Nature Inspired Computing

K.Dimopoulos

Asking the big questions

Science is defined as: *"The systematic study of the natural world and its physical and biological processes, through observation, identification, description, experimental investigation, and theoretical explanations."*

- Oxford Dictionary

Science aims to produce more and more accurate natural explanations of how the natural world works, what its components are, and how the world got to be the way it is now.

This includes the big questions:

- Why are we here?
- What is the meaning of life?
- What is life?
- What is intelligence?
- Are we alone in the universe?

and the always important question

- What is the airspeed velocity of an unladen swallow?

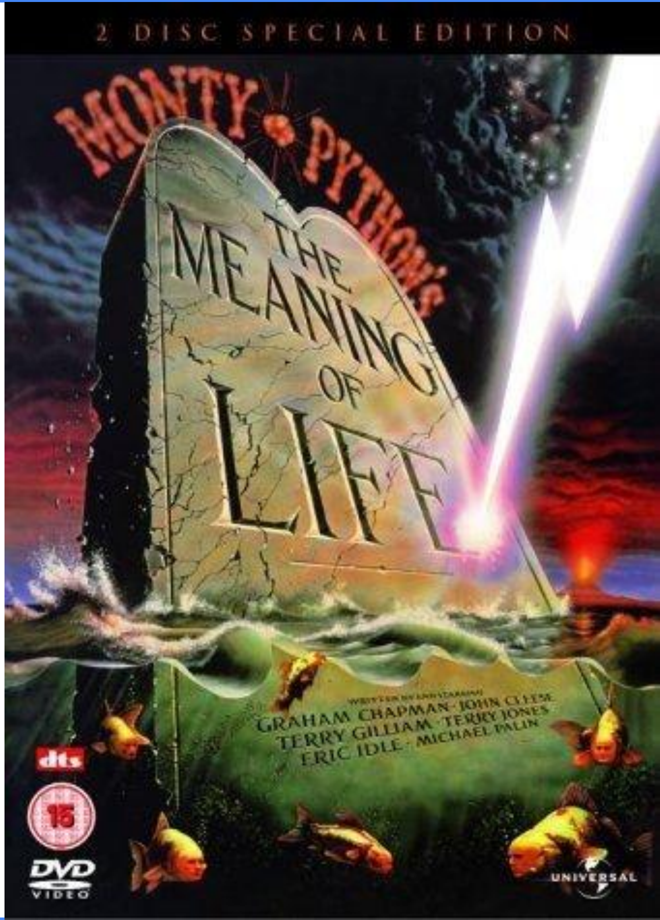
What is Life?

Like all big questions there is **no unique or universal definition**. According to Britannica:

"life, living matter and, as such, matter that shows certain attributes that include responsiveness, growth, metabolism, energy transformation, and reproduction."

According to Oxford dictionary:

"the ability to breathe, grow, produce young, etc. that people, animals and plants have before they die and that objects do not have"



What is Nature Inspired Computing (NIC)?

Nature-inspired computing (NIC) refers to a class of meta-heuristic algorithms that imitate or are inspired by some natural phenomena explained by natural sciences.

- Nazmul Siddique, Hojjat Adeli : Nature Inspired Computing: An Overview and Some Future Directions, 2015

It consists in the use of methods inspired by nature to solve problems in a computer. The inspiration is mainly taken from natural biological information processing systems, such as chemical processes, cooperation between beings and so on.

A main field of research related to NIC is Artificial Life

What do all living things share

- **Growth and development** - ability to change with time by growing and increasing complexity
- **Reproduction** - ability to create offspring that inherit (some of) the parent characteristics
- **Metabolism** - ability to assimilate energy and convert it to its needs
- **Homeostasis** - ability to maintain a stable internal environment despite changes in the environment
- **Adaptation** - ability to change in response to changes in the environment for your benefit
- **Response to stimuli**
- **(Cellular) structure**

Are all these properties required for something to be considered alive?

Edge cases in Biology

- Viruses:
  - Can reproduce and evolve but require a host to do so
  - Lack cellular structure and independent metabolism
  - Example: Influenza virus adapting to new hosts
- Crystals:
  - Exhibit growth and replication of patterns but lack metabolism or evolutionary adaptation
  - Example: Salt crystals forming naturally in evaporating water
- Bacteria:
  - Simplest forms of life capable of growth, reproduction, and metabolism
  - Example: Escherichia coli (E. coli) as a model organism in biology
- Other Examples:
  - Prions: Infectious proteins that cause diseases like mad cow disease, but lack genetic material
  - Protozoa: Single-celled organisms with complex behaviors despite their simplicity

What is Artificial Life?

Again from Britannica:

"Artificial Life (ALife for short), [is a] computer simulation of life, often used to study essential properties of living systems (such as evolution and adaptive behaviour)."

It is organised under computational optimisation and modelling.

"Artificial Life … investigates the scientific, engineering, philosophical, and social issues involved in our rapidly increasing technological ability to synthesize life-like behaviors from scratch in computers, machines, molecules, and other alternative media."

-Artificial Life – Journal MIT press

Types of ALife

Alife can be distinguished into three types:

- **Soft ALife:** Simulated systems (e.g., cellular automata, genetic algorithms)
- **Hard ALife:** Physical robots with life-like behavior (e.g., swarm robotics)
- **Wet ALife:** Synthetic biology mimicking life using chemical processes

A comparison

Biological Life	**Artificial Life (ALife)**
Carbon-based	Digital, robotic, or synthetic
Slow evolutionary processes	Rapid, simulated evolution
Genetics-driven	Algorithm-driven
Limited by biology	Limited by computational resources

How does ALife relate to AI?

Artificial Life (ALife) and Artificial Intelligence (AI) are closely related fields, but they focus on different aspects of simulating life and intelligence. Here’s how they connect:

- Shared Goal of Simulation: Both ALife and AI aim to replicate aspects of natural systems—ALife focuses on life-like behaviors, while AI focuses on intelligent behaviors.
- Overlapping Techniques: They often use similar computational methods, like neural networks, genetic algorithms, and machine learning, to simulate adaptation, problem-solving, and evolution.
- Mutual Inspiration: ALife models, such as swarm intelligence (inspired by ant colonies or bird flocks), have influenced AI approaches like optimization algorithms and robotics. Meanwhile, AI techniques help ALife systems improve their adaptability and complexity.
- Differences in Focus: While AI aims to mimic human-like thinking and decision-making, ALife explores how life-like properties (like self-replication, adaptation, and evolution) emerge from simple rules.

In essence, ALife helps AI by providing models of decentralized, adaptive behavior, while AI helps ALife by enhancing learning and decision-making within artificial ecosystems.

Why is it worth studying ALife

1. Studying ALife helps understand emergent behavior and self-organization
2. ALife provides models for AI systems that are resilient, decentralized, and adaptive
    - Example: Using evolutionary algorithms to optimize neural networks
3. It is fun playing God!

How can principles from ALife improve AI applications in robotics, machine learning, and problem-solving?

History of ALife

The prophets

From **Heron of Alexandria** who created life-like moving automata using pneumatics. mechanics and hydraulics, to the middle ages **Al-Jazari** humanoid automata, to the renaissance automata: the Bell-ringing Death in Prague's astronomical clock, to **Mary Shelley's** Frankenstein written in 1818, humanity had always a fascination about living machines.

In 1816, Mary Shelley on a bet with lord Byron that she could tell the scariest story, came up with the idea of a doctor Frankenstein, who was obsessed with death and how to create life.



The visionaries

John Von Neumann (the father of AI) in the late 40s defined an "automaton" as any machine whose behavior proceeded logically from step to step by combining information from the environment and its own programming.

He also spoke about the idea of **self-replicating machines**. He postulated a made-up of a control computer, a construction arm, and a long series of instructions, floating in a lake of parts, capable of creating an identical machine. He followed this idea by creating (with **Stanislaw Ulam**) a purely logic-based automaton, not requiring a physical body but based on the changing states of the cells in an infinite grid – the first cellular automaton.

Homer Jacobson illustrated basic self-replication in the 1950s with a model train set – a seed "organism" consisting of a "head" and "tail" boxcar could use the simple rules of the system to consistently create new "organisms" identical to itself, so long as there was a random pool of new boxcars to draw from.

John Horton Conway invented the most famous cellular automaton in the 1960s. He called it the Game of Life, and publicized it through Martin Gardner's column in Scientific American magazine.

Freeman Dyson also studied the idea, envisioning self-replicating machines sent to explore and exploit other planets and moons, and a NASA group called the Self-Replicating Systems Concept Team performed a 1980 study on the feasibility of a self-building lunar factory.

The pioneers

John Holland published the book "Adaptation in Natural and Artificial Systems" in 1975. His work originated with studies of cellular automata, conducted by Holland and his students at the University of Michigan. Holland introduced a formalized framework for predicting the quality of the next generation, known as Holland's Schema Theorem. Research in GAs remained largely theoretical until the mid-1980s, when The First International Conference on Genetic Algorithms was held in Pittsburgh, Pennsylvania.

Christopher Langton was an unconventional researcher, with an undistinguished academic career that led him to a job programming DEC mainframes for a hospital. He became enthralled by Conway's Game of Life, and began pursuing the idea that the computer could emulate living creatures. After years of study he succeeded in creating the first self-replicating computer organism in October 1979, using only an Apple II desktop computer. He entered Burks' graduate program at the Logic of Computers Group in 1982, at the age of 33, and helped to found a new discipline.

The practitioners

In 1982, **Stephen Wolfram** explored and categorized the types of complexity displayed by one-dimensional CAs, and showed how they applied to natural phenomena such as the patterns of seashells and the nature of plant growth.

Craig Reynolds similarly used three simple rules to create recognizable flocking behaviour in a computer program in 1987 to animate groups of boids. With no top-down programming at all, the boids produced lifelike solutions to avoiding obstacles placed in their path. Computer animation has continued to be a key commercial driver of alife research as the creators of movies attempt to find more realistic and inexpensive ways to animate natural forms such as plant life, animal movement, hair growth, and complicated organic textures.

In 1994, **Karl Sims** while looking for a case study to demonstrate the abilities of a new supercomputer at MIT developed simulations of 3D virtual creatures that evolved to walk, swim, compete for resources in a virtual environment

Also in 1994, **Larry Yaeger** published Polyworld a computational ecology developed to explore issues in Artificial Life. Simulated organisms reproduce sexually, fight and kill and eat each other, eat the food that grows throughout the world, and either develop successful strategies for survival or die. An organism's entire behavioral suite (move, turn, attack, eat, mate, light) is controlled by its neural network "brain".

Module details

Topics we will cover

We will learn about:

1. Simulations of physical systems
2. Particle Life
3. Primordial Particle Systems
4. Cellular Automata, Fractals
5. Intelligent Agents
6. Genetics Algorithms, and
7. Evolving Neural network structures

We need to get to grips with concepts from :

1. Some simple **Maths**
   a. Vectors
   b. Simple trigonometry
2. Some simple **Physics**
   a. Newton's laws
   b. motion
3. A bit of **Biology**

Format of the unit

- Contact hours:
  - Weeks 1 to 8 : lectures, covering the main theoretical aspects of ALife
  - Weeks 2 to 8: labs, practicing and demonstrating the main concepts
  - Week 9: Coursework Demonstrations
- Assessment:
  - 100% coursework: Group project (of 3-4) developing your own simulated ALife system
- Resources:
  - Book: Daniel Shiffman, **The nature of code**, https://natureofcode.com/book/introduction/ [online]