CS 790R Seminar
Modeling & Simulation

Computational Models of Complex Systems

~ Introductory Lecture 1 ~

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Computational Models of Complex Systems

Introductory Lecture 1

- Examples of complex systems 1
- Course organization
- Paper reviews (first period)

Introductory Lecture 2

- Examples of complex systems 2
- Common elementary features of CS
- Common global properties of CS

Computational Models of Complex Systems

Introductory Lecture 1

- Examples of complex systems 1
  - Pattern formation
  - Insect colonies
  - Group motion
  - Synchronization
- Course organization
- Paper reviews (first period)

Computational Models of Complex Systems

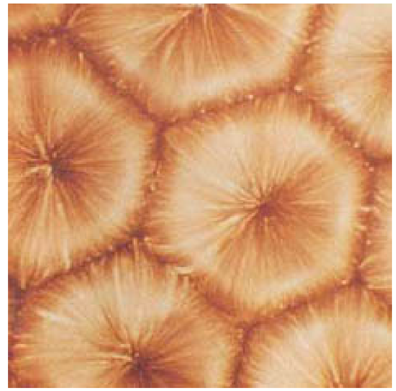
Introductory Lecture 1

- Examples of complex systems 1
  - Pattern formation
    - Physical: convection cells
    - Chemical: BZ reaction
    - Biological: animal colors
    - Biological: slime mold
  - Insect colonies
  - Group motion
  - Synchronization
- Course organization
- Paper reviews (first period)

Examples of complex systems

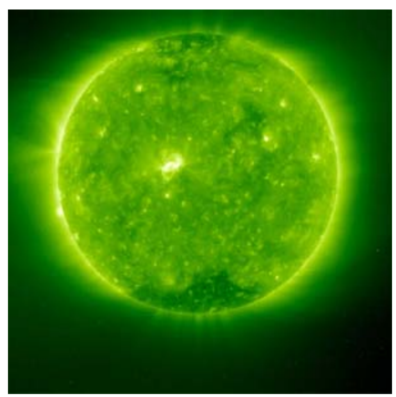
Pattern formation – *Physical: convection cells*

Rayleigh-Bénard convection cells
in liquid heated uniformly from below
(Scott Camazine, http://www.scottcamazine.com)



Convection cells in liquid (detail)
(Manuel Velarde, Universidad Complutense, Madrid)

Sand dunes
(Scott Camazine, http://www.scottcamazine.com)

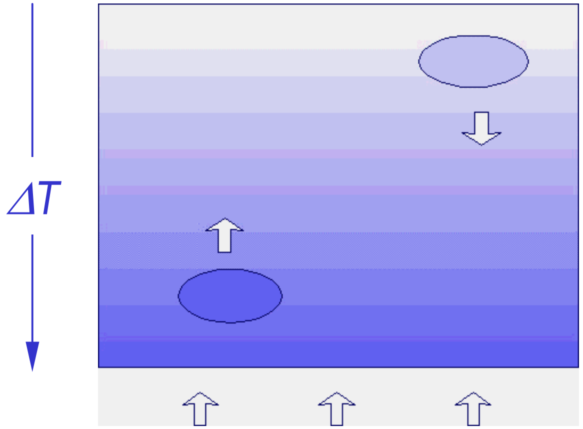


Solar magnetoconvection
(Steven R. Lantz, Cornell Theory Center, NY)

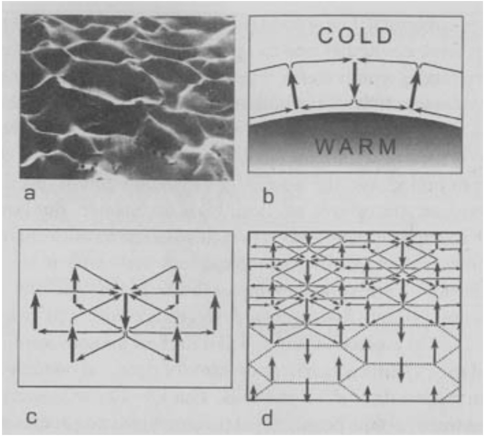
Phenomenon

- “thermal convection” is the motion of fluids caused by a temperature differential
- observed at multiple scales, whether frying pan or geo/astrophysical systems
- spontaneous symmetry-breaking of a homogeneous state
- formation of stripes and cells, several order of magnitudes larger than molecular scale

Examples of complex systems
Pattern formation – *Physical: convection cells*



Schematic convection dynamics
(Arunn Narasimhan, Southern Methodist University, TX)

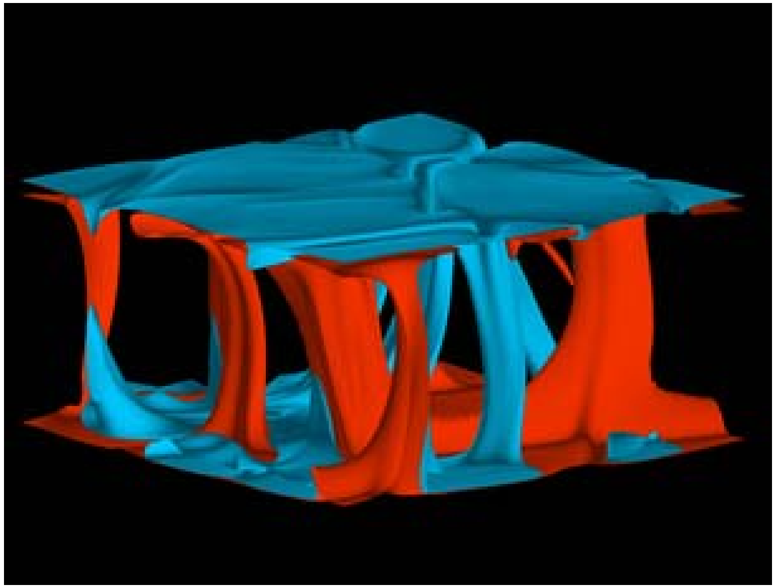


Hexagonal arrangement of sand dunes
(Solé and Goodwin, "Signs of Life", Perseus Books)

Mechanism

- warm fluid is pushed up from the bottom by surrounding higher density (buoyancy force)
- cold fluid sinks down from the top due to surrounding lower density
- accelerated motion
- viscosity and thermal diffusion normally counteract buoyancy...
- ... but only up to a critical temperature differential ΔT_c
- beyond ΔT_c buoyancy takes over and breaks up the fluid into alternating rolls

Examples of complex systems
Pattern formation – *Physical: convection cells*



Convection dynamics
(Stéphane Labrosse, Institut de Physique du Globe, Paris)

Modeling & simulation

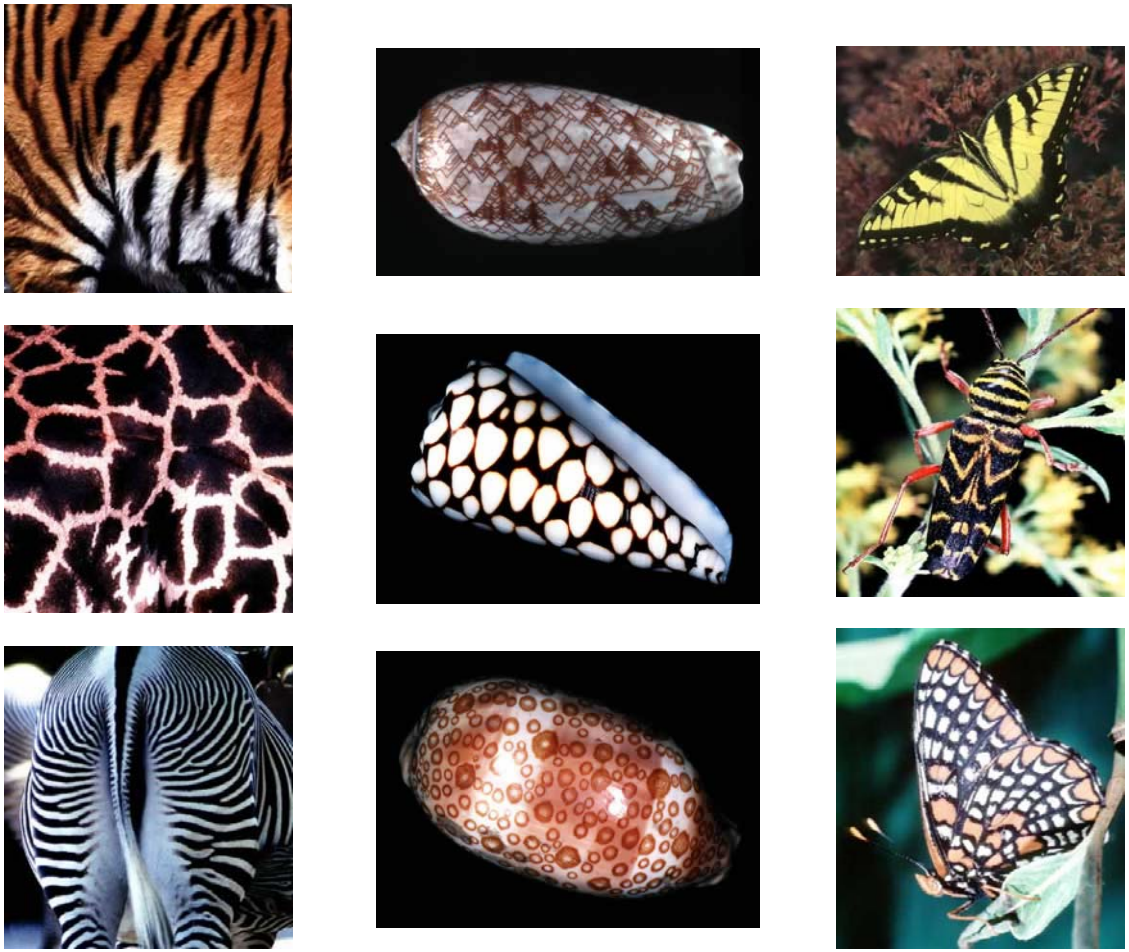
- surfaces of constant temperatures (red for hot, blue for cold)
- visualization of ascending and descending currents
- notice the moving cell borders at the top

Examples of complex systems
Pattern formation – *Physical: convection cells*

Concepts collected from this example

- large number of elementary constituents
- emergence of macroscopic structures (convection cells >> molecules)
- self-arranged patterns
- amplification of small fluctuations (positive feedback, symmetry breaking)
- phase transition
- far from equilibrium

Examples of complex systems
Pattern formation – *Biological: animal colors*

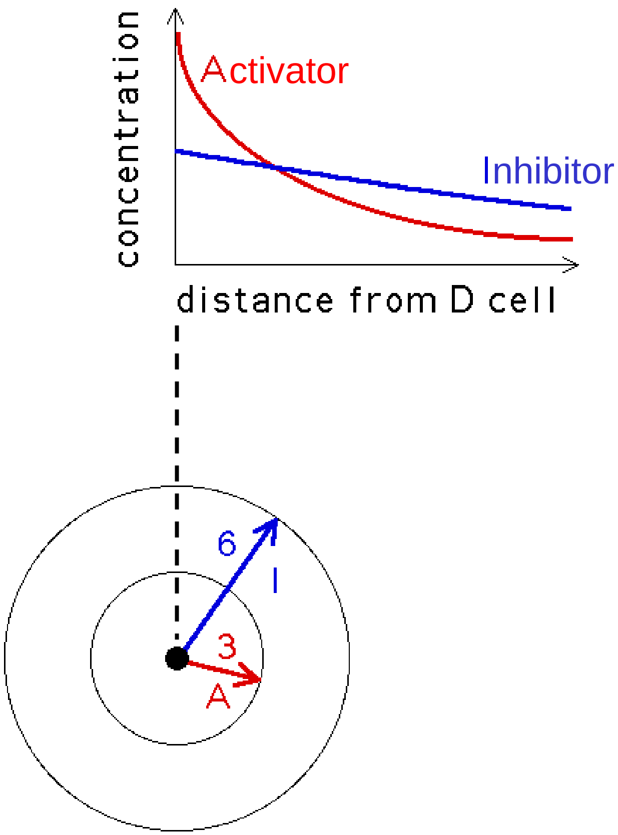


Mammal fur, seashells, and insect wings
(Scott Camazine, http://www.scottcamazine.com)

Phenomenon

- ➢ rich diversity of pigment patterns across species
- ➢ evolutionary edge:
  - warning
  - camouflage, mimicry
  - sexual attraction
  - individual recognition
  - amaze humans :-)
  - etc.

Examples of complex systems
Pattern formation – *Biological: animal colors*

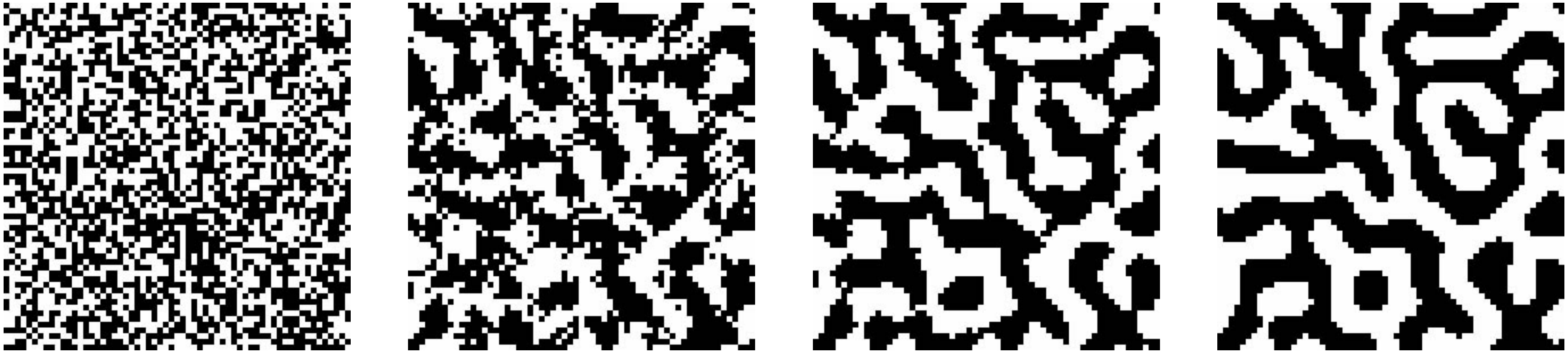


David Young's model of fur spots and stripes
(Michael Frame & Benoit Mandelbrot, Yale University)

Mechanism

- development of spots and stripes on mammal fur
- melanocytes (pigment cells) can be undifferentiated "U", or differentiated "D"
- only D cells produce color → they diffuse two morphogens, activator "A" and inhibitor "I"
- neighboring cells differentiate or not according to:
  - short-range activation
  - long-range inhibition
- a classical case of *reaction-diffusion*

Examples of complex systems
Pattern formation – *Biological: animal colors*



NetLogo fur coat simulation, after David Young's model
(Uri Wilensky, Northwestern University, IL)

Modeling & simulation

- example of *cellular automaton*
- each cell has 2 states:
  - "pigmented" (black)
  - "undifferentiated" (white)

- each cell's state is updated by:
  - counting pigmented neighbors within radius 3 (they contribute to activation)
  - counting pigmented neighbors between radius 3 and 6 (they contribute to inhibition)
  - calculating weighted vote

Examples of complex systems
Pattern formation – *Biological: animal colors*

Concepts collected from this example

- simple microscopic rules
- emergence of macroscopic structures (spots >> cells)
- self-arranged patterns
- amplification of small fluctuations (positive feedback, symmetry breaking)
- local cooperation, distant competition (cell $\leftrightarrow$ cell)

Computational Models of Complex Systems

Introductory Lecture 1

- Examples of complex systems 1
  - Pattern formation
  - Insect colonies
    - Ant trails
    - Termite mounds
  - Group motion
  - Synchronization
- Course organization
- Paper reviews (first period)

Examples of complex systems
Insect colonies – *Ant trails*

White-footed ants trailing on a wall
(J. Warner, University of Florida)

Phenomenon

- insect colonies are the epitome of complex systems, self-organization and emergence
- one striking example of collective behavior: spontaneous trail formation by ants
- two-way trails appear between nest and food source, brooding area or cemetery
- ants carry various items back and forth on these trails
- the colony performs *collective optimization* of distance and productivity without a leader

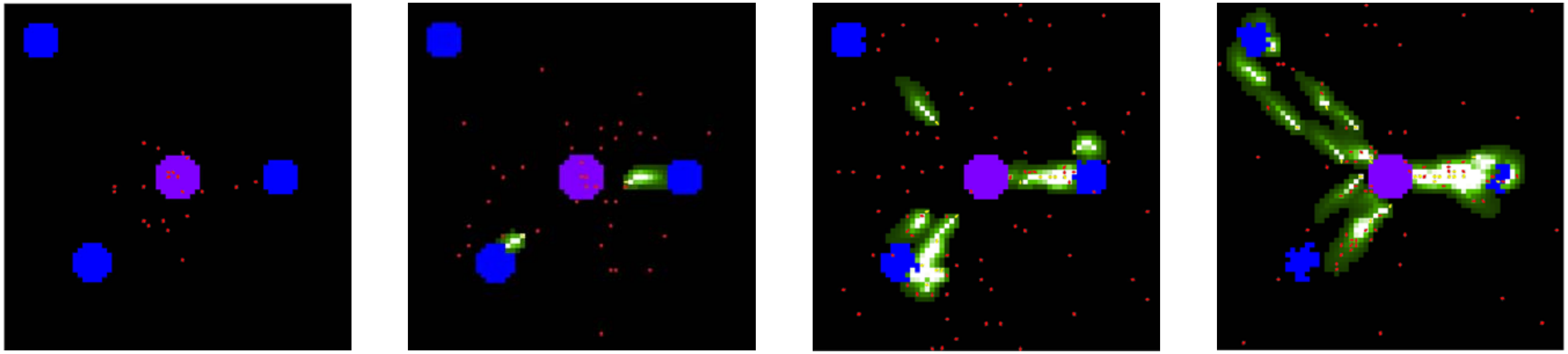
Examples of complex systems
Insect colonies – *Ant trails*

Harvester ant
(Deborah Gordon, Stanford University)

Mechanism

- while moving, each ant deposits a chemical ("pheromone") to signal the path to other ants
- each ant also "smells" and follows the pheromone gradient laid down by others

Examples of complex systems
Insect colonies – *Ant trails*



StarLogo ant foraging simulation, after Mitchel Resnick
(StarLogo Project, MIT Media Laboratory, MA)

Modeling & simulation

- setup:
  - 1 nest (purple)
  - 3 food sources (blue spots)
  - 100 to 200 ants (moving red dots)

- ant's behavioral repertoire:
  - walk around randomly
  - if bump into food, pick it and return to nest
  - if carrying food, deposit pheromone (green)
  - if not carrying food, follow pheromone gradient

- result: food sources are exploited in order of increasing distance and decreasing richness
- emergence of collective decision

Examples of complex systems
Insect colonies – *Ant trails*

Concepts collected from this example

- simple individual rules
- emergence of collective computation
- no leader, no map (decentralization)
- amplification of small fluctuations (positive feedback)
- local interactions (ant $\leftrightarrow$ environment)
- phase transition (critical mass)

Computational Models of Complex Systems

Introductory Lecture 1

- Examples of complex systems 1
  - Pattern formation
  - Insect colonies
  - Group motion
    - Natural: flocks, schools, herds
    - Artificial: traffic jams
  - Synchronization
- Course organization
- Paper reviews (first period)

Examples of complex systems

Group motion – *Natural: flocks, schools, herds*

Giant flock of flamingos
(John E. Estes, UC Santa Barbara, CA)

Fish school
(Eric T. Schultz, University of Connecticut)

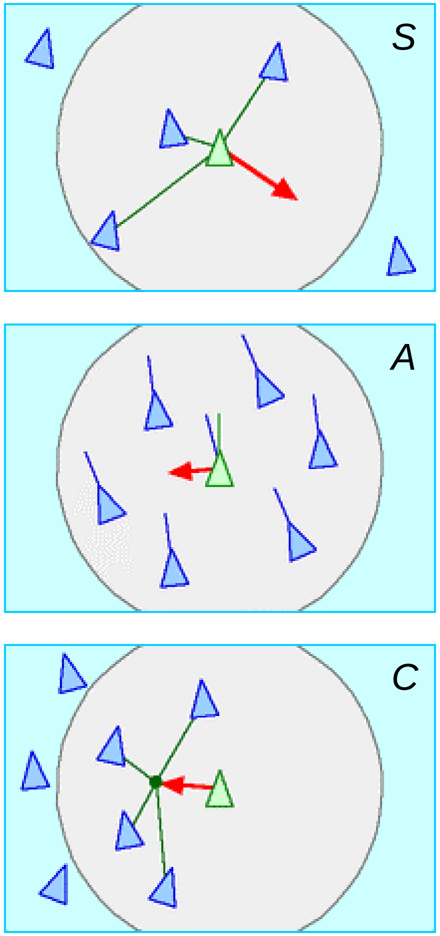
Bison herd
(Center for Bison Studies, Montana State University, Bozeman)

Phenomenon

- coordinated collective movement of dozens or thousands of individuals
- adaptive significance:
  - preys confuse predator
  - predators close in on prey
  - increased aero/hydrodynamic efficiency

Examples of complex systems

Group motion – *Natural: flocks, schools, herds*

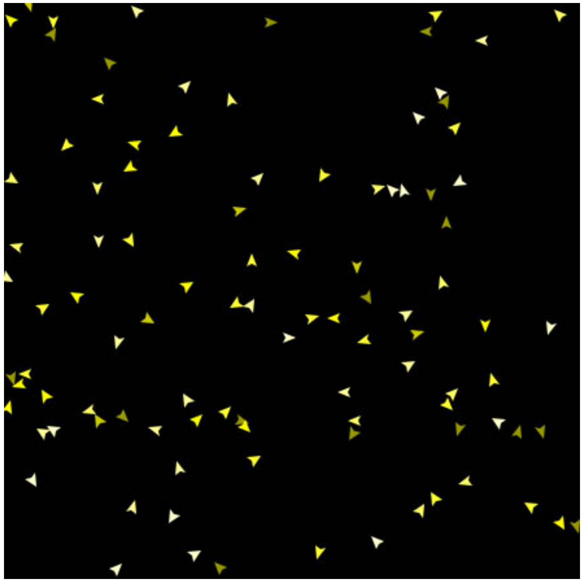
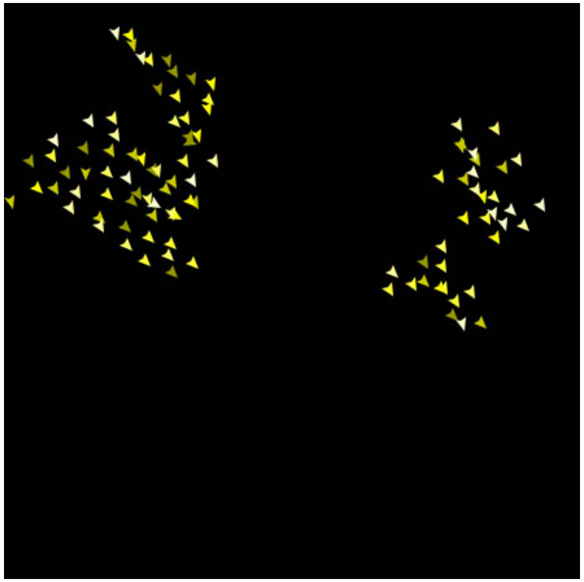


Separation, alignment and cohesion
("Boids" model, Craig Reynolds, http://www.red3d.com/cwr/boids)

Mechanism

- Reynolds' "boids" model
- each individual adjusts its position, orientation and speed according to its nearest neighbors
- steering rules:
  - separation: avoid crowding local flockmates
  - alignment: adopt average heading of local flockmates
  - cohesion: move toward average position of local flockmates

Examples of complex systems
Group motion – *Natural: flocks, schools, herds*

NetLogo flocking simulation, after Craig Reynolds' "boids" model
(Uri Wilensky, Northwestern University, IL)

Modeling & simulation

Examples of complex systems

Group motion – *Natural: flocks, schools, herds*

Concepts collected from this example

- simple individual rules
- emergence of coordinated collective motion
- no leader, no external reference point (decentralization)
- local interactions (animal $\leftrightarrow$ animal)
- cooperation

Computational Models of Complex Systems

Introductory Lecture 1

- Examples of complex systems 1
  - Pattern formation
  - Insect colonies
  - Group motion
  - Synchronization
    - Fireflies
    - Neurons
- Course organization
- Paper reviews (first period)

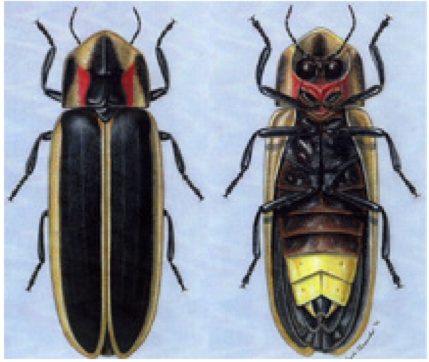
Examples of complex systems
Synchronization – *Fireflies*

Fireflies flashing in sync on the river banks of Malaysia

Phenomenon

- a swarm of male fireflies (beetles) synchronize their flashes
- starting from random scattered flashing, pockets of sync grow and merge
- adaptive significance:
  - still unclear...
  - cooperative behavior amplifies signal visibility to attract females (share the reward)?
  - cooperative behavior helps blending in and avoiding predators (share the risk)?
  - ... or competition to be the first to flash?
- famous example of synchronization among independently sustained oscillators

Examples of complex systems
Synchronization – *Fireflies*



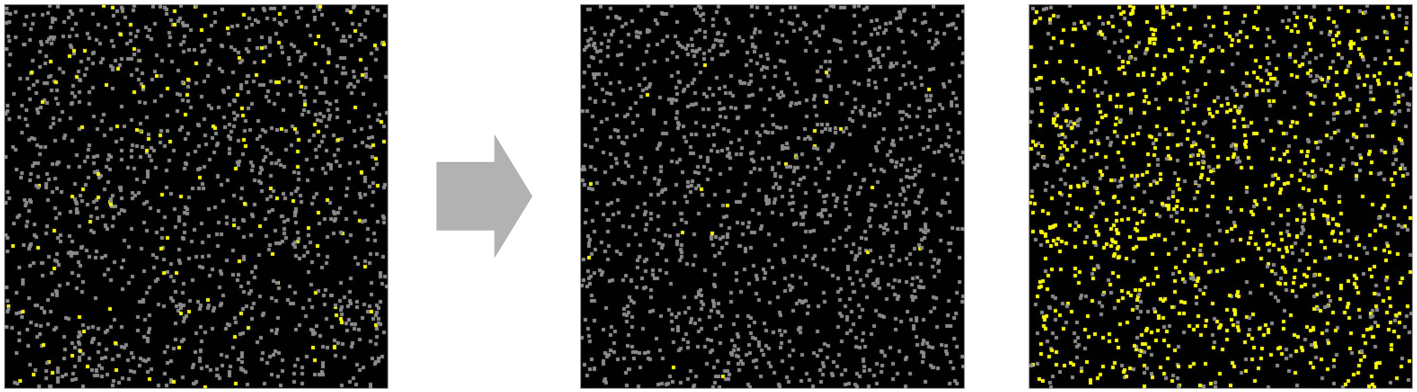
Say's firefly, in the US
(Arwin Provonsha, Purdue Dept of Entomology, IN)

Firefly flashing (slow motion)
(Biology Department, Tufts University, MA)

Mechanism

- light-emitting cells (photocytes) located in the abdomen
- 1. each firefly maintains an internal regular cycle of flashing:
  - physiological mechanism still unclear...
  - pacemaker cluster of neurons controlling the photocytes?
  - autonomous oscillatory metabolism?
  - ... or just the movie in repeat mode? :-)
- 2. each firefly adjusts its flashing cycle to its neighbors:
  - pushing/pulling or resetting phase
  - increasing/decreasing frequency

Examples of complex systems
Synchronization – *Fireflies*



NetLogo fireflies simulation
(Uri Wilensky, Northwestern University, IL)

Modeling & simulation

- each firefly "cell":
  - hovers around randomly
  - cycles through an internal flashing clock
  - resets its clock upon seeing flashing in the vicinity

- distributed system coordinates itself without a central leader

Examples of complex systems
Synchronization – ***Fireflies***

Concepts collected from this example

- simple individual rules
- emergence of collective synchronization
- no conductor, no external pacemaker (decentralization)
- local interactions (insect ↔ insect)
- cooperation

Computational Models of Complex Systems

Introductory Lecture 1

- Examples of complex systems 1
- Course organization
  - Topic
  - Objectives
  - Assignments
    - Paper reviews
    - Programming exercises
    - Research project
  - Credits & grading
  - Schedule
- Paper reviews (first period)

Course organization
Topic

- ✓ exploration of complex systems by modeling and simulation (cellular automata, numerical integration of differential eqs.)
- ✓ complex systems = large number of elements interacting locally (with each other and/or environment)
- ✓ simple microscopic behaviors $\rightarrow$ complex *emergent* behavior
- ✓ difficult to predict or explain analytically
- ✓ complex systems pervade nature and human structures, yet “complexity” is only a recent scientific topic
- ✓ fast computers allow us to see new patterns and convince ourselves that decentralized order is possible

Course organization
Objectives

a) to examine case studies and models of complex systems

b) to understand the concepts that unify these phenomena

c) to introduce some of the disciplines dealing with complexity

(a)	(b)	(c)
• spin glasses, convection cells	✓ emergence	➢ cellular automata
• excitable media & waves	✓ self-organization	➢ artificial life, virtual ants
• genes & cell differentiation	✓ nonlinear dynamics	➢ swarm intelligence
• animal patterns (coats, shells)	✓ order, chaos, complexity	➢ pattern formation
• insect societies (ants, termites)	✓ competition & cooperation	➢ oscillators, synchronization
• flocks, herds, schools	✓ feedback	➢ Boolean networks
• ecosystems & evolution	✓ phase transitions	➢ genetic algorithms
• neurons, brain & cognition	✓ adaptation	➢ neural networks
• cities, economy, Internet	✓ edge of chaos, criticality . . .	➢ small worlds . . . . .

✓ . . . immensely VAST interdisciplinary topic!

✓ disclaimer: this seminar offers a discovery through "sampling"; *not systematic or exhaustive*

Course organization
Assignments – *Paper reviews*

- ✓ papers = journal articles or book chapters
- ✓ 1 or 2 assigned papers per session (possibly combined with additional sources) to be *read by everyone* and presented by 1 or 2 students
- ✓ paper presentation tasks:
  - prepare a PowerPoint presentation *with figures*
  - run a companion demo (ready-made or self-made): explore parameters and explain code
- ✓ paper session timing:
  - 5 mn recap/foreword by instructor
  - max 60 mn student presentation, including demo
  - min 10 mn questions/discussion

Course organization
Assignments – *Programming exercises*

- ✓ 3.0-credit students have home assignments
- ✓ purpose: convince yourself about the emergence of complex behavior from simple rules
- ✓ easy level programming: NetLogo scripts
- ✓ advanced level: language of your choice (C, Java, Fortran, MATLAB, etc.) *with charts and/or GUI*
- ✓ frequency: about every other week (every 4 sessions)

Course organization
Assignments – *Research project*

- ✓ 3.0-credit students must prepare *individual* research projects
- ✓ topics must address complex systems and may be:
  - selected from list (TBA), in relation with paper reviews
  - overlapping with another *current* work (M.S., Ph.D.)
  - original for this seminar
- ✓ project tasks:
  - 1 modeling & simulation program
  - 1 journal-style report
  - 1 conference-style presentation, *with live demo*
- ✓ project deadlines:
  - in 1 month: proposal reports & presentations
  - in 2 months: status reports & presentations
  - in 4 months: final code, reports & presentations

Course organization
Credits & grading (tentative)

- ✓ Attendance, participation in discussions
  - 1.0 credit: 40% — 3.0 credits: 20%
- ✓ Paper review presentation
  - 1.0 credit: 60% — 3.0 credits: 20%
- ✓ Programming exercises
  - 1.0 credit: -- — 3.0 credits: 20%
- ✓ Research project
  - 1.0 credit: -- — 3.0 credits: 40%

Grading scale:

- 90%-100%: A-, A
- 80%-90%: B-, B, B+
- 65%-80%: C-, C, C+
- 55%-65%: D
- 0%-55%: F

Course organization
Schedule (tentative)

1. T, Jan 18: Lecture 1 2. R, Jan 20: Lecture 2	1st period (sampling)	13. T, Mar 1: Paper review* 14. R, Mar 3: Paper review*	2nd period	23. T, Apr 12: Paper review* 24. R, Apr 14: Paper review*	3rd period
3. T, Jan 25: Paper review 4. R, Jan 27: Paper review		15. T, Mar 8: Paper review* 16. R, Mar 10: Paper review*		25. T, Apr 19: Paper review* 26. R, Apr 21: Paper review*	
5. T, Feb 1: Paper review 6. R, Feb 3: Paper review		17. T, Mar 15: Paper review* 18. R, Mar 17: Paper review*		*T, Apr 26: Project preparation* *R, Apr 28: Project preparation*	
7. T, Feb 8: Paper review 8. R, Feb 10: Paper review		19. T, Mar 22: Paper review* 20. R, Mar 24: Project status present.		27. T, May 3: Project presentations 28. R, May 5: Project presentations	
9. T, Feb 15: Paper review 10. R, Feb 17: Project proposal present.		*T, Mar 29: Spring break* *R, Mar 31: Spring break*		29. T, May 10: Conclusion/discussion	
11. T, Feb 22: Paper review* 12. R, Feb 24: Paper review*		21. T, Apr 5: Paper review* 22. R, Apr 7: Paper review*			

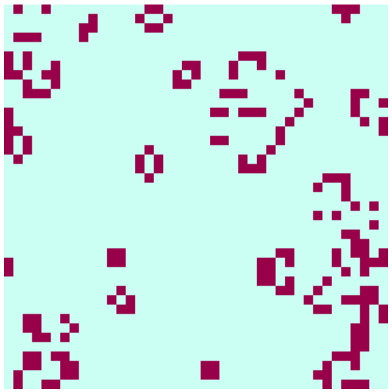
(*) Note: A few of the paper review sessions might be replaced with invited talks (to be announced)

Computational Models of Complex Systems

Introductory Lecture 1

- Examples of complex systems 1
- Course organization
- Paper reviews (first period)
  - Jan 25: Cellular automata
  - Jan 27: Slime mold
  - Feb 1: Animal patterns
  - Feb 3: Ant trails
  - Feb 8: Spatial ecology
  - Feb 10: Artificial neural networks
  - Feb 15: Synchronization

Paper reviews (first period)
Jan 25: Cellular automata



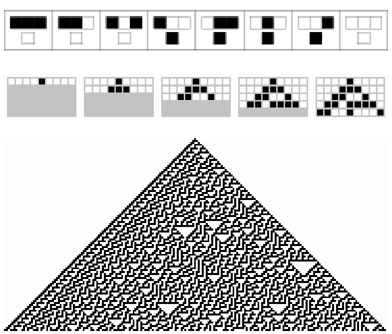
NetLogo Game of Life simulation
(Uri Wilensky, Northwestern University, IL)

Preliminary paper (< 10')

Gardner, M. (1970) Mathematical Games: The fantastic combinations of John Conway's new solitaire game “life". *Scientific American*, 223(4): 120-123.

http://ddi.cs.uni-potsdam.de/HyFISCH/Produzieren/lis_projekt/proj_gamelife/ConwayScientificAmerican.htm

NetLogo demo: “Life”

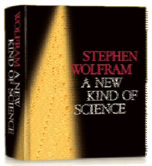


Rule 30 of 1-D cellular automaton
(“A New Kind of Science”, Stephen Wolfram)

Main reading (50')

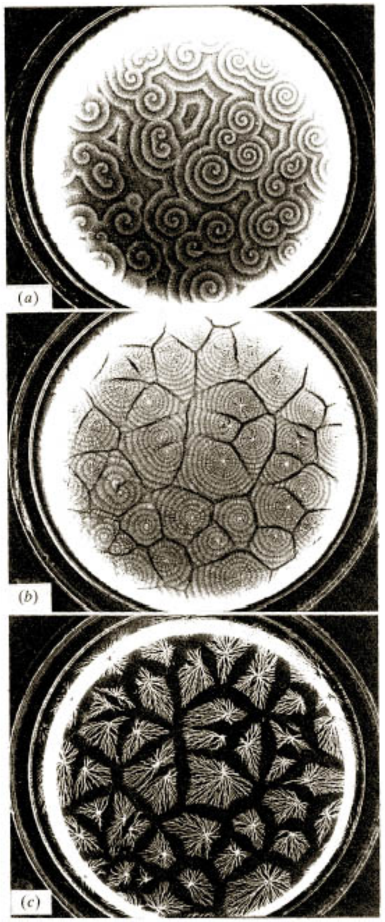
Wolfram, S. (2002) **Chapters 1, 2 & 3**, in *A New Kind of Science*. Wolfram Media, Inc.

http://www.wolframscience.com/nksonline/toc.html



NetLogo demo: “CA ...”

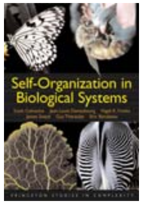
Paper reviews (first period)
Jan 27: Slime mold



Aggregation of slime mold
(P. C. Newell)

Main reading (60')

Camazine, S., Deneubourg, J.-L., Franks, N. R., Sneyd, J., Theraulaz, G., and Bonabeau, E. (2003) **Chapter 8: Pattern formation in slime molds and bacteria**, in *Self-Organization in Biological Systems*. Princeton University Press.



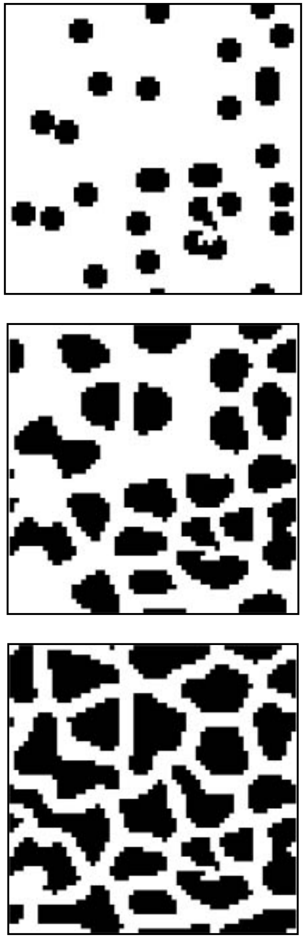
NetLogo demo: "B-Z", "Slime" & "Slime Stream"

Background papers

Hofer, T., Sherratt, J. A., and Maini, P. K. (1995) Dictyostelium discoideum: cellular self-organisation in an excitable biological medium. *Proc. R. Soc. Lond. B*, 259: 249-257.

Pálsson, E., and Cox, E. C. (1996) Origin and Evolution of Circular Waves and Spiral in Dictyostelium discoideum Territories. *Proc. Natl. Acad. Sci. USA*, 93: 1151-1155.

Paper reviews (first period)
Feb 1: Animal patterns

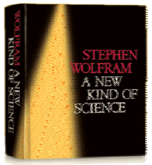


CA simulation of giraffe spots
(Y. Bar-Yam, "Dynamic of Complex Systems", Perseus Books)

Preliminary reading (5')

Wolfram, S. (2002) Chapter 8, pp422-429, in _A New Kind of Science. Wolfram Media_, Inc.

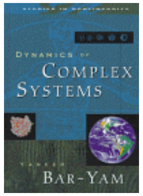
http://www.wolframscience.com/nksonline/toc.html



Main reading (55')

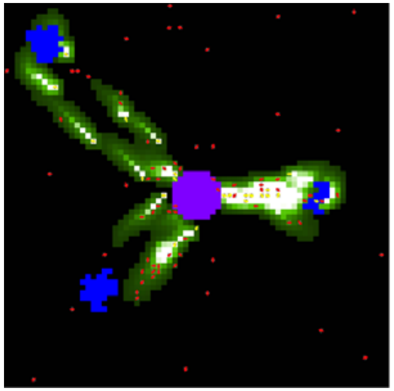
Bar-Yam, Y. (1997) Chapter 7: Developmental Biology, Sections 7.1, 7.2.1 - 7.2.5, in _Dynamics of Complex Systems_. Perseus Books.

http://www.necsi.org/publications/dcs/



NetLogo demo: "Fur"

Paper reviews (first period)
Feb 3: Ant trails

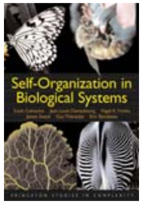


StarLogo ant foraging simulation
(StarLogo Project, MIT Media Laboratory, MA)

Main reading (60')

Camazine, S., Deneubourg, J.-L., Franks, N. R., Sneyd, J., Theraulaz, G., and Bonabeau, E. (2003) **Chapter 13: Trail formation in ants**, in *Self-Organization in Biological Systems*. Princeton University Press.

NetLogo demo: "Ants"



Paper reviews (first period)
Feb 8: Spatial ecology

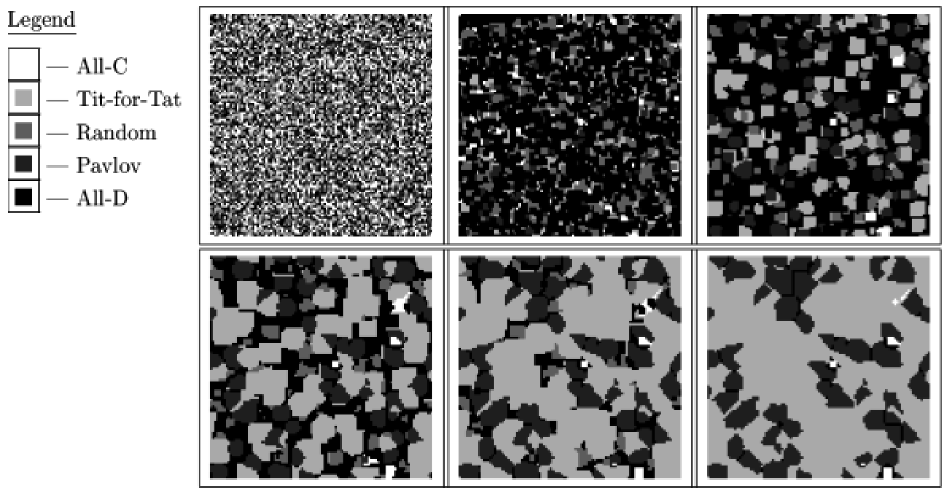
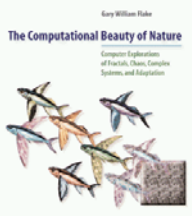


Figure 17.4 Competition in the spatial iterated Prisoner's Dilemma without noise

Main reading (60')

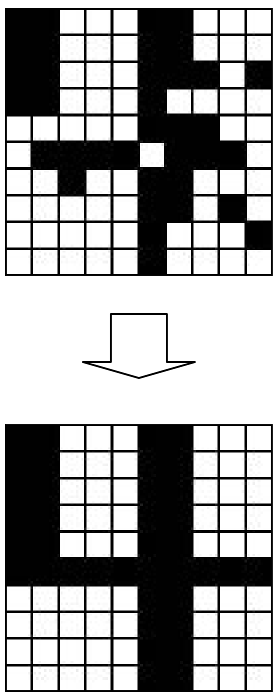
Flake, G. W. (1998) **Chapter 17: Competition & cooperation**, in *The Computational Beauty of Nature*. MIT Press.



http://mitpress.mit.edu/books/FLAOH/cbnhtml/

NetLogo demo: "PD ..."

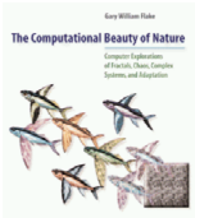
Paper reviews (first period)
Feb 10: Artificial neural networks



Main reading (60’)

Flake, G. W. (1998) Chapter 18: Natural & analog computation, in *The Computational Beauty of Nature*. MIT Press.

http://mitpress.mit.edu/books/FLAOH/cbnhtml/



Hopfield applet demo

http://diwww.epfl.ch/mantra/tutorial/english/hopfield/html/

Paper reviews (first period)
Feb 15: Synchronization

Computational Models of Complex Systems

Introductory Lecture 1

- Examples of complex systems 1
- Course organization
- Paper reviews (first period)

Introductory Lecture 2

- Examples of complex systems 2
- Common elementary features of CS
- Common global properties of CS