CS 420/527

Biologically-Inspired Computation

Bruce MacLennan
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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)

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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
- Graduate students will do additional experiments and mathematical exercises
- No exams

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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

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Textbook

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

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Contents of Flake CBN

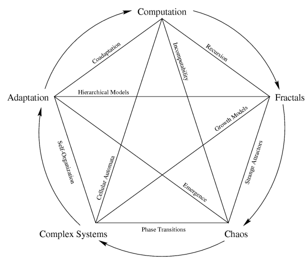

Figure 1.1 An association map of the contents of this book

What We Will Cover

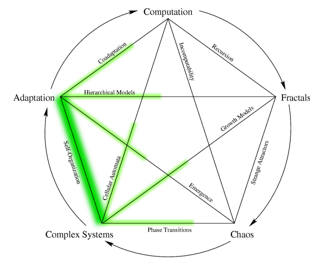

Figure 1.1 An association map of the contents of this book *that we will cover*

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

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

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Lecture 2
✺
Ants
✺
Emergence and Self-Organization

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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 source: Deborah Gordon: *Ants at Work* (1999)

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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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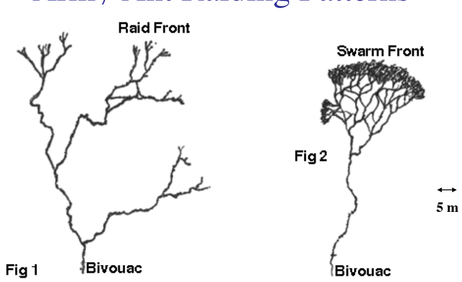
Army Ant Raiding Patterns

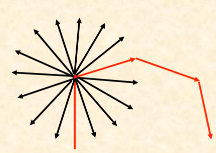


Eciton hamatum ***Eciton burchelli***

8/19/10 from Solé & Goodwin, *Signs of Life* 23

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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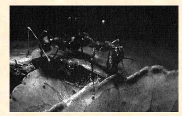
Weaver Ants

- 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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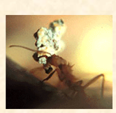
Adults Using Larvae as "Glue Guns"

8/19/10 (fig. from *Self-Org. Biol.Sys.*) 28

Fungus Cultivator Ants

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



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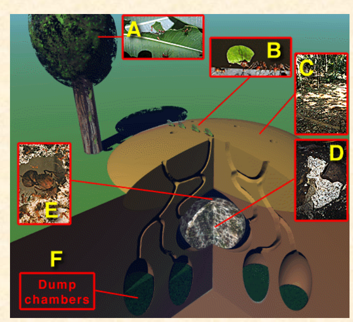
Fungus Cultivator Nest



8/19/10 (fig. from AntColony.org) 30

Leaf Cutting

- Leaves being cut by workers

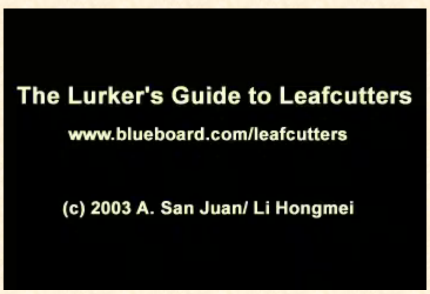
8/19/10 (fig. from AntColony.org) 31

Transport of Cut Leaves

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

8/19/10 (fig. from AntColony.org) 32

Transporting Cut Leaves to Nest



8/19/10 (vid. from www.blueboard.com/leafcutters) 33

Protection by Minims

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

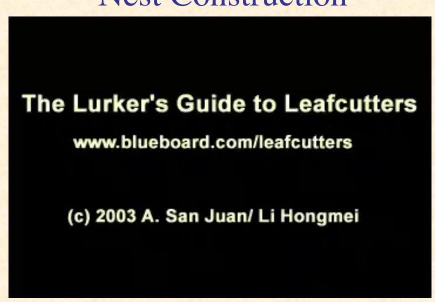
8/19/10 (fig. from AntColony.org) 34

A Large Nest

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

8/19/10 (fig. from AntColony.org) 35

Nest Construction



- Several tons of earth may be removed by large colony

8/19/10 (vid. from www.blueboard.com/leafcutters) 36

Leaf Brought to Fungus Garden

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

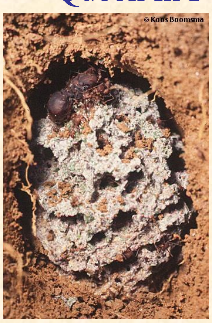
8/19/10 (fig. from AntColony.org) 37

The Fungus Garden

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

8/19/10 (fig. from AntColony.org) 38

Queen in Fungus Garden



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

8/19/10 (fig. from AntColony.org) 39

Dump Chambers

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

8/19/10 (fig. from AntColony.org) 40

Maeterlinck on Ants

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

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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!

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How Do They Do It?

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

8/19/10 (video from *Stanford Report*, April 2003) 43

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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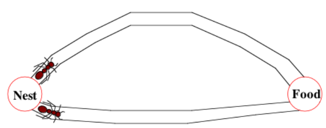
Ant foraging

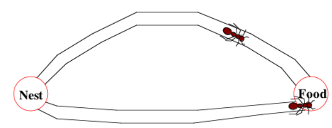
Cooperative search by pheromone trails



8/19/10 slides from EVALife 45

Ant foraging

Cooperative search by pheromone trails



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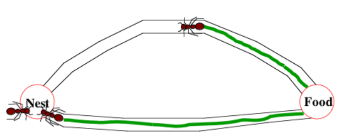
Ant foraging

Cooperative search by pheromone trails



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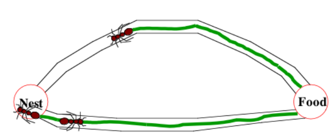
Ant foraging

Cooperative search by pheromone trails



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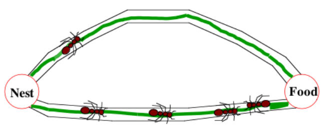
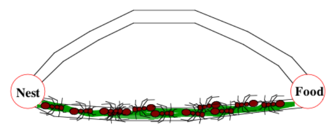
Ant foraging

Cooperative search by pheromone trails



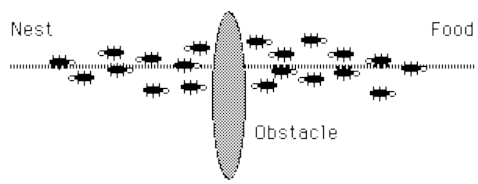
Ant foraging

Cooperative search by pheromone trails

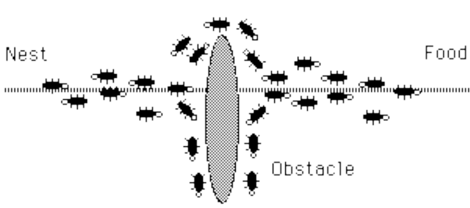


Adaptive Path Optimization

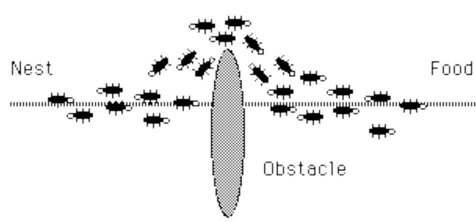
Adaptive Path Optimization



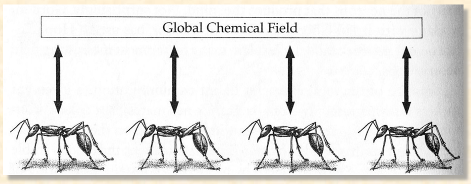
Adaptive Path Optimization



Adaptive Path Optimization



Circular Causality



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

8/19/10 fig. from Solé & Goodwin 55

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

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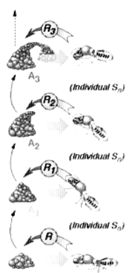
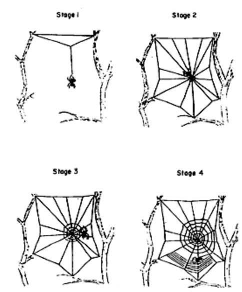
Stigmergy in termite nest building

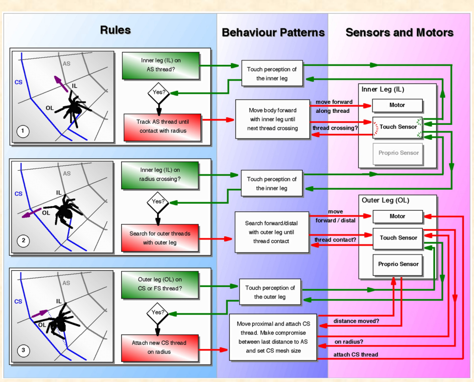


8/19/10 Fig, from EVALife 57

Stigmergy in spider webs



8/19/10 Fig, from EVALife 58



8/19/10 Fig. from EVALife 59

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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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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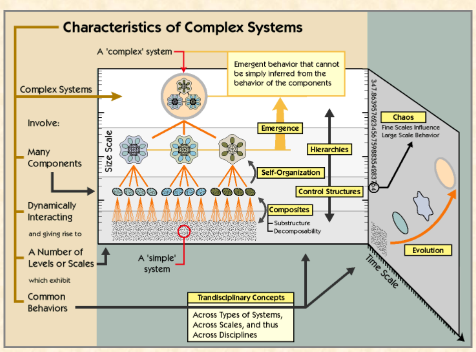

8/19/10 Fig. from NECSI 63

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

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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.

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Similar Principles of SO

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

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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

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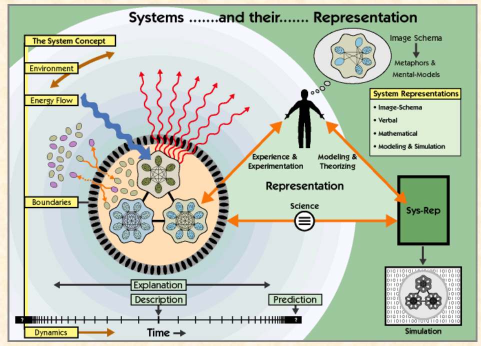

8/19/10 Fig. from NECSI 74

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.

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