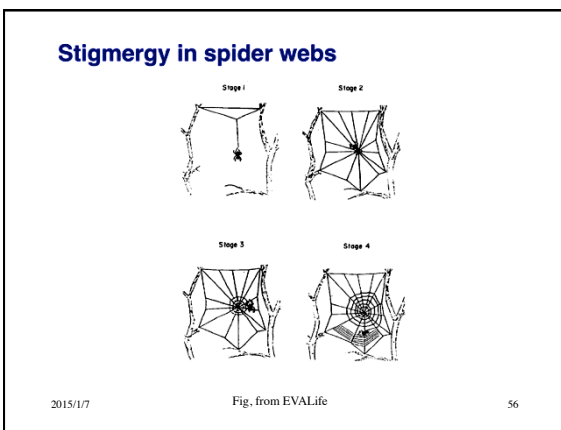
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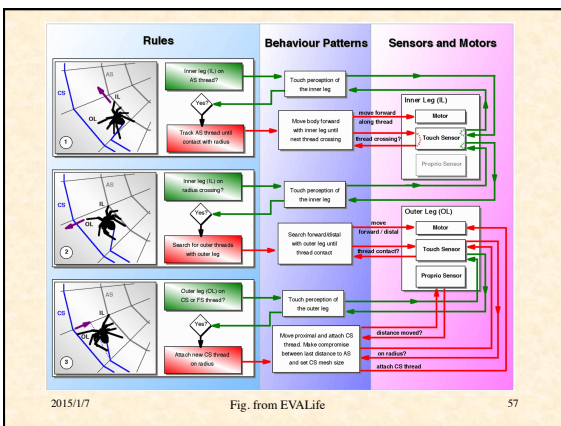
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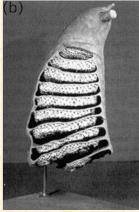
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### Advantages of Stigmergy

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



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### 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*

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### 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

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## 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

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Part II

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## 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.

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Part II

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