Computational Models of Complex Systems

CS 790R Seminar

1. Introductory Lecture 1

René Doursat

Department of Computer Science & Engineering
University of Nevada, Reno

Spring 2006

Instructor

René Doursat

- **Experience**
  - ✓ Visiting Assistant Professor, CSE, UNR, 2004-2006
  - ✓ Senior Software Engineer & Architect, 1995-2004
  - ✓ Research Associate, Ecole Polytechnique, Paris, 1996-1997
  - ✓ Postdoctoral Fellow, Ruhr-Universität Bochum, 1991-1995
- **Education**
  - ✓ Ph.D. in applied mathematics, Université Paris VI, 1991
  - ✓ M.S. in physics, Ecole Normale Supérieure, Paris, 1987
- **Research interests**
  - ✓ computational modeling and simulation of complex systems: neural networks, brain computing, biological modeling

Instructor

René Doursat

- Contact information
  - ✓ **E-mail**: doursat@unr.edu
  - ✓ **Phone**: (775) 327-2246 / (775) 784-6974
  - ✓ Web page: http://www.cse.unr.edu/~doursat
  - ✓ **Office**: SEM 230 (Scrugham Engineering-Mines)
  - ✓ **Office hours (tentative)**:
    - Monday, 4 - 5:30pm
    - Tuesday, 5:30 - 7pm
    - Wednesday, 4 - 5:30pm
    - or by appointment

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)

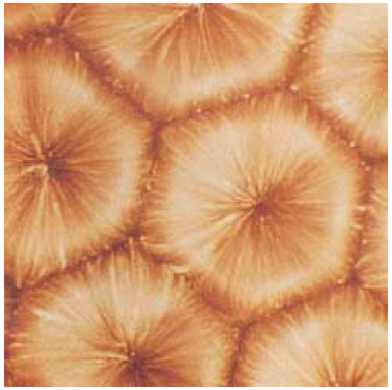
Computational Models of Complex Systems

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)

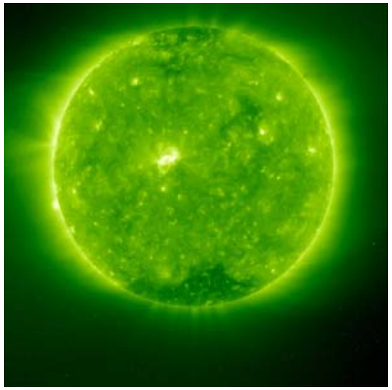
Examples of complex systems
Pattern formation – *Physical: convection cells*

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)

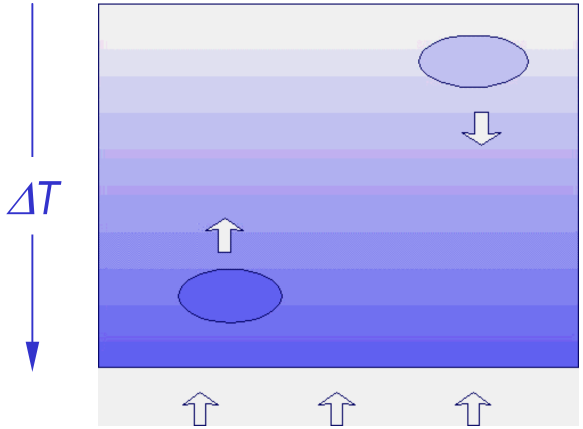


Solar magnetoconvection
(Steven R. Lantz, Cornell Theory Center, NY)

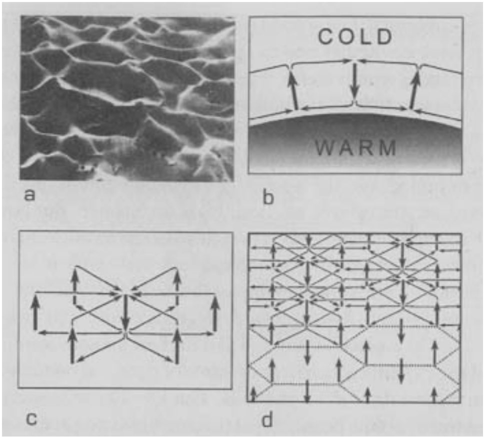
Phenomenon

- "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)

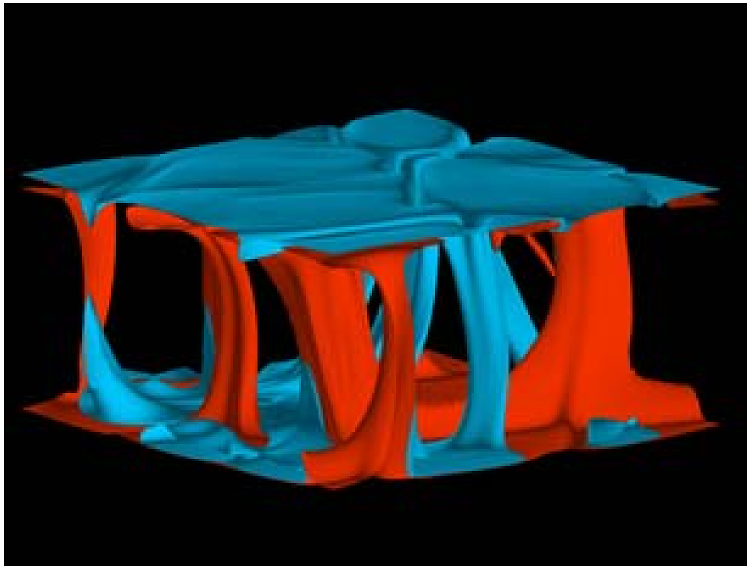


Hexagonal arrangement of sand dunes
(Solé and Goodwin, "Signs of Life", Perseus Books)

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

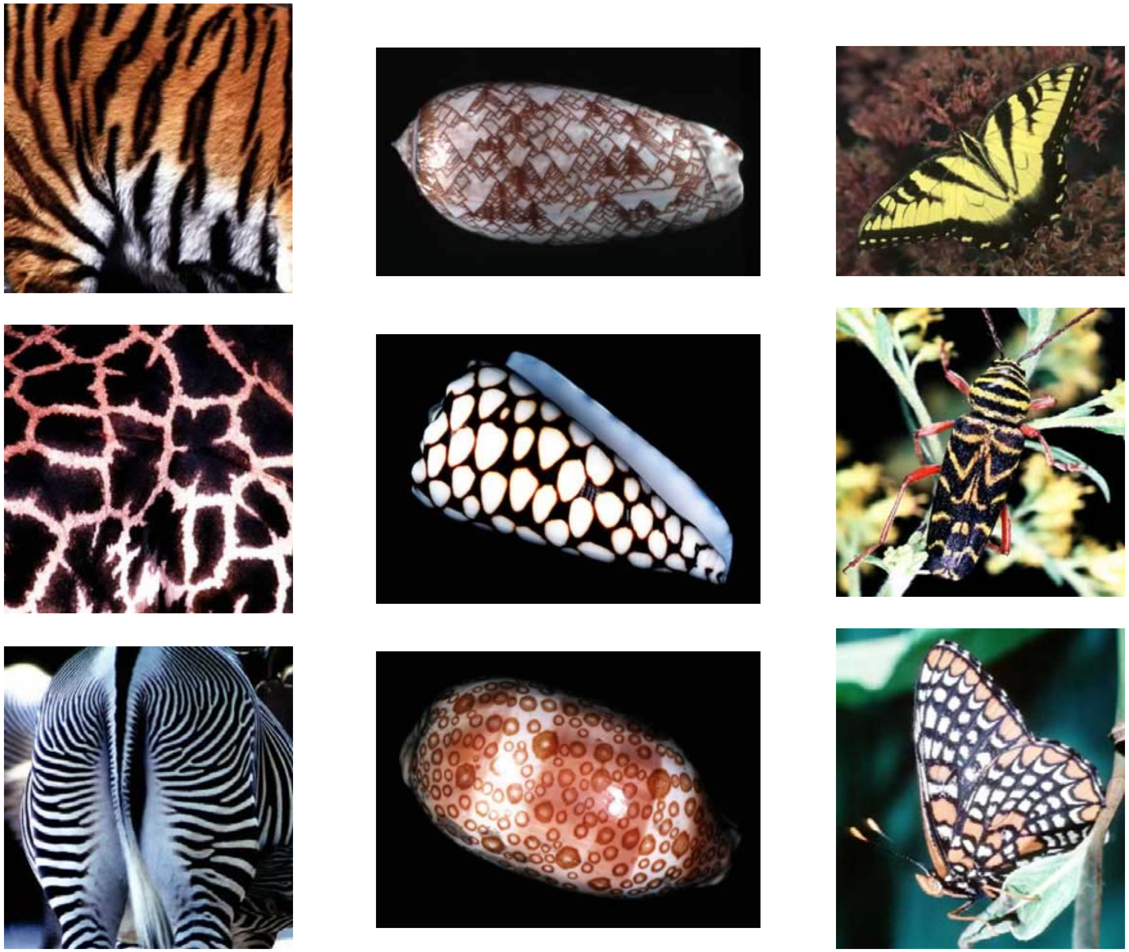
- surfaces of constant temperatures (red for hot, blue for cold)
- visualization of ascending and descending currents
- notice the moving cell borders at the top

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*



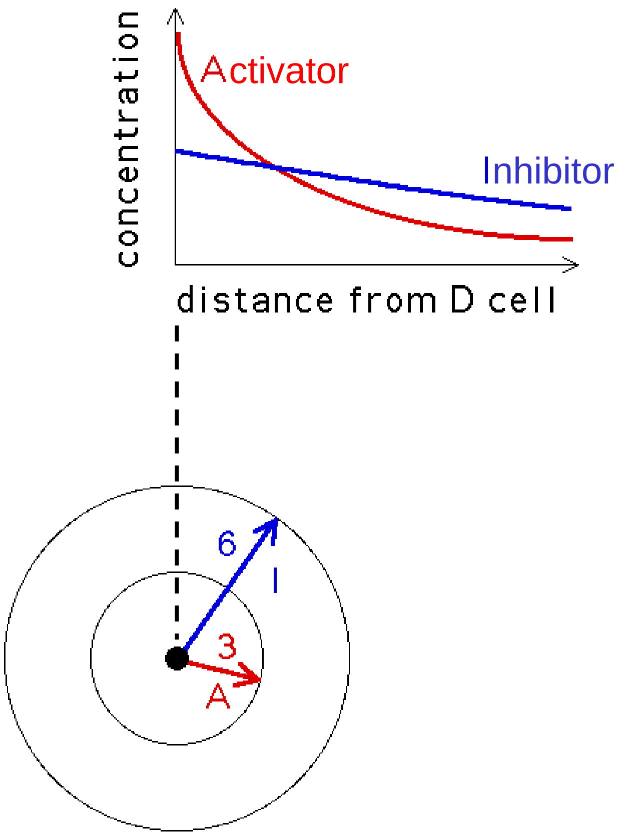
Mammal fur, seashells, and insect wings
(Scott Camazine, http://www.scottcamazine.com)

Phenomenon

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

Examples of complex systems

Pattern formation – *Biological: animal colors*

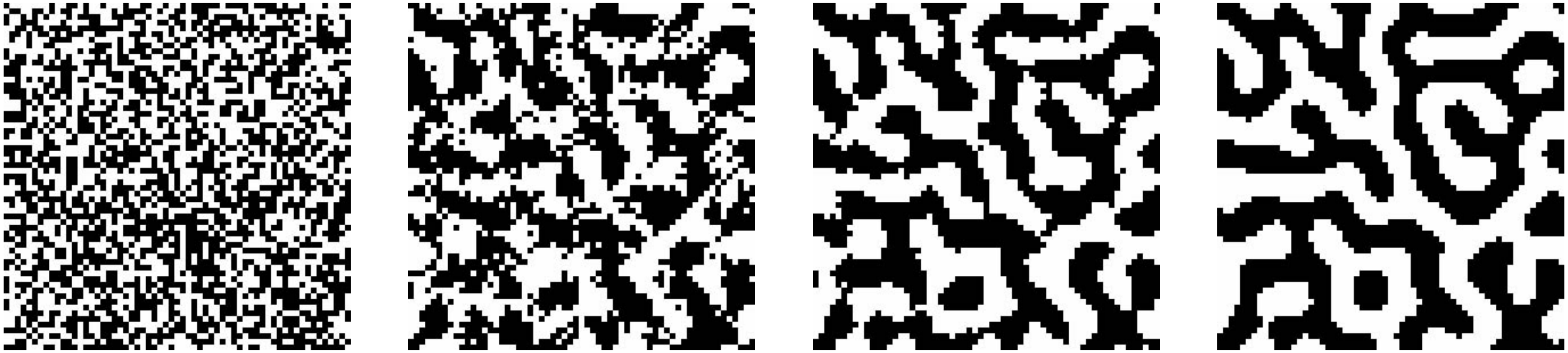


David Young's model of fur spots and stripes
(Michael Frame & Benoit Mandelbrot, Yale University)

Possible mechanism (schematic)

- development of spots and stripes on mammal fur
- melanocytes (pigment cells) can be undifferentiated "U", or differentiated "D"
- only D cells produce color $\rightarrow$ 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 ↔ 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, without anyone having a map
- 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

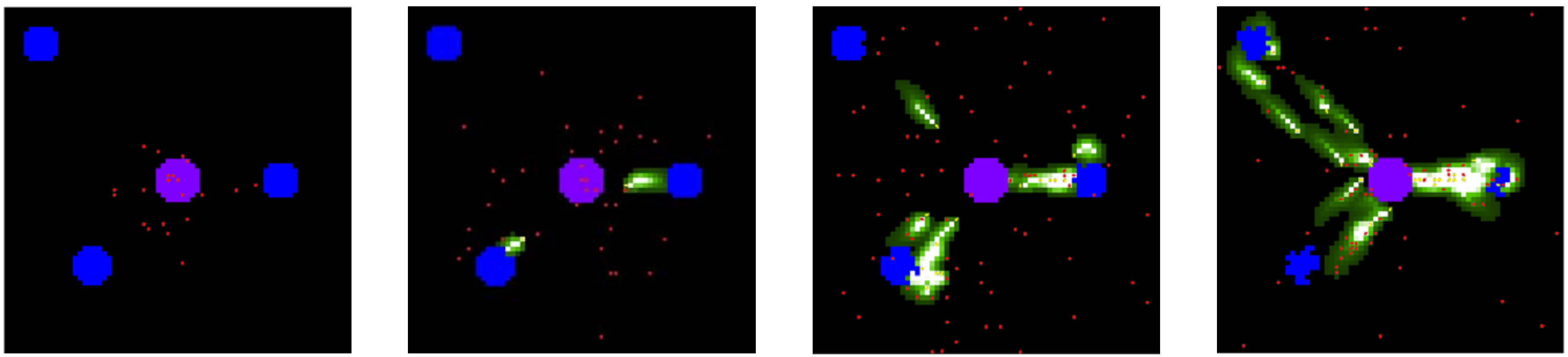
Examples of complex systems
Insect colonies – *Ant trails*

Harvester ant
(Deborah Gordon, Stanford University)

Basic 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

- typical result: food sources are exploited in order of increasing distance and decreasing richness

- emergence of a 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 = minimal number of ants)

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)

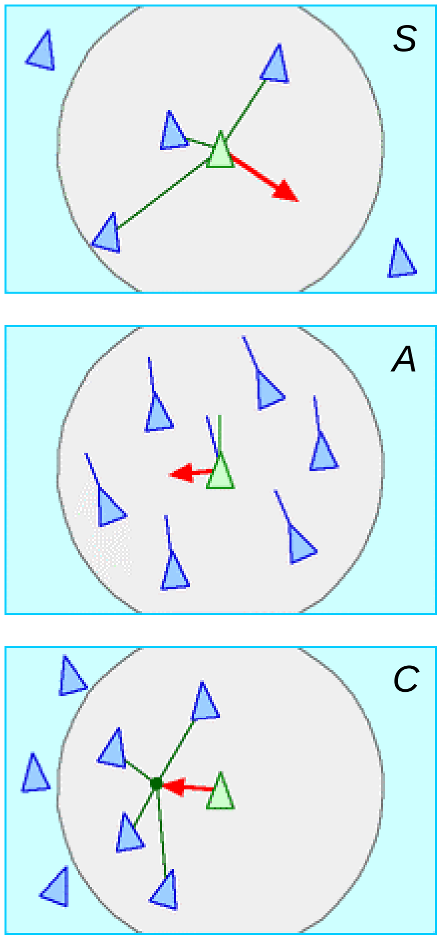
Bison herd
(Center for Bison Studies, Montana State University, Bozeman)

Phenomenon

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

Examples of complex systems

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



Separation, alignment and cohesion

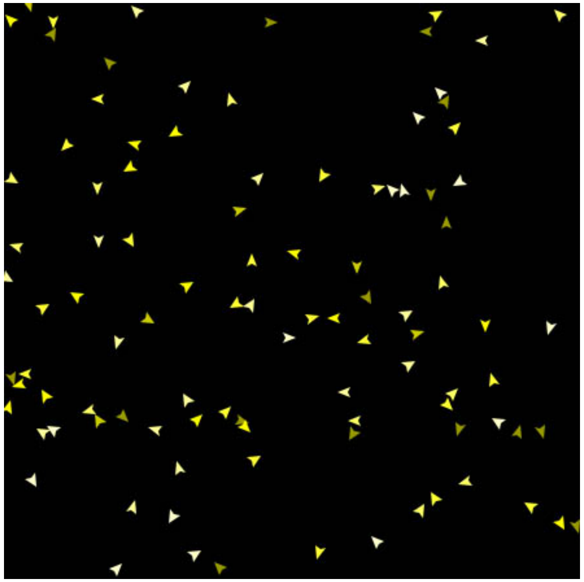
("Boids" model, Craig Reynolds, http://www.red3d.com/cwr/boids)

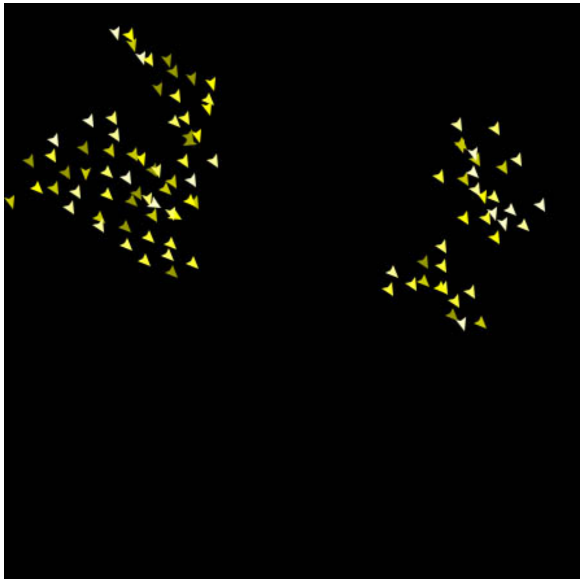
Mechanism

- 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)

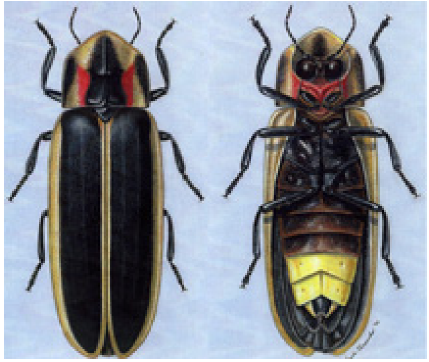
Examples of complex systems
Synchronization – *Fireflies*

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***



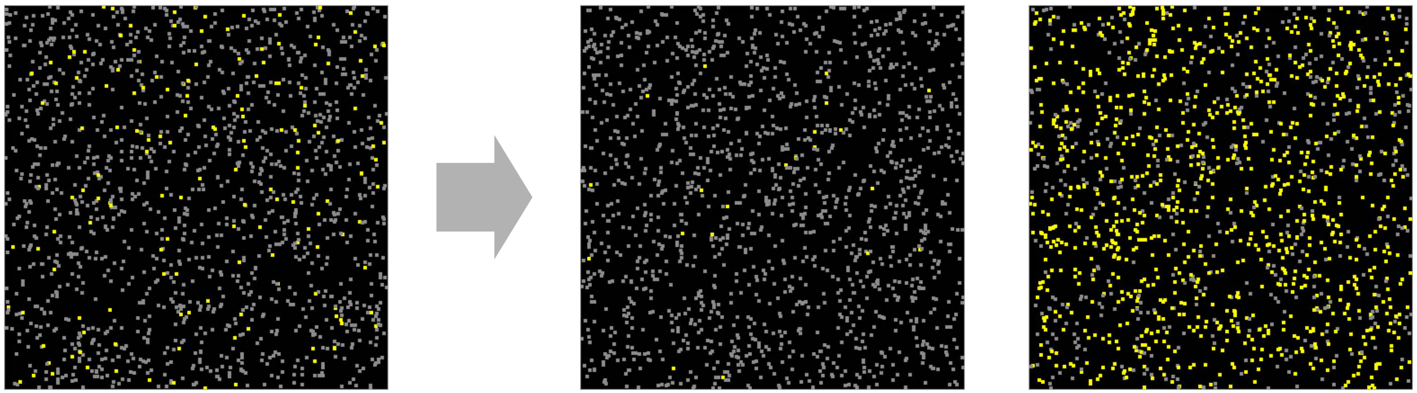
Say's firefly, in the US
(Arwin Provonsha, Purdue Dept of Entomology, IN)

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 → 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

ex: brain

specific natural or societal complex system

ex: bird flocks

biological neural models

model simulating this system

3-D collective flight simulation

binary neuron, linear synapse

generic principles and mechanisms (schematization, caricature)

"boid", separation, alignment, cohesion

artificial neural networks applied to association, classification or optimization

new computational discipline exploiting these principles to solve engineering problems

particle swarm optimization (PSO) "flying over" solutions in high-D spaces

Course organization
Objectives

a) examine case studies and models of complex systems

b) understand the concepts that unify these phenomena

c) introduce some of the disciplines deriving from 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..	➢ complex networks . . .

✓ . . . immensely VAST interdisciplinary topic!

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

Course organization
Objectives

- ✓ we will try to find a balance between the exploration of (1) natural models and (2) generic techniques
- ✓ some of you might have a preference for (1), some of you for (2)
- ✓ the tendency *could* be to have nonprogramming students generally review topics from (1) and programming students review topics from (2)
- ✓ often, there won't be a clear-cut correspondence between the two sides:
  - models don't always generate techniques or
  - techniques don't always come from natural systems

Course organization
Assignments – *Paper reviews*

- ✓ reading assignments: journal papers, book chapters, Web
- ✓ quantity per meeting: a few papers forming a logical group, possibly accompanied by additional background sources
- ✓ to be *read by everyone* and presented by 1 or 2 participants
- ✓ paper presentation tasks:
  - prepare a PowerPoint presentation *with figures*
  - possibly 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 also have home assignments
- purpose: convince oneself 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: probably 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 deliverables:
  - modeling & simulation program
  - journal-style report
  - 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: 20% 3.0 credits: 10%

- ✓ Paper review presentation

  1.0 credit: 60% 3.0 credits: 20%

- ✓ Quizzes

  1.0 credit: 20% 3.0 credits: 10%

- ✓ 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%-89%: B-, B, B+
- 65%-79%: C-, C, C+
- 55%-64%: D
- 0%-54%: F

Course organization
Schedule (tentative)

- Schedule (on Web page)
  - ✓ important dates (tentative):
    - project **proposal** presentations: Wednesday, February 22
    - project **status** presentations: Monday, March 27
    - ***final** project presentations: Monday, May 15, 4:30-6:30pm*
  - ✓ *check this schedule often*, as new course notes, reading assignments, homeworks, announcements, etc., will be posted there frequently
  - ✓ as much as possible, important news between classes will be emailed to you, however *do not count on receiving emails!* you must check the Web page proactively

Computational Models of Complex Systems

Introductory Lecture 1

- Examples of complex systems 1
- Course organization
- Paper reviews (first period)
  - Jan 30: Cellular automata 1: Wolfram 1, 2, 3
  - Feb 1: Cellular automata 2: Wolfram 7, 8
  - Feb 6: Pattern formation 1: reaction-diffusion
  - Feb 8: Pattern formation 2: excitable media
  - Feb 13: Swarm intelligence 1: particle swarm opt.
  - Feb 15: Swarm intelligence 2: ant colony opt.

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