Natural Computing

An Introduction

http://natcomp.liacs.nl

Prof. dr. Thomas Bäck
Sample ...

http://www.youtube.com/watch?v=clgHEhziUxU&feature=related

http://www.traffic-simulation.de/
Introduction - Organizational

• Prof. dr. Thomas Bäck
  – Head of the Natural Computing Group
  – T.H.W.Baeck@liacs.leidenuniv.nl
  – Room 169
  – Cell: +49 177 329 5153

• Zhiwei Yang; Kaifeng Yang
  – z.yang@liacs.leidenuniv.nl; k.yang@liacs.leidenuniv.nl
  – Room 160

• Web page: http://natcomp.liacs.nl/NC
Introduction - Organizational

- Exam (70%)
- Practical Assignment (30%) in MATLAB - mandatory
- You can work in teams of 2!
- Practical exercises for fun – and graded
- Hoping to convince you that this is exciting stuff
- Very little math required
- ... but a lot of creativity, intuition, etc.
- Enter the discussion, go on the web, ...
Introduction - Assignment

• Test problem: TSP (traveling salesperson problem)
  – SA, GA to be implemented, by completing "code skeletons" provided
• Use template provided to report algorithm/results
  – See web page
• Deadline: Friday May 8th 2015, 5 pm
  – Every week late: 1.0 pts grade degradation
• Exam: Monday June 1st, 2015 14:00-17:00
Traveling Salesperson Problem

• Given a list of cities and their pairwise distances, the task is to find a shortest possible tour that visits each city exactly once.
• Based (here) on Euclidean distance metric.

\[ d(p, q) = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2}. \]

• tspplib contains very large problem instances.
• Most heavily researched NP-complete problem.

Optimal tour for Germany's 14 largest Cities. Note there are 43 589 145 600 possible tours (14!/2).
Introduction – Natural Computing

• Natural Computing:

1. Computing Inspired by Nature
   - Simulated Annealing
   - Evolutionary Computing
   - Neurocomputing
   - Swarm Intelligence
   - Immunocomputing

2. Simulation and Emulation of Nature
   - Fractals
   - Artificial Life

3. Computing with Natural Materials
   - Molecular Computing
   - Quantum Computing
Introduction – Natural Computing

Experimental Studies

Natural Materials

Empirical Observations

Natural Computing

New Forms of Synthesizing Nature

New Problem Solving Techniques

New Computing Paradigms

Theoretical Studies
When to use it? – Some Ideas

- Problem to be solved is complex
- Impossible to guarantee that a potential solution found is optimal
- Problem cannot be suitably modeled
- Single solution is not good enough
- Biological, physical, chemical systems and processes have to be simulated with realism
- Life behaviors and phenomena have to be synthesized in artificial media
- Limits of current technology are reached or new computing materials have to be sought
NACO Concepts

- **Model:** _Abstraction of real-world systems or implementation of a hypothesis in order to investigate particular questions or to demonstrate particular features of a system or a hypothesis._
  - Many details discarded
  - Simple enough to understand, but
  - Rich enough to provide (emergent) behaviors which are surprising, interesting, useful, significant.
NACO Concepts

• Model is more concerned with quantitatively reproducing some behavior
• Metaphor is usually a high level abstraction taken from a system in order to develop another
• Models can
  – Assist in prediction
  – Simulate behavior of natural systems
  – Aid in critical analysis of processes
  – Quantitatively describe the system
Simulation, Realization, Emulation

• **Simulation:** Metaphorical models that “stand for” something else.

• **Realization:** A literal, material model that implements certain functions of the original.

• **Emulation:** Imitation or reproduction of a system’s functions using another system or medium.

• NACO does all of this.
Concepts (I): Individuals, Entities, Agents

• Individual Entities, Components – *Agents.*
  – Anything between a subroutine and an intelligent organism
  – Some degree of autonomy/identity
  – Entity endowed with a (partial) representation of the environment, capable of acting upon itself and the environment, capable of communicating with other agents.
  – Biological, physical, virtual, ....
  – Give examples!
Agents

Robots

Boids

Agent based model

Social segregation

Epidemics
Concepts (II): Parallelism

• Parallel Processing
  – Insect societies, brain processing, immune functioning, evolution of species, ...
  – $10^{12}$ lymphocites in the immune system
  – $10^{11}$ nervous cells in the brain
Concepts (III): Interactivity

- Agents interact with each other!
  - Reproductively
  - Symbiotically
  - Competitively
  - Predator-prey
  - Parasitically
  - ...  
- Two main types: Connectivity vs. Stigmergy
Concepts (IV): Connectivity

- Nodes and connections encode information
- Connectionist systems:
  - Pathways of interaction between units
  - Connection quantifies degree of interaction
  - Structural organization in a network
Concepts (V): Stigmergy

- General mechanism that relates individual and colony-level behaviors
  - Individual behaviors modify environment
  - Environment modifies behavior of other individuals
  - Indirect communication
  - Example:
    - Termite workers stimulated to act during nest building according to configuration of construction of other workers.
Concepts (VI): Adaptation

- **Adaptation**: Ability of a system to adjust its response to stimuli depending upon the environment.
  - **Learning**: Level of Individuals
    - The act, process, or experience of gaining knowledge, comprehension, skill, mastery, through experience, study, interactions
    - Changing, with the end result of knowledge acquisition
    - Supervised, unsupervised, reinforcement
Concepts (VII): Adaptation

- **Adaptation**: Ability of a system to adjust its response to stimuli depending upon the environment.
  - Evolution: Level of Populations
    - Population, reproduction, variation, selection
Concepts (VIII): Feedback

- **Feedback**: Occurs when a response to a stimulus has an effect of some kind on the original stimulus
  - Positive: Response enhances original stimulus.

  ![Feedback Diagram]

  More termites ➔ More pheromone ➔ More termites

- Examples: Human breeding, avalanche, scratching an itch, ripening fruits, ...
Concepts (VIII): Feedback

- **Feedback**: Occurs when a response to a stimulus has an effect of some kind on the original stimulus
  - Negative: Response diminishes original stimulus.

Regulates positive feedback to maintain an equilibrium

- Examples: Ecosystems (predator-prey), metabolism, homeostasis, ...
Concepts (IX): Self-Organization

• Where does order come from?
  – Birds gathering, chemical reaction patterns, fish schools, cells making tissues, patterns, ...
  – Pattern: An organized arrangement of objects in space or time.
  – E.g., ants, termites, bees, ...
Self-Organization

Swarms showing coordinated behavior

Ants finding shortest paths
Self-Organization
Concepts (X): Self-Organization

- Characteristics:
  - Collectivity and interactivity
  - Dynamics in time
  - Emergent patterns
  - Nonlinearities
  - Complexity
  - Rule-based
  - Feedback loops
Concepts (XI): No Self-Organization

- Following a leader ...
- Building a blueprint
- Following a recipe
- Templates
Concepts (XII): Complexity

- Large number of interacting components
- Aggregate behavior is
  - Nonlinear
  - Exhibits self-organization
- Unable to understand behavior by examining its component parts alone
- Behavior of the whole is more than a sum of the individual behaviors
Concepts (XIII): Complexity

• Complex adaptive systems
  – Interaction
  – Diversity
  – Adaptivity

• Emergence: The properties of the whole are not possessed by or directly derivable from any of the parts.

• Bottom-up systems – behavior emergent from components.
Concepts (XIV): Determinism, Chaos, Fractals

• Deterministic system: time evolution predictable
• Chaos theory: Processes can be deterministic but unpredictable
  – Small changes in initial conditions
  – Major perturbations in long-term behavior
• Fractals: self-similarity.
Fractals

Self-similarity breaks down at some scale
Bionics

• Natural model → Engineering

Termite mound as a model for cooling in buildings (Harare).

Airplane wing structures
Bionics

Shark skin and airplane riplet foil

Architectural design
Overview of the Course

• Feb. 4: Introduction & Practical Assignment
• Feb. 11: MATLAB & Simulated Annealing
• Feb. 18: Nonlinear Dynamical Systems
• Feb. 25: Cellular Automata
• Mar. 4: Particle Swarm Optimization
• Mar. 18: Ant Colony Optimization
• Mar. 25: Evolutionary Computation
• Apr. 1: Fractal Geometry
• Apr. 8: Firefly Synchronization
• Apr. 15: Artificial Immune Systems
• Apr. 22: DNA Computing
• Apr. 29: Agent Based Systems
• May. 6: Reaction Diffusion Systems
  – May 8: Submission deadline PA
• May. 13: Reaction Diffusion Systems (cont’d)
Other Courses at LIACS

• Neural Networks – Dr. W.J.Kowalczyk
• Evolutionary Algorithms – TB
• Multicriteria Optimization and Decision Analysis – Dr. M.Emmerich
• Advances in Data Mining – Dr. W.J.Kowalczyk
• Quantum Computing – Dr. A.H.Deutz
• Seminar Swarm Based Computation – Hao Wang, TB
A Hierarchy

- Subatomic  Quantum Computing
- Atoms     Simulated Annealing
- Molecules Molecular Computing
- Individual Immunocomputing
- Individual Neural Networks
- Populations Evolutionary Computation
- Populations Swarm Computing
- Populations Artificial Life
Literature (not mandatory)

Leandro Nunes de Castro:
Fundamentals of Natural Computing
Chapman & Hall/CRC; 1 edition (June 2, 2006)

Marco Dorigo and Thomas Stützle:
Ant Colony Optimization
MIT Press (6 Jul 2004)
Homework

- Traffic simulation:
  - Assume there is a road with a single lane, a radar trap is installed on this road, and a number of cars are allowed to run on the road. Embody the following rules in each car:
    - If there is a car close ahead of you, slow down.
    - If there isn’t any car close ahead of you, speed up (unless you are at maximum speed).
    - If you detect a radar trap, slow down.
  - What types of emergent behavior would you expect from this system?
  - Can you implement this? (not mandatory)