Artificial Life: Introduction

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Outline

What is Artificial Life?

- Study of man-made systems that exhibit behaviors characteristic of natural living systems
- Investigating the essence of life and the ability to construct life or life-like systems
- Investigation of biological/natural occurring systems
- Attempts to develop life-like behaviors within computers

Core Principle

Creating complex behaviors and properties from simple rules and interactions

Interdisciplinary Nature of Artificial Life

- Connections with many existing fields:
  - Physics
  - Artificial Intelligence
  - Computer Science
  - Social Science
  - Philosophy
  - Psychology
- Has been explored as a means to understand the emergence of:
  - Language
  - Order
  - Culture - norms, artefacts
  - Social structures
  - .....

Applications and Approaches

Modeling Approaches:

- Simulation
- Robotics
- Virtual environments

Key Areas of Study:

- Emergence
- Self-organization
- Adaptation
- Evolution
- Collective behavior

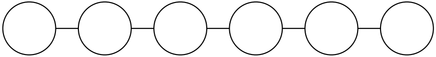
Many models of creatures and animals have been built in robotics and in simulation which allows exploration of issues of cooperation and competition in these 'species'

Cellular Automata: Introduction

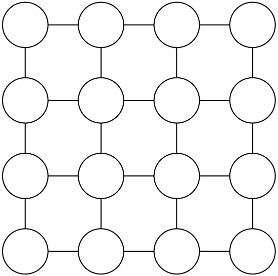
- A Cellular Automaton (CA) is a model of a parallel computer
- Consists of processors (cells), connected usually in an n-dimensional grid
- Characterized by:
  - Very simple rules
  - Potentially very complex emergent behaviors
- Very simple rules govern interactions between neighboring cells but give rise to recognizable groups of patterns
  - Static, dynamic, mobile, cyclic patterns

Types of Cellular Automata

1-D Cellular Automata:



2-D Cellular Automata:



John von Neumann's Universal Constructor

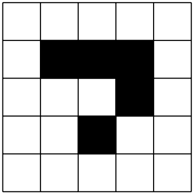
- Developed in the 1940s
- A self-replicating machine existing in a cellular automata environment
- Von Neumann aimed to specify an abstract machine which when run, would replicate itself
- Original experiment created to see if a simple rule system could create a "universal computer"
- Universal Computer (Turing): a machine capable of emulating any kind of information processing through a simple rule system

Significance

First theoretical demonstration that self-reproduction based on logical rules was possible

Conway's Game of Life

- A simple mathematical game where patterns unfold according to a set of rules
- A form of cellular automata
- Rectangular grid of "living" (on) and "dead" (off) cells
- Complex patterns result from simple structures



Example: Glider pattern

Game of Life: Rules

Three simple rules govern the Game of Life:

1. A live cell dies if it has fewer than 2 live neighbors (loneliness)
2. A live cell dies if it has more than 3 live neighbors (overcrowding)
3. A dead cell becomes alive if it has exactly 3 live neighbors (reproduction)

The Emergent Complexity

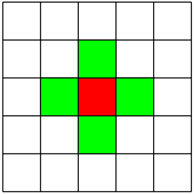
From these simple rules emerge stable structures, oscillators, gliders, and even computational elements!

Which patterns lead to stability? To chaos?

Cellular Automata: Neighborhoods

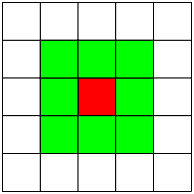
Different neighborhoods possible:

Von Neumann Neighborhood:



4 adjacent cells (N, E, S, W)

Moore Neighborhood:



8 adjacent cells (including diagonals)

Computational Properties of Cellular Automata

- Many open questions:
  - What kind of patterns will emerge given a certain starting pattern?
  - Update rules and their effect?
  - Can CA be used to perform computation?
- Stephen Wolfram's classifications:
  - Class 1: Evolution leads to a stable homogeneous state
  - Class 2: Evolution leads to simple stable or periodic structures
  - Class 3: Evolution leads to chaotic patterns
  - Class 4: Evolution leads to complex structures with long transients

Parallels in other domains - Evolutionary Game Theory, Multi Agent Systems

- Similar emergent properties witnessed in evolutionary spatial game theory
- Similarly, witnessed in models and simulations of multi-agent systems

Ant Colony Optimisation: Introduction

- Ant colonies:
  - Distributed systems of social insects
  - Consist of simple individuals with limited 'processing' capabilities
  - Intelligence of the colony is far greater than the intelligence of the individuals
  - Emergent intelligence through simple local interactions

- Have been studied in detail; exhibit lots of properties desirable in computational systems:
  - Responsive to changes in environment
  - Robust solutions
  - Task decomposition and allocation

Ant Colony Behavior: Task Allocation

- Complex tasks are broken down into simpler subtasks:
  - Leaf cutting
  - Transportation
  - Transformation to pulp and pellets
  - Planting fungi into pellets
  - Tending to pellets
- Several million ants per colony working collectively
- Tasks are assigned based on local conditions and the needs of the colony
- Individual ants can switch roles as needed

Emergent Organization

Without central control, ants self-organize into efficient work groups

Self-Organisation

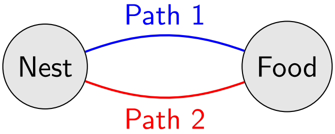
- Set of dynamical mechanisms whereby structure appears at the global level as the result of interactions among lower-level components.
- The rules specifying the interactions among the constituent units of the system are executed based on purely local information

Self-Organisation: Four basic ingredients

- Multiple interactions
- Randomness
- Positive feedback
- Negative feedback

Indirect Communication in Ant Colonies

- Stigmergy: coordination through environment modification
- Pheromone trails:
  - Ants deposit pheromones as they travel
  - Strength of trail indicates desirability
  - Trails evaporate over time (negative feedback)
  - Double bridge experiments (Deneubourg):
    - When presented with two paths, ants collectively select the shorter one
    - Demonstrates collective problem-solving capability



- Indirect communication mediated by modifications of environmental states which are only locally accessible by the communicating agents (Dorigo et al)
- Features of artificial stigmergy:
    - Indirect communication
    - Local accessibility
- Ant algorithms are multi-agent systems that exploit artificial stigmergy as a means for coordinating artificial ants for the solution of computational problems

- Shortest path
- Network routing
- Task allocation of labour
- Robot and coordination
- Graph partitioning

Ant Colony Optimisation: The Algorithm

Mapping idea to a search algorithm:

- Originally applied to the Traveling Salesman Problem (TSP)
- Can be applied to a range of optimisation problems
- Algorithm overview:
  - Ants perform a random walk (initially) on the graph
  - As they walk they leave a pheromone trail
  - Can include domain knowledge/heuristics on edges
  - Place ants on cities randomly
  - Choose paths (initially randomly)
  - Update pheromone level as function of solution quality
- Many extensions and variants

Ant Colony Optimisation: Formula

The probability of ant k at node i choosing to move to node j is:

$$p_{ij}^k = \begin{cases} \frac{[\tau_{ij}]^\alpha \cdot [\eta_{ij}]^\beta}{\sum_{l \in N_i^k} [\tau_{il}]^\alpha \cdot [\eta_{il}]^\beta} & \text{if } j \in N_i^k \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

Where:

- τ_{ij} is the pheromone intensity on edge (i, j)
- η_{ij} is the heuristic information (typically $\eta_{ij} = 1/d_{ij}$ where d_{ij} is the distance)
- α and β are parameters controlling the relative importance of pheromone versus heuristic
- N_i^k is the set of feasible nodes for ant k when at node i

Pheromone Trail

- The pheromone intensity influences which edges are followed.
- The value τ_{ij} on edge (i, j) is updated periodically.
- The value is updated by two factors: evaporation and re-inforcement

Swarm Intelligence in Other Species

Similar phenomena identified in other species:

- Termites:
  - Complex nest building behavior
  - Temperature and humidity regulation
- Honeybees:
  - Nest location identification and decision-making
  - Several scouts explore and decisions are made through communication
  - Waggle dance for communicating food sources
- Bird flocking and fish schooling:
  - Simple rules: separation, alignment, cohesion
  - Creates complex, coordinated movement patterns

Digital Evolution Systems

- Avida: Digital platform for studying evolution
  - Digital organisms compete for resources
  - Mutations affect their ability to process information
  - Natural selection emerges without being explicitly programmed
- Tierra: Created by Thomas Ray
  - Self-replicating computer programs
  - Programs evolve, compete for CPU time
  - Parasites, immunity, and other biological phenomena emerge
- Polyworld: Artificial ecosystem with 3D physics
  - Organisms with neural networks as brains
  - Evolution of complex behaviors and strategies

Summary

- Artificial Life attempts to simulate and understand aspects of living systems
- Typified by:
    - Decentralized computation
    - Simple local interactions
    - Emergent phenomena
- Cellular Automata is just one example
- Other examples include ant colony optimisation and swarm intelligence
- Several ideas from Alife have inspired approaches in AI

Recent Advances and Future Directions

Recent Advances:

- Synthetic biology creating novel organisms
- Open-ended evolution in computational systems
- Integration with deep learning approaches

Future Directions:

- Creating truly open-ended evolving systems