

COSC 420/427/527

Biologically-Inspired
Computation

Bruce MacLennan

Contact Information

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1/13/16 2

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 4207

1/13/16 3

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

1/13/16

4

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

1/13/16

5

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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6

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 it in class

Contents of Flake CBN

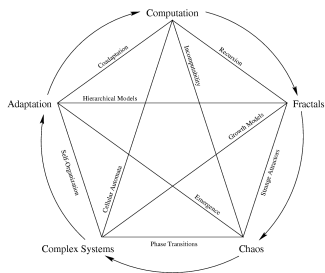


Figure 1.1 An association map of the contents of this book

Figure 1.1 The Computational Beauty of Nature: Computer Experiments of Fractal, Chaos, Complex Systems, and Adaptation. Copyright © 1998-2008 by Gary William Flake. All rights reserved. Permission is granted for educational, scholarly, and personal use provided that the source remains intact and unaltered. This part of this work may be reproduced for commercial purposes without prior written permission from the MIT Press.

What We Will Cover

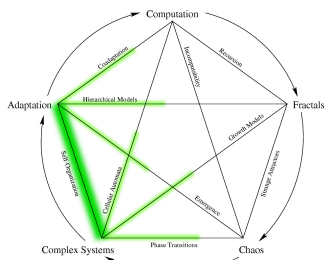


Figure 1.1 An association map of the contents of this book that we will cover

Figure 1.1 The Computational Beauty of Nature: Computer Experiments of Fractal, Chaos, Complex Systems, and Adaptation. Copyright © 1998-2008 by Gary William Flake. All rights reserved. Permission is granted for educational, scholarly, and personal use provided that the source remains intact and unaltered. This 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)

1/13/16 10

Course Web Site

- web.eecs.utk.edu/~mclennan/Classes/420 or [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,...

1/13/16 11

**B. Biologically-Inspired
Computation**

1/13/16 12

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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13

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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14

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

1/13/16

15

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

1/13/16

16

Why Do Bio-Inspired Computation?

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

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17

Some of the Natural Systems We Will Study

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

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18

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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19

C. Ants

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

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20

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)

1/13/16

21

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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22

Army Ants

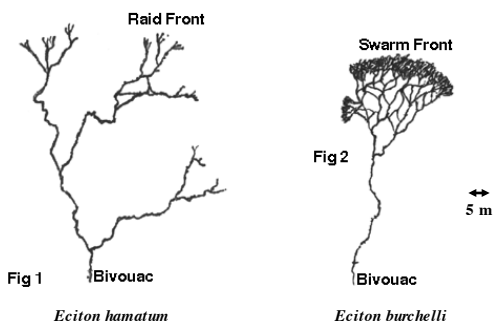


- No permanent nest
- Create temporary “bivouacs” from bodies of workers
- Raiding parties of up to 200 000
- Act like unified entity

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23

Army Ant Raiding Patterns



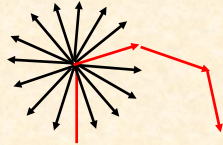
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from Solé & Goodwin, *Signs of Life*

24

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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25

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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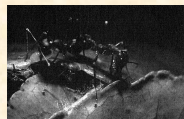
26



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



1/13/16

27

Workers Bridging Gap



1/13/16

28

Adults Using Larvae as “Glue Guns”



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

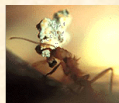
29

Fungus Cultivator Ants

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



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30

Fungus Cultivator Nest

The diagram shows a cross-section of an ant nest. Part A is a tree trunk. Part B is a large chamber containing a fungus. Part C is a trail leading to the chamber. Part D is a chamber containing a fungus. Part E is a chamber containing a fungus. Part F is a chamber containing a fungus. A label 'Dump chambers' points to several chambers at the bottom of the nest.

1/13/16 (fig. from AntColony.org) 31

Leaf Cutting

A close-up photograph of several ants on a green leaf, cutting it into small pieces. The ants are positioned around the edges of the leaf, which has several irregular holes cut out of it.

• Leaves being cut by workers

1/13/16 (fig. from AntColony.org) 32

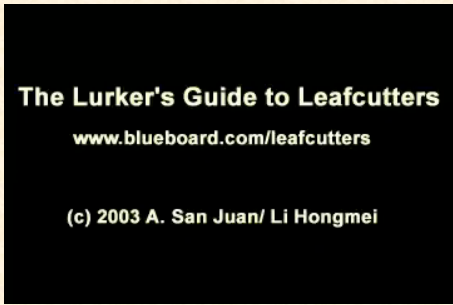
Transport of Cut Leaves

A photograph showing several ants on a surface. One ant is carrying a large, circular piece of a green leaf fragment on its back. Other ants are visible nearby.

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

1/13/16 (fig. from AntColony.org) 33

Transporting Cut Leaves to Nest



1/13/16

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

34

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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(fig. from AntColony.org)

35

A Large Nest



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

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(fig. from AntColony.org)

36

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

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

37

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)

38

The Fungus Garden



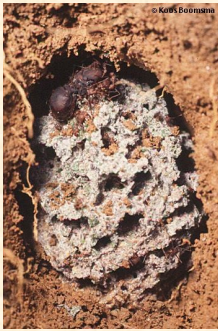
- Fungus grows special nutritional structures
- Ant larvae and adults can eat these

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(fig. from AntColony.org)

39

Queen in Fungus Garden



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

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(fig. from AntColony.org)

40

Dump Chambers

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



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(fig. from AntColony.org)

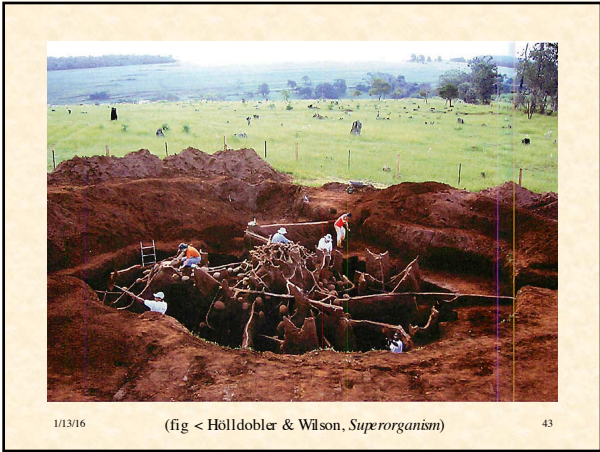
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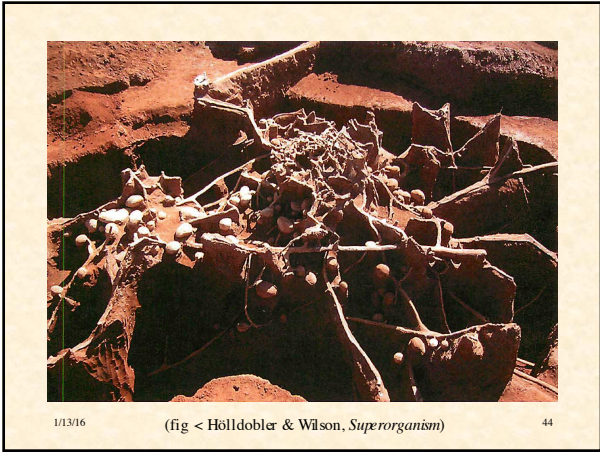


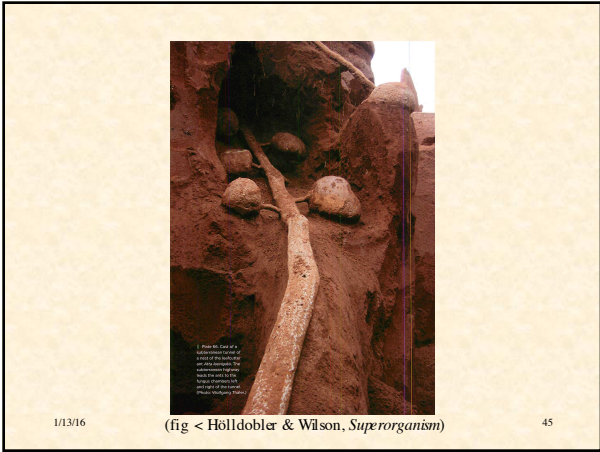
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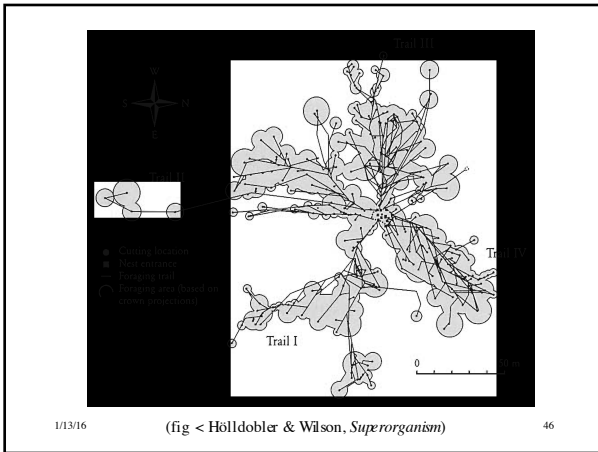
(fig < Hölldobler & Wilson, *Superorganism*)

42

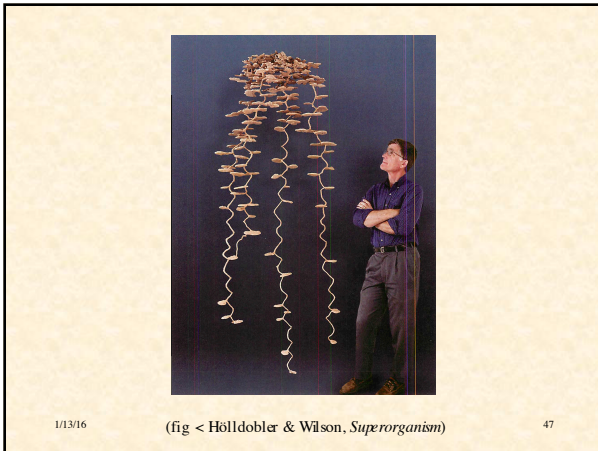








1/13/16 (fig < Hölldobler & Wilson, *Superorganism*) 46



1/13/16 (fig < Hölldobler & Wilson, *Superorganism*) 47

**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?”

1/13/16 48

Emergent Aspects

- Colony size $\sim 8 \times 10^6$
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!

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49

How Do They Do It?

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



1/13/16

(video from Stanford Report, April 2003) 50

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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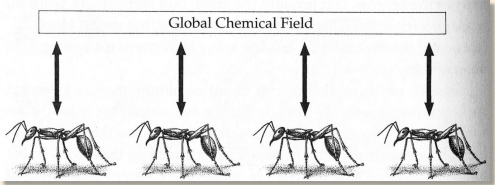
51

Demonstration: Simulation of Ant Foraging

[Run NetLogo Ant-Foraging](#)

1/13/16 52

Macro-Micro Feedback



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

1/13/16 53
fig. from Soké & Goodwin

Stigmergy

- From $\sigma\tau\iota\gamma\mu\acute{o}\varsigma$ = pricking + $\acute{\epsilon}\rho\gamma\omicron\nu$ = 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

1/13/16 54

Stigmergy in termite nest building

Fig. from EVALife

1/13/16 55

Stigmergy in spider webs

Fig. from EVALife

1/13/16 56

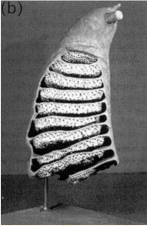
Rules	Behaviour Patterns	Sensors and Motors
<p>Inner leg (IL) on AS thread?</p> <p>Touch AS thread until contact with spider</p>	<p>Touch perception of the inner leg</p> <p>Move body forward with inner leg until next thread crossing</p> <p>move forward along thread</p> <p>thread crossing?</p>	<p>Inner Leg (IL)</p> <p>Motor</p> <p>Touch Sensor</p> <p>Proprio Sensor</p>
<p>Inner leg (IL) on radius crossing?</p> <p>Search for outer threads with outer leg</p>	<p>Touch perception of the inner leg</p> <p>Search forward/delay with outer leg until thread contact</p> <p>move forward/delay</p> <p>thread contact?</p>	<p>Outer Leg (OL)</p> <p>Motor</p> <p>Touch Sensor</p> <p>Proprio Sensor</p>
<p>Outer leg (OL) on CS or FS thread?</p> <p>Attach new CS thread on spider</p>	<p>Touch perception of the outer leg</p> <p>Move posterior and attach CS thread. Make compromise between the distance to AS and set CS mesh size</p> <p>distance moved?</p> <p>on radial?</p> <p>attach CS thread</p>	<p>Outer Leg (OL)</p> <p>Motor</p> <p>Touch Sensor</p> <p>Proprio Sensor</p>

Fig. from EVALife

1/13/16 57

Advantages of Stigmergy

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



1/13/16 58

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*

1/13/16 59

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

1/13/16 60

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

61

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.

1/13/16

Part II

62
