Computing Systems

Lecture 12

Future Computing

Natural computing

- Take inspiration from nature for the development of novel problem-solving techniques. Include:
  - Artificial Neural Networks
  - Evolutionary Algorithms
  - Swarm Intelligence
  - Artificial Immune Systems
  - Artificial Life
  - Molecular Computing
  - Quantum Computing

Nature as Information Processing

- One can view processes occurring in nature as information processing.
- Understanding the universe itself from the point of view of information processing. The Zuse-Fredkin thesis, dating back to the 1960s, states that the entire universe is a huge cellular automaton which continuously updates its rules. Recently it has been suggested that the whole universe is a quantum computer that computes its own behaviour.

Nature-Inspired Models of Computation

- The most established "classical" nature-inspired models of computation are
  - cellular automata
  - neural computation
  - evolutionary computation

Nature-Inspired Models of Computation

- More recent computational systems abstracted from natural processes include
  - swarm intelligence
  - artificial immune systems
  - amorphous computing

Cellular Automata

- A cellular automaton is a dynamical system consisting of a two-dimensional grid of cells. Space and time are discrete and each of the cells can be in a finite number of states. The cellular automaton updates the states of its cells synchronously according to the transition rules given *a priori*. The next state of a cell is computed by a transition rule and it depends only on its current state and the states of its neighbours.

Cellular Automata

- Cellular automata have been applied to modelling a variety of phenomena such as communication, growth, reproduction, competition, evolution and other physical and biological processes.

Game of Life

- Probably the most widely discussed and investigated cellular automata is that known as the Game of Life which was developed by John Conway. The Game is played on a square draughts-like board (and so each cell has precisely 8 neighbours) with only three very simple rules:

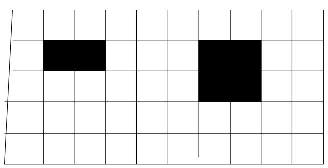
Game of Life

- A cell that is white becomes black at the next time if it has precisely three black neighbours.
- A cell that is black becomes white at the next time if it has four or more black neighbours.
- A cell that is black at one instant becomes white at the next if it has one or no black neighbours.
- All other cells retain their colour.

Game of Life

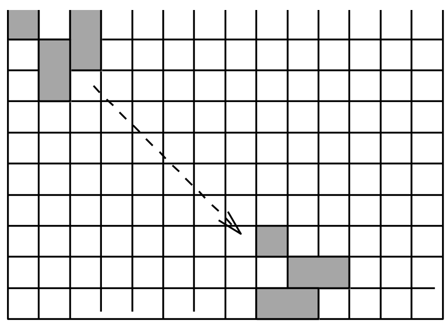
- Life is started with a small black object and the rest of the board white. Two very simple starting shapes are shown in next slide. These are of no great interest since the first immediately dies while the second reproduces itself without change for all time.

Game of Life

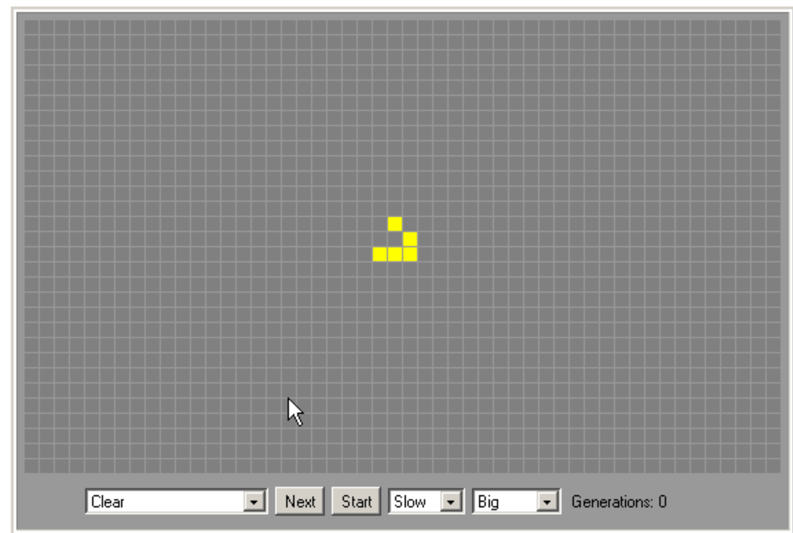


Immediate death

Everlasting life



A Glider



Game of Life

- More complicated (and more interesting) objects are possible, however, such as a “glider” which moves across the screen changing its shape in a regular manner. One particular glider is shown on the right of the diagram.

Logic Operations by CA

- Further we can create “glider-guns” which emit regular streams of gliders. Finally we can position our streams of gliders so that one knocks out the other. It is using objects such as these that we can prove that CA are capable of being thought of as computers.

Logic Operations by CA

- For example if we wish to represent the (binary) number 1100111, we could do so using

glider glider noglider noglider glider glider glider

where the nogliders have been removed from a stream of gliders by a collision with another stream.

Logic Operations by CA

- By positioning glider-guns in the appropriate positions, we can perform any logic operation.

Neural Computation

- Neural computation is the field of research that emerged from the comparison between computing machines and the human nervous system. This field aims both to understand how the brain of living organisms works (brain theory or computational neuroscience), and to design efficient algorithms based on the principles of how the human brain processes information (Artificial Neural Networks, ANN).

Evolutionary Computation

- Evolutionary computation is a computational paradigm inspired by Darwinian evolution. An artificial evolutionary system is a computational system based on the notion of simulated evolution.
- Evolution strategies
- Evolution strategies
- Genetic algorithms

Swarm Intelligence

- Swarm intelligence, sometimes referred to as collective intelligence, is defined as the problem solving behaviour that emerges from the interaction of individual agents (e.g., bacteria, ants, termites, bees, spiders, fish, birds) which communicate with other agents by acting on their local environments.
- Particle swarm optimization
- Ant algorithms

Complex Systems

- It becomes apparent that most of the complex systems share a common "swarm-like" architecture. The essential characteristic of this kind of system is a non-centralized collection of relatively autonomous entities interacting with each other and a dynamic environment.

Complex Systems

- Typically, there is no central authority dictating the behaviour of the collection of individuals: each of the many individuals making up the “swarm” makes its own behavioural choices on the basis of its own sampling and evaluation of the world, its own internal state, and through communication with other individuals.

Swarm

We use the term “swarm” in a general sense to refer to any such loosely structured collection of interacting agents. The classic example of a swarm is a swarm of bees, but the metaphor of a swarm can be extended to other systems with a similar architecture.

Swarm

An ant colony can be thought of as a swarm whose individual agents are ants, a flock of birds is a swarm whose agents are birds, traffic is a swarm of cars, a crowd is a swarm of people, an immune system is a swarm of cells and molecules, and an economy is a swarm of economic agents.

Individual → Group

- What makes swarms scientifically interesting, and often mathematically intractable, is the coupling between the individual and the group behaviours.

Simplicity → Complexity

- Although the individuals are usually relatively simple, their collective behaviour can be quite complex. Swarms allow us to focus directly on the fundamental roots of complexity: they capture the point at which simplicity becomes complexity.

Swarm Emergent Behaviour

The behaviour of a swarm as a whole emerges in a highly nonlinear manner from the behaviours of the individuals. This emergence involves a critical feedback loop between the behaviour of the individuals and the behaviour of the whole collection. In a swarm, the combination of individual behaviours determines the collective behaviour of the whole group.

Swarm Emergent Behaviour

- In turn, the behaviour of the whole group determines the conditions (spatial and temporal patterns of information) within which each individual makes its behavioural choices. These individual choices again collectively determine the overall group behaviour, and on and on, in a never-ending loop.

Emergent Behaviour

This is a behaviour exhibited by a system consisting of a large number of simple and similar (or identical) components, which is surprisingly complex given the simplicity of the individual components of the system. The essential characteristic of this kind of system is a non-centralized collection of relatively autonomous entities interacting with each other and a dynamic environment.

Ant colony optimization

- Wander randomly.
- Search for food.
- Lay down pheromone.
- Follow pheromone.
- Pheromone trail evaporates.
- Longer paths less likely to survive.
- Positive feedback.

Artificial Immune Systems

- Artificial immune systems are computational systems inspired by the natural immune systems of biological organisms.
- Viewed as an information processing system, the natural immune system of organisms performs many complex tasks in parallel and distributed computing fashion.

Amorphous Computing

- In biological organisms, morphogenesis (the development of well-defined shapes and functional structures) is achieved by the interactions between cells guided by the genetic program encoded in the organism's DNA.

Amorphous Computing

- Inspired by this idea, amorphous computing aims at engineering well-defined shapes and patterns, or coherent computational behaviours, from the local interactions of a multitude of simple unreliable, irregularly placed, asynchronous, identically programmed computing elements (particles).

Artificial Life

- Artificial life (ALife) is a research field whose ultimate goal is to understand the essential properties of life organisms by building, within electronic computers or other artificial media, *ab initio* systems that exhibit properties normally associated only with living organisms. Early examples include Lindenmayer systems (L-systems), that have been used to model plant growth and development.

Artificial Life

- Pioneering experiments in artificial life included the design of evolving "virtual block creatures" acting in simulated environments with realistic features such as kinetics, dynamics, gravity, collision, and friction.[These artificial creatures were selected for their abilities endowed to swim, or walk, or jump, and they competed for a common limited resource (controlling a cube).

Artificial Life

- The simulation resulted in the evolution of creatures exhibiting surprising behaviour: some developed hands to grab the cube, others developed legs to move towards the cube. This computational approach was further combined with rapid manufacturing technology to actually build the physical robots that virtually evolved.

Molecular Computing

- Molecular computing (a.k.a. biomolecular computing, biocomputing, biochemical computing, DNA computing) is a computational paradigm in which data is encoded as biomolecules such as DNA strands, and molecular biology tools act on the data to perform various operations (e.g., arithmetic or logical operations).

Quantum Computing

- A quantum computer[processes data stored as quantum bits (qubits), and uses quantum mechanical phenomena such as superposition and entanglement to perform computations. A qubit can hold a "0", a "1", or a quantum superposition of these. A quantum computer operates on qubits with quantum logic gates.

Quantum Computing

- Quantum cryptography

  A successful open air experiment in quantum cryptography was reported in 2007, where data was transmitted securely over a distance of 144 km.

- Quantum teleportation is another promising application, in which a quantum state (not matter or energy) is transferred to an arbitrary distant location.