lecture 18

biologically-inspired computing

Collective Behavior
Lab Assignments: 35% (ISE-483), 25% (SSIE-583)
- Complete 4/5 assignments based on algorithms presented in class
  - Lab 4: April 12th (Wednesday after Spring break)
    - Evolutionary Algorithms, (Lab 4 in Brightspace Assignments)
    - Due April 24th
  - Lab 5: May 1st
    - Ant Clustering Algorithm, (Lab 5 in Brightspace Assignments)
    - Due May 8th

SSIE – 583 -Presentation and Discussion: 35%
- Present and lead the discussion of an article related to the class materials
  - Enginet students post/send video or join by Zoom
- All presentations completed?
Class Book
  - Chapters 1, 4, and 7

Lecture notes
- Chapter 1: What is Life?
- Chapter 2: The logical Mechanisms of Life
- Chapter 3: Formalizing and Modeling the World
- Chapter 4: Self-Organization and Emergent Complex Behavior
- Chapter 5: Reality is Stranger than Fiction
- Chapter 6: Von Neumann and Natural Selection
- Chapter 7: Modeling Evolutionary Systems
  - posted online @ http://informatics.indiana.edu/rocha/i-bic

Papers and other materials
- Optional
    - Chapter 2, 7, 8
    - Chapter 3, sections 3.1 to 3.5
    - Chapters 10, 11, 14 – Dynamics, Attractors and chaos
    - Chapter 20
Projects

- Due by May 8th 12th in Brightspace, “Final Project Paper” assignment
  - ALIFE 2023
    - Not to submit to actual conference due date (March 13th)
    - https://2023.alife.org/
    - 8 pages, author guidelines:
      - /calls/call-for-papers-extended-abstracts
      - MS Word and Latex/Overleaf templates
  - Preliminary ideas by March 27
    - Submit to “Project Idea” assignment in Brightspace.

- Individual or group
  - With very definite tasks assigned per member of group

ALIFE 2023
Tackle a real problem using bio-inspired algorithms, such as those used in the labs.
Wilson, David Sloan, and Edward O. Wilson. "Evolution 'for the Good of the Group' "
units of selection

moral men might not do any better than immoral men but tribes of moral men would certainly “have an immense advantage” over fractious bands of pirates. (Charles Darwin)

- **Multilevel selection theory**
  - Selection occurs in multiple levels simultaneously
  - No general-case scenario, each organism on a case-by-case basis
    - David Wilson and E.O. Wilson
- **Experiments with *Pseudomonas fluorescens***
  - Oxygen-exhausting bacteria in liquid
  - Groups with enough altruists survive
- **Kin-selection as special case of group selection**
  - Leading to various, diverse (selectable) groups with high genetic similarity
- **Sociobiology**
  - Selfishness beats altruism within groups. Altruistic groups beat selfish groups.

“Morality is herd instinct in the individual”. (Friedrich Nietzsche)
Multilevel selection theory
- Selection occurs in multiple levels simultaneously
- No general-case scenario, each organism on a case-by-case basis

Experiments
- Oxygen-exhausting bacteria in liquid
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Kin-selection as a special case of group selection
- Leading to various, diverse (selectable) groups with high genetic similarity

Sociobiology
- Selfishness beats altruism within groups. Altruistic groups beat selfish groups.

units of selection

"Morality is herd instinct in the individual" (Friedrich Nietzsche)


Sci. American, Jan 2009 (Steve Mirsky)

"Altruists" Pseudomonas fluorescens bacteria (below left) carry a gene for secreting a polymer that enables mats of bacteria to float and thus access oxygen easily; "freeizers" (below right) lack the gene. Producing the polymer costs extra energy, so freeizers reproduce faster than altruists. Natural selection acting on individuals alone would drive the altruists to extinction.

GROUP SELECTION
But group selection appears to operate, too—at least in the laboratory. Floating mats of P. fluorescens bacteria in which some altruists persist. Only mats that include enough polymer-secreting altruists will float and thus survive to reproduce themselves; altruists included (below left). Mats in which individual selection leads to too many freeizers will sink, drowning the entire bacterial colony (below right). Such mats leave no progeny.
**encoding**

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\[ h_0 = (a_0) \]

\[ h_1 = (a_1, a_0) \]

\[ h_m = (a_{m-1}, \ldots, a_1, a_0) \]

Lindgren’s iterated game for agents with memory

4 possible strategies (genotype=2 bits)

16 possible strategies (genotype=4 bits)

Used in the evolutionary search by GA (tournament selection)
Iterated prisoner's dilemma

memory 0 strategies

Figure 1: The evolution of a population of strategies starting with equal fractions of the memory one strategies [00], [01], [10], and [11] is shown for the first 600 generations. The fractions of different strategies are shown as functions of time (generation).

\[ h_0 = (a_0) \]

<table>
<thead>
<tr>
<th>D</th>
<th>0</th>
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<tbody>
<tr>
<td>C</td>
<td>1</td>
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\[
\begin{array}{ccc}
0 & 0 & 1 \\
0 & 1 & 0 \\
1 & 0 & 1 \\
1 & 1 & 0 \\
\end{array}
\]

4 possible strategies
iterated prisoner’s dilemma

higher memory rules

$$h_1 = (a_1, a_0)$$

Used in the evolutionary search by GA (tournament selection)

GA uses variable length genotype

$\begin{array}{c|c}
0 & 0 \\
0 & 1 \\
1 & 0 \\
1 & 1 \\
\end{array}$

$\begin{array}{c|c|c}
0 & 0 & 0 \\
1 & 1 & 1 \\
0 & 1 & 1 \\
1 & 1 & 1 \\
\end{array}$
Natural design principles

exploring similarities across nature

- **self-similar structures**
  - Trees, plants, clouds, mountains
    - Morphogenesis
  - Mechanism
    - Iteration, recursion, feedback

- **dynamical systems and unpredictability**
  - From limited knowledge or inherent in nature?
  - Mechanism
    - Chaos, measurement

- **self-organization, collective behavior, emergence**
  - Complex behavior from collectives of many simple units or agents
    - Cellular automata, dynamical networks, morphogenesis, swarms, brains, social systems
  - Mechanism
    - Parallelism, multiplicity, multi-solutions, redundancy

- **evolution**
  - Adaptation, learning, social evolution
  - Mechanism
    - Reproduction, transmission, variation, selection, Turing’s tape

- **Collective behavior** Behavior derived from many inseparable sources
  - Multi-level selection, swarm intelligence, immune system, anticipatory systems, brain-body-environment-culture, embodiment, epigenetics, culture
  - Mechanism
    - Network causality, odularity, control, hierarchy, connectivity, stigmergy, redundancy
Bio-inspired methodology for solving distributed problems
- biological examples
  - social insects
    - ants, termites, bees, wasps
  - swarming, flocking, herding behaviors in vertebrates.

Collective behavior algorithms
- Distributed or decentralized control
  - No central control or agent
- Local communication among agents
- Self-organization
  - Simple agents, complicated emergent behavior
- Robust
  - To individual loss
- Adaptive and Flexible
  - Capability to respond to perturbations

swarm intelligence
dumb agents, intelligent collective
Z-4195:
- Why'd I have to be born a worker? You soldiers get all the glory. Plus, you get to go out in the world. You know, you meet interesting insects; you get to kill them.

Weaver:
- Yeah, but you get to spend all day with those beautiful worker girls.

Z-4195:
- Weaver, they're CAREER girls. They're obsessed with digging.

Z-4195
- I'm supposed to do everything for the colony? What about my needs?
**stigma + ergon = mark + work**

**Process of communication by changing environment**
- Pheromone trails
- Nest Building
  - Termites use a simple rule:
    - Each agent scoops up a 'mudball' and covers it with pheromones
    - Others are attracted by pheromone and are therefore more likely to drop their own mudballs near their neighbors

**Introduced by Pierre-Paul Grassé in 1959**
- "Stimulation of workers by the performance they have achieved."
  - Regulation of behavior (and constructions) is dependent on the behavior of others and the environment they build
  - Worker is guided by work
- Used in optimization algorithms
- Stigmergy: Ant colony algorithms
- Flocking behavior: Particle Swarm Optimization
natural achievements

termite mounds
Aimless bots

- Very simple Agents that primarily wander around randomly
  - Mitchell Resnick

- Rules
  - **Wander** aimlessly until bumping into a wood chip (Random walk)
    - If carrying a wood chip, drop it and **wander**
    - Else, pick chip up and **wander**

Figure by Gary Flake in *The Computational Beauty of Nature*. 
Probabilistic cleaning

- Very simple rules for colony clean up
  - **Pick dead ant.** if a dead ant is found pick it up (with probability inversely proportional to the quantity of dead ants in vicinity) and wander.
  - **Drop dead ant.** If dead ants are found, drop ant (with probability proportional to the quantity of dead ants in vicinity) and wander.

**Real and Simulated Ants Clustering**


Figure by Marco Dorigo in *Real ants inspire ant algorithms*
ant-inspired robots

Clustering by collective or swarm robots

- Becker et al Rules
  - **Move**: with no sensor activated move in straight line
  - **Obstacle avoidance**: if obstacle is found, turn with a random angle to avoid it and **move**.
  - **Pick up and drop**: Robots can pick up a number of objects (up to 3)
    - If shovel contains 3 or more objects, sensor is activated and objects are dropped. Robot backs up, chooses new angle and **moves**.

- Results in clustering
  - The probability of dropping items increases with quantity of items in vicinity

Figure from R Beckers, OE Holland, and JL Deneubourg [1994]. “From local actions to global tasks: Stigmergy and collective robotics”. In *Artificial Life IV.*
becker et al experiments
Very simple rules for colony clean up

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ant clustering algorithm (ACA) for multivariate data

Group n-dimensional data samples in 2-dimensional grid

Data vector: $X_1$

$\begin{array}{cccccc} x_1 & x_2 & x_3 & \ldots & x_{n-1} & x_n \\ \hline \end{array}$

Data vector: $X_2$

$\begin{array}{cccccc} x_{2,1} & x_{2,2} & x_{2,3} & \ldots & x_{2,n-1} & x_{2,n} \\ \hline \end{array}$

Distance between two data samples (in original multivariate space):

$$D(x_i, x_j) = \sqrt{\sum_{k=1}^{n} (x_{i,k} - x_{j,k})^2}$$

e.g. Euclidean

Ants see data points in a certain neighborhood

$s^2$: area of neighborhood (side $s$, radius 1)
Clustering rules
- **Pick data sample**
  If there are few similar
- **Drop data sample**
  If there are many similar

Reduces dimensionality
No a priori number of clusters
Overshoots number of clusters

Probability of picking up
\[ P_p(x_i) = \left( \frac{k_1}{k_1 + f(x_i)} \right)^2 \]

Probability of dropping
\[ P_d(x_i) = \begin{cases} 
2f(x_i) & \text{if } f(x_i) < k_2 \\
1 & \text{otherwise} 
\end{cases} \]

Neighborhood Similarity or density measure
\[ f(x_i) = \begin{cases} 
\frac{1}{s^2} \sum_{x_j \in \text{Neigh}(x_i)} \left(1 - \frac{D(x_i, x_j)}{\alpha}\right) & \text{if } f > 0 \\
0 & \text{otherwise} 
\end{cases} \]

Improved with
Different moving speeds, Short-term memory, Behavioral switches
Cooling cycle for thresholds, progressive vision, pheromone reinforcement
1. Project high-dimensional data items onto 2-dimensional grid randomly
2. Distribute $N$ ants randomly on grid
3. repeat
   - For every ant $i$ in colony
     - Compute neighborhood density $f(x_i)$
     - If ant $i$ is unloaded and its cell is occupied with data item $x_i$ then pick up $x_i$ with probability $p_p(x_i)$
     - Else if ant $i$ is loaded with $x_i$ and its cell is empty drop $x_i$ with probability $p_d(x_i)$
     - Move randomly to neighbor cell with no ant
4. Until maximum iterations
Inspired by brood sorting

Same principle as Clustering
- **Pick data sample of type** $t$
  - If there are few of type $t$
- **Drop data sample of type** $t$
  - If there are many of type $t$

### Probability of picking up item of type $t$

$$p_p(x_i \mid t) = \left( \frac{k_1}{k_1 + f_t(x_i)} \right)^2$$

### Probability of dropping item of type $t$

$$p_d(x_i \mid t) = \left( \frac{f_t(x_i)}{k_2 + f_t(x_i)} \right)^2$$

### Neighborhood density of type $t$

$$f_t(x_i) = \begin{cases} 
\frac{1}{s^2} \sum_{x_j \in \text{Neigh}(s \times s)} \left( 1 - \frac{D(x_i, x_j)}{\alpha} \right) & \text{if } f > 0 \\
0 & \text{otherwise}
\end{cases}$$
based on ant algorithm


Bristol Robotics Laboratory.
Artificial ecosystems

- **Automata with diverse characteristics**
  - Bugs have an identity separate from the world
    - Bug: data structure and set of rules
    - World: Arena for information exchange plus set of rules

Figure by Rudy Rucker in *Artificial Life Lab.*
Artificial Bug Worlds

- Automata with diverse characteristics
  - Bugs have an identity separate from the world
    - Bug: data structure and set of rules
    - World: Arena for information exchange plus set of rules

- Typical bug implementation
  - ID#
  - Transition tables, rules of operations
  - Position in world
  - Fitness value
  - State (e.g. mood)
  - Velocity
    - Speed and direction
  - Group membership

Figures by Rudy Rucker in *Artificial Life Lab*.

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<tr>
<td>Change in Y</td>
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<td>2</td>
<td>2</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
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simple rules, complex behavior

- Boids by Craig Reynolds (1986)
  - 3 Steering behaviors
    - **Alignment**: move towards the average heading of local flockmates
      - Adjust velocity direction according to others in vicinity
    - **Separation**: steer to avoid crowding local flockmates
      - Maintain minimum distance to others (adjusting speed)
    - **Cohesion**: steer to move toward the average position of local flockmates
      - Adjust velocity direction according to others in vicinity
  - Each boid sees only flockmates within a certain small neighborhood around itself.
Flocking Behavior

simple rules, complex behavior

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Each boid sees only flockmates within a certain small neighborhood around itself.

http://www.red3d.com/cwr/boids/
Boid rules

Separation: maintain minimum distance adjusting speed

1. **Boids closer than cruising distance**
   - Desired cruising distance
   - Front boid speeds up
   - Rear boid slows down

2. **Boids farther than cruising distance**
   - Desired cruising distance
   - Front boid slows down
   - Rear boid speeds up

Figures by Rudy Rucker in *Artificial Life Lab.*

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic
Boid rules

**Velocity vector update**

1. \[ \text{TAN} \rightarrow \text{COPY VECTOR} \]
   - **Boid's nearest neighbor**

2. \[ \text{TAN} \rightarrow \text{CENTER VECTOR} \]
   - **Position of centroid**

3. \[ \text{SUM} = \text{TAN} + \text{COPY} + \text{CENTER} \]
   - **New TAN = unit vector in direction of sum**

**Alignment**: steer towards the average heading of local flockmates

**Cohesion**: steer to move toward the average position of local flockmates

Figure by Rudy Rucker in *Artificial Life Lab.*
Flocking Behavior

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Boids Used in Movies

classics

- Batman Returns
  - to simulate bats and penguins
- Cliffhanger
  - Simulation of bats
- Jurassic Park
  - Simulation of gallamunus herd
- The Lion King
  - Scene of wildbeast stampede
- Jumanji
  - Stampede of zoo animals
- Star Trek Voyager "Elogium"
  - Simulation a swarm of space creatures
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based on boids

Cybernetic Intelligence Research Group, University of Reading, England

Intelligent Autonomous Systems Laboratory.
University of the West of England.
readings

- **Class Book**
    - Chapter 7

- **Lecture notes**
  - Chapter 1: What is Life?
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