Natural Computing

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INTRODUCTION

There are several artifacts developed by taking inspiration from natural organisms and phenomena. For instance, Velcro was inspired by a plant burr, bullet- proof vests were inspired by spider silk, sonars were inspired by bats, airplanes were motivated by the flying of birds, and the list goes on. The observation of nature has also allowed the development of several laws and theories that describe how parts of nature work; the laws of physics are a great example – laws of thermodynamics (conservation, entropy, and absolute zero); laws of movement (Newton's laws); laws of electromagnetism (Maxwell's laws); and others. They are used to explain the trajectories, attraction and other aspects of objects.

With the advent of computing, the way humans interact with nature changed dramatically. Nowadays, we not only observe, explain and use nature as an environment for living and providing us with food, we also use nature as a source of inspiration for the development of new technologies – new computing approaches, and we use computers to simulate and/or emulate natural phenomena as well. This scenario has changed even more remarkably over the last decade when researchers realized that it is actually possible to use natural mechanisms and means as a brand new computing paradigm, which is distinct from the well-known *in silico* computation. We are in the beginning of a new age: the natural computing age!

Background

Originally, the terminology *natural computing* was used to describe only those systems that employed natural means, such as DNA or RNA strands, to perform computation. Nowadays, the terminology has broadened to encompass three major areas: *computing inspired, or motivated, by nature*; 2) *the study of natural phenomena by means of computation;* and 3) *computing with natural means*. These three branches of natural computing have one aspect in common: a strong and computer-based or computer-oriented relationship with nature. This brief overview provides a taxonomy for natural computing based on these three sub-branches and lists the most important and well-known methods of each part.

COMPUTING INSPIRED BY NATURE

The first branch of natural computing is also the oldest one. With the discovery of many principles and theories about nature and the development of its several (theoretical) models, researchers from other areas realized that these could be useful as sources of inspiration for the development of computational systems for problem solving. In particular, computer scientists, engineers and others found many works on theoretical biology that could be used for the development of novel computing approaches. Computing inspired by nature has many subareas: 1) *artificial neural networks;* 2) *evolutionary algorithms;* 3) *swarm intelligence;* 4) *artificial immune systems;* and 5) others (models based on *growth, development, culture, etc*.).

A landmark work in the branch of biologically inspired computing was the paper by McCulloch and Pitts (1943), which introduced the first mathematical model of a neuron. This neuronal model, also known as artificial neuron, gave rise to a field of investigation of its own, the so-called artificial neural networks (Bishop, 1996; Fausett, 1994; Haykin, 1999; Kohonen, 2000).

Another computing approach motivated by biology arose in the mid 1960s with the works of I. Rechenberg (1973), Schwefel (1965), Fogel (Fogel et al., 1966), and Holland (1975). These works gave rise to the field of evolutionary computation (Bäck et al., 2000a, b; Bahnzaf & Reeves, 1998; Beyer, 2001; Fogel, 1998; Goldberg, 1989; Koza, 1992; Michalewicz, 1996; Mitchell, 1998), which uses ideas from evolutionary biology to develop (evolutionary) algorithms for search and optimization.

Swarm intelligence has two main frontlines: algorithms based on the collective behavior of social insects (Bonabeau et al., 1999), and algorithms based on sociocognition (Kennedy et al., 2001). In the first case, the collective behavior of ants and other insects has led to the development of algorithms for solving combinatorial optimization and clustering problems, among others. Algorithms based on sociocognition demonstrated effectiveness in performing search on continuous spaces.

Artificial immune systems borrow ideas from the immune system and its corresponding models to design computational systems for solving complex problems (Dasgupta, 1999; de Castro & Timmis, 2002; Timmis et al., 2003). This is also a young field of research that emerged around the mid 1980s. Its application areas range from biology to robotics. The other emerging types of algorithms inspired by nature are the cultural algorithms, the simulated annealing algorithm, the systems based on growth and development, the cells and tissues models, and various others (Aarts & Korst, 1989; Kochenberger & Glover, 2003; Kumar & Bentley, 2003; Paton, 1994; Paton et al., 2003).

STUDY OF NATURAL PHENOMENA BY MEANS OF COMPUTING

Differently from computing inspired by nature, studying natural phenomena by means of computing is a synthetic approach aimed at creating patterns, forms, behaviors, and organisms that do not necessarily resemble "life-as-we-know-it". It can result in completely new phenomena never observed in nature, but that possess enough features to be qualified as "natural" or "living". For example, artificial organisms can be created that do not bear any resemblance whatsoever to any known living being on Earth. The idea is to use computers to simulate and emulate natural phenomena in a non-deterministic fashion. The study of nature by means of computing has two main branches: 1) *artificial life* (ALife); and 2) the *computational, or fractal, geometry of nature*.

As put by C. Langton in his pioneering chapter on ALife:

"Artificial Life is the study of man-made systems that exhibit behaviors characteristic of natural living systems. It complements the traditional biological sciences concerned with the analysis *of living organisms by attempting to* synthesize *life-like behaviors within computers and other artificial media. By extending the empirical foundation upon which biology is based* beyond *the carbon-chain life that has evolved on Earth, Artificial life can contribute to theoretical biology by locating* life-as-we-know-it *within the larger picture of* life-as-it-could-be.*" (Langton, 1988, p. 1)*

In summary, ALife can be defined as the synthetic or virtual approach to the study of life-like patterns (forms), behaviors, systems, and organisms (Adami, 1998; Levy, 1992).

The computational visualization of (mathematical) models of natural structures and processes results in images, animations, and interactive systems useful as scientific, research and educational tools in computer science, engineering, biosciences and many other domains. This is the core of the computational geometry of nature: how to visualize models of natural phenomena. There are several techniques that can be used with this purpose, for example, cellular automata (Ilachinski, 2001; Wolfram, 1994), particle systems (Reeves, 1983), Lindenmayer systems (Lindenmayer, 1968), iterated function systems (Barnsley, 1988; Barnsley & Demko, 1985; Hutchinson, 1981), Brownian motion (Fournier et al., 1982; Voss, 1985), and so forth.

The applications of this branch of natural computing include computer-assisted landscape architecture, design of new varieties of plants, crop yield prediction, the study of developmental and growth processes, and the modeling and synthesis (and the corresponding analysis) of an innumerable amount of natural patterns and phenomena (Flake, 2000; Mandelbrot, 1983; Peitgen et al., 1992).

COMPUTING WITH NATURAL MEANS

In 1965, G. Moore observed that there is an exponential growth in the number of transistors that can be placed in an integrated circuit. According to the "Moore's law," there is a doubling of transistors in a chip every couple of years. If this scale remains valid, by the end of this decade silicon-based computers will have reached their limits in terms of processing power. One question that remains, thus, is what kind of medium, rather than silicon, can provide an alternative for the design and implementation of a computing device?

The last decade has seen the proposal and development of several of these alternative means of computing and their corresponding computing techniques. These approaches are mostly of two types: 1) the ones based on biomolecules, and 2) the ones based on quantum bits. The approaches that use biological molecules, such as DNA and RNA strands, or membranes for computing, are usually called *molecular computing* (Calude & Pâun, 2001; Gramß et al., 2001; Pâun et al., 1998; Pâun & Cutkosky, 2002; Sienko et al., 2003). By contrast, the approaches based on quantum bits constitute what is known as *quantum computing* or *quantum computation* (Hirvensalo, 2000; Nielsen & Chuang, 2000; Pittenger, 2000).

In the first case, biomolecules are used as means to store information and techniques from molecular (genetic) and chemical engineering are used to manipulate these molecules so as to process information. Note that this approach relies on the sophistication and efficiency of the genetic engineering techniques. Quantum computing, on the other hand, stores information in quantum bits and the evolution of the "quantum computer" follows the principles of quantum mechanics.