Biological Traits in Artificial Self-Reproducing Systems

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ABSTRACT

This article presents an artificial taxonomy of 2-D, self-replicating cellular automata (CA) that can be considered as proto-organisms for structure replication. The authors found that the process of self-reproduction is a widespread mechanism. In fact, self-reproducers in 2-D CA are very common and the authors discovered almost 10 methods of self-replication. The structures these systems produce, from ordered to complex ones, are very similar to those found in biological endeavor. After examining self-replicating structures and the way they reproduce, the authors consider their behavior in relation to the patterns they realize and to the function they manifest in realizing artificial organisms. According to the authors, many methods produced by CA are based on universal models of biological cell development. The relevance of such work consists in the goal of modeling the evolution of living systems that can lead us to a better understanding of the essential properties of life.

Keywords: Artificial Taxonomy, Behavior, Biological Cell Development, Cellular Automata (CA), Self-Replication, Self-Reproduction

INTRODUCTION

What is the evolutionary process that has brought about the generation of self-reproducing systems and how do such configurations form and unite, giving life to more complicated organisms through a process of self-reproduction? What are the fundamental mechanisms that bring about the creation of self-reproducers? And what are the internal mechanisms that make self-reproducers create some forms rather than others? How have the tails of tigers been formed, or the wings of a butterfly, or even the cellular structures that cover our bodies, the epithelium (Groves, Wilson, & Reeder, 2005)? What are the functional motives in evolution that have created self-reproducers, or rather structures capable of replicating themselves with a purpose or even without one, to follow other specific objectives of the system or environment in which such organisms are found? In other words, what is the function of self-reproduction and how can such a function be reproduced in the digital machines now in our possession?
Almost all the applications that deal with the simulation and synthesis of living systems are related to the influential work of John von Neumann (1966), who proposed a machine capable of reproducing itself: the universal constructor. In fact, the automatic treatment of the self-reproducing process has become a mathematical problem—the “logic of life” or rather how to extract mathematical algorithmic structures from biological phenomena, structures that can be useful to the understanding of the biology of the phenomena and their possible reinvention in digital worlds.

The study of self-reproducing structures has continued to search for a minimum system capable of nontrivial reproduction (Langton, 1984; Morita & Imai, 1996), other computing capabilities of the self-reproducers (Perrier, Sipper, & Zahnd, 1996; Tempesti, 1995), and the self-reproducers’ emergence and evolution (Chou & Reggia, 1997; Lohn & Reggia, 1995; Sayama, 1998, 2000). Here we propose an alternative approach, through which, using genetic algorithms on two-dimensional cellular automata (CA), we obtain the emergent phenomena of self-replication. We have found and classified different kinds of self-reproducer systems that have genetic maps, as if they were biological agents in a real environmental situation (Bilotta, Lafusa, & Pantano, 2003). We argue that the study of these self-reproducing systems may be deeply significant for both natural and artificial evolutionary systems.

In this chapter, we present a taxonomy of self-reproducers that are particularly interesting and present behavior analogous to that of biological nature, and we analyze how these construct colonies. The nature of these colonies, apart from the complexity of the structure of the self-reproducer, is regulated by precise rules of fractal nature, which throw light on the growth of the form.

The chapter is organized as follows. The second section discusses CA and GA formal aspects. The third section reports on self-reproducers’ taxonomy. Finally, conclusions are presented.

### FORMAL ASPECTS

The considered environment is a two-dimensional CA, which can be thought of as the following tuple:

\[ A = (d, S, N, f) \]  

where \(d\) is a positive integer that indicates the CA dimension (one-, two-, three-dimensional or more), \(S\) a set of finite states, \(N = (x_1, \ldots, x_n)\) is a neighborhood vector of \(n\) different elements of \(\mathbb{Z}^d\), and \(f\) is a local rule defined as:

\[ f : S^n \rightarrow S \]  

In our case \(d=2\), and the neighborhood identifies the cells with a local interaction ray \(r\), so Equation 2 to the \((2r + 1)^2\) elements of \(S\) associates with another element of \(S\), that is:

\[
\begin{array}{c c c c c c c c c c c}
... & ... & ... \\
... & s_{ij} & ... \\
... & ... & ... \\
\end{array}
\rightarrow s_{ij}
\]  

with \(s_{ij} \in S\) for all \(i, j\).

A rule that discriminates all possible cases is expressed in exhaustive form, and considers all \(k^{(2r+1)^2}\) possible cases. With the increase of \(k=|S|\) and of \(r\), the exhaustive rule becomes not very manageable. Here we define a particular form of rule (called hereafter k-totalistic rule), considering rules that do not distinguish the position of neighbours in the surrounding area, but just consider how many cells are in a given stage (Bilotta et al., 2002-2003).

Let \(h_i(t)\) be the number of cells in the neighborhood that is in stage \(s\) at time \(t\). We denote as \(V\) the set of all possible configurations of the neighborhood whose elements can be represented by a numerical string \((h_0, h_1, \ldots, h_{k-1})\); \(h_i\) values are not arbitrary, but they must satisfy the following constraints:
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