

CS 420/594

(Advanced Topics in Machine Intelligence)

Biologically-Inspired Computation

Bruce MacLennan

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

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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)

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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 & 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

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Textbook

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

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Contents of Flake CBN

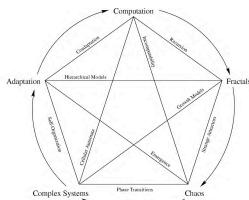


Figure 1.1 An association map of the contents of this book

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What We Will Cover

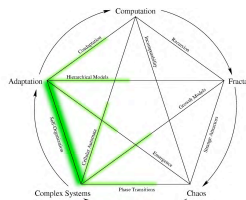


Figure 1.1 An association map of the contents of this book that we will cover

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Reading for Next Week

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

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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 formats (revised after class)

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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: bio-inspired 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
 - 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

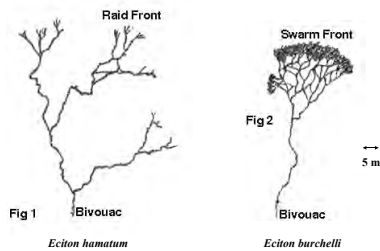


- No permanent nest
- Create temporary "bivouacs" from bodies of workers
- Raiding parties of up to 200 000
- Act like unified entity

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Army Ant Raiding Patterns



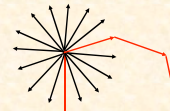
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from Solé & Goodwin, *Signs of Life*

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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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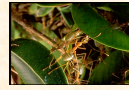
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Collective Navigation

- 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

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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”



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

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Fungus Cultivator Ants

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

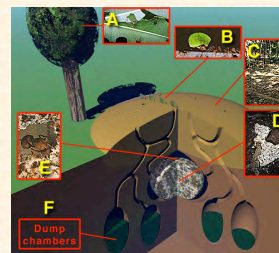


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Fungus Cultivator Nest



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(fig. from AntColony.org)

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Leaf Cutting



- Leaves being cut by workers

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(fig. from AntColony.org)

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Transport of Cut Leaves



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

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(fig. from AntColony.org)

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Transporting Cut Leaves to Nest

The Lurker's Guide to Leafcutters

www.blueboard.com/leafcutters

(c) 2003 A. San Juan/ Li Hongmei

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

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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)

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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)

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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)

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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)

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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)

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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

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(fig. from AntColony.org)

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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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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 $\sim 8 \times 10^6$
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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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) 43

How do they do it?

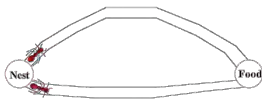
- Semiochemically: deposit pheromones
 - 10-20 signs, many signal tasks
 - ants detect pheromone gradients and frequency of encounter
- Follow trails imperfectly
 - ⇒ exploration
- Feedback reinforces successful trails
 - ⇒ biased randomness

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Ant foraging

Cooperative search by pheromone trails



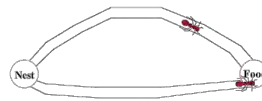
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slides from EValife

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Ant foraging

Cooperative search by pheromone trails



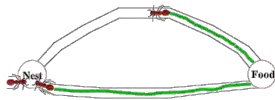
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Ant foraging

Cooperative search by pheromone trails



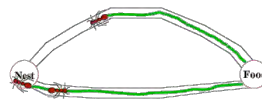
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Ant foraging

Cooperative search by pheromone trails



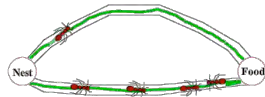
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Ant foraging

Cooperative search by pheromone trails



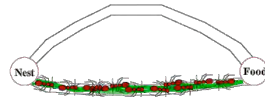
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slides from EVALife

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Ant foraging

Cooperative search by pheromone trails



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Adaptive Path Optimization

Nest Food



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slides from iridia.ulb.ac.be/~mdorigo

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Adaptive Path Optimization

Nest Food



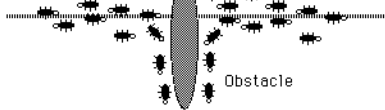
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Adaptive Path Optimization

Nest Food



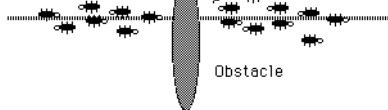
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Adaptive Path Optimization

Nest Food

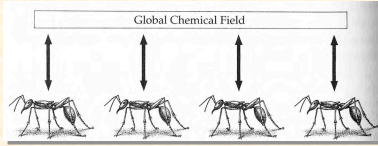


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Circular Causality



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

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fig. from Solé & Goodwin

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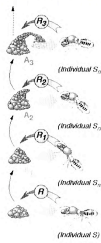
Stigmergy

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

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Stigmergy in termite nest building

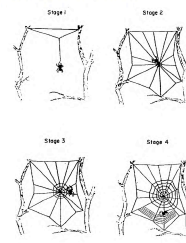


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Fig. from EVALife

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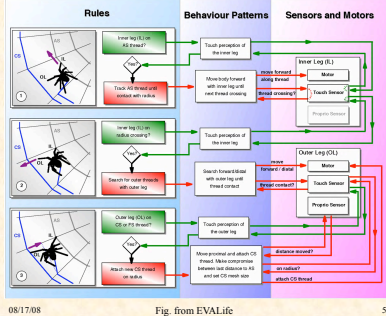
Stigmergy in spider webs



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Fig. from EVALife

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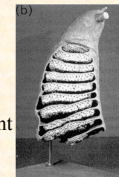
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Fig. from EVALife

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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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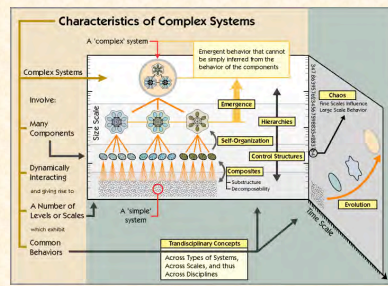
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Self-Organization

- 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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Fig. from NECSI

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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

	<i>Ant Colonies</i>	<i>Neural Nets</i>
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

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from Solé & Goodwin: *Signs of Life*, p. 149

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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

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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

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Characteristics of Self-Organized System

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

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— Bonabeau, Dorigo & Theraulaz, *Swarm Intelligence*, pp. 12-14

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Two Approaches to the Properties of Complex Systems

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Focal Issue: Emergence

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

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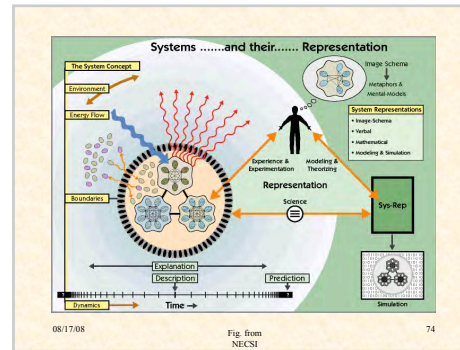
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Focal Issue: Complexity

- 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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Fig. from
NECSM

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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. 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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