The Origin of Evolution in Physical Systems

Jean-Claude Heudin

International Institute of Multimedia
Pôle Universitaire Léonard de Vinci – 92916 Paris La Défense
Jean-Claude.Heudin@devinci.fr

Abstract. A tentative outline for a model for the evolution of physical systems is presented. The universal classes of dynamical behaviors found in Cellular Automata experiments provide the basis for introducing the variation-stabilization principle as a synthetic interpretation of these phenomena. It is suggested that biological evolution takes its root in the evolution of physical systems as a particular case of the variation-stabilization principle that occurs at the transition phase between ordered and chaotic regimes.

Keywords: variation, stabilization, evolution, complex physical system.

1 Introduction

In 1794, Erasmus Darwin, grandfather of the great Charles Darwin, published his book entitled *Zoonomia or the Laws of Organic Life*. In the first lines, he suggested that "the whole of Nature" is governed by physical laws [1]. Reciprocally, many physicists have proposed theories inspired by the Darwinian approach. For example, the path explored by Ludwig Boltzmann was similar in essence to the one of Darwin. Charles Darwin's theory begins with the assumption of the spontaneous fluctuation of species. Then natural selection leads to irreversible biological evolution. Boltzmann's order principle also shows that randomness leads to irreversibility, even if the result is the destruction of initial structures [2]. More recently, Lee Smolin proposed natural selection as a speculative hypothesis for the evolution of cosmological complexity [3]. All these interpretations of "evolution" in physical systems may be more than a coincidence. It seems clear that there is a continuum from the "evolution" of physical systems to biological evolution, but there is no theory that makes a convincing link between them.

In this paper, we try to establish a bridge between the evolution in physical systems and biological evolution by means of the variation-stabilization principle. We begin in section 2 by introducing this principle as a model for the evolution of complex physical phenomena. In section 3, we describe an experiment that illustrates this principle based on a two-dimensional Generalized-Life Cellular Automata [4]. We verify that this system exhibits the four universal complexity classes discovered by Stephen Wolfram [5] and we locate complex dynamics at the transition between ordered and chaotic phases [6]. In section 4, we discuss these results in the framework of the variation-stabilization principle. We argue that this principle represents a valuable synthetic

J. Zhou (Ed.): Complex 2009, Part I, LNICST 4, pp. 550 – 559, 2009.

re-conceptualization for the evolution of complex physical systems, replacing biological evolution as a particular case that occurs at the transition phase between ordered and chaotic regimes.

2 The Variation-Stabilization Principle

Any physical system can be represented as a hierarchical model. Evidence have been presented that a hierarchical modeling approach is required to obtain the necessary precision for studying complex natural phenomena [7]. In most cases, this hierarchal model of complexity is pyramidal: as a phenomenon increases in complexity, it decreases in number of elements. Thus, like a pyramid, the model is composed of a finite set of *n* layers *L* (vertical complexity) with an order relation:

$$\Delta = \{ L_n \} \text{ with } L_0 \rightarrow L_1 \rightarrow \dots \rightarrow L_{n-1} \rightarrow L_n.$$

Each layer *n* is composed of a dynamical network of structural elements *S* with similar behavioral repertoire (horizontal complexity):

$$L_n = \{ S_i^n \}.$$

Each structural element S_i of a given level L_n details the way in which it reacts to local situation and interactions with other structural elements of this level. The fluctuations of the environment and the structural interactions between elements lead to the formation of transitory structures S_j which are finite set of elements S_i. This stochastic phenomena can be noted as a *variation* function: *V(s)*. Due to their structural properties, some of these S_j elements continue to exist for some arbitrary times. They represent potential structural elements of the higher level L_{n+1}. If there are no more external fluctuations (i.e. closed world hypothesis), the system evolves after some transitory time to a stable state. Note that, the terms "stable state" must be understood as a statistical stability of global dynamics over time. This phenomena can be noted as a *stabilization* function *Z(s)*. The next figure summarizes this principle.

Variations create emergent temporary structures that achieve stability if their structural properties make them "adapted" to the environment. This principle of variation and stabilization applies at the same time in parallel at all levels of the hierarchical model.

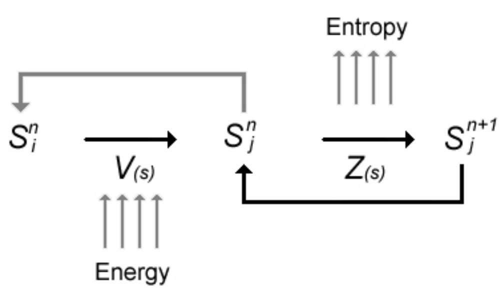

Fig. 1. Global relations in the variation-stabilization principle

The variation-stabilization process potentially leads to different macroscopic states. Throughout the physical world one can observe such different states of matter. The most familiar examples are the solid, liquid and gas phases. Other existing phases include crystals, colloids, glasses, amorphous, and plasma. These different forms can be grouped into four basic classes based on their attractor in the phase space: fixed point, limit cycle, chaotic and complex. It has been shown that Cellular Automata (CA) represent a good approach for modeling these different phases of matter. In particular, Stephen Wolfram proposed a correspondence with four universal complexity classes in one-dimensional Cellular Automata [5]: Class I includes CA whose dynamics reaches a steady state; Class II consists of CA characterized by periodic behaviors ; Class III CA produce structures that seem random; Class IV CA exhibit complex dynamics with both periodic and random patterns. Thus, CA seems a good experimental model for studying the variation-stabilization principle.

3 The Generalized-Life Experiment

3.1 Generalized-Life Cellular Automata

In order to study the variation-stabilization principle using a CA, we used a two-dimensional CA space based on a generalization of John Conway's "Game of Life" [8, 9]. This CA set has shown a wide diversity of dynamics in terms of *growth* (infinite, bounded and fall) and *periodicity* (chaotic, periodic and stable) [4]. In these experiments, a randomized initialization simulates an initial *variation* of the CA environment and its transition rule simulates the *stabilization* function.

Each stabilization rule can be written in the form $E_bE_hF_bF_h$ where E_b is the minimum number of living neighbor cells that must touch a currently "living" cell in order to guarantee that it will remain alive in the next generation. Fb is the minimum number of "living" cells touching a currently "dead" cell in order that it will come to life in the next generation and E_h and F_h are the corresponding upper limits. According to this notation, Conway's Life would be written "Life 2333," that is $E_b = 2$, $E_h = 3$, $F_b = 3$, and $F_h = 3$. More formally, let S_t define the state of a cell and N_t be the number of living cells in the neighborhood at time t. The stabilization function is then:

$$if\ (S_t = 0\ \&\ N_t \leq F_b\ \&\ N_t \geq F_h) \mid (S_t = 1\ \&\ N_t \leq E_b\ \&\ N_t \geq E_h)\ \ S_{t+1} = 1,\ else\ S_{t+1} = 0. \quad (1)$$

In a 2D grid, a cell is surrounded at most by 8 neighbors. The rule parameters are bound between 1 and 8, since 0 is prohibited for quiescent reasons. So intervals can be any among (1,1) (1,2) … (1,8) (2,2) (2,3) … (8,8). Thus there are (8 + 7 + … + 1) = 36 possible intervals. This CAspace thus contains 36 × 36 = 1,296 rules.

3.2 Universal Complexity Classes

We conducted a systematic study of this set of rules. As expected, we were able to classify the Generalized-Life CA set using Wolfram's universal complexity classes. The following sections give a brief overview of these results with some typical CA examples.

Fixed Dynamics Class. Class I is associated to limit points in the phase space. For almost all initial random configurations, cellular elements have the same value after a relatively short transient period. This stabilization process leads to a homogeneous state of the cell matrix. Figure 2 gives examples of such dynamics.

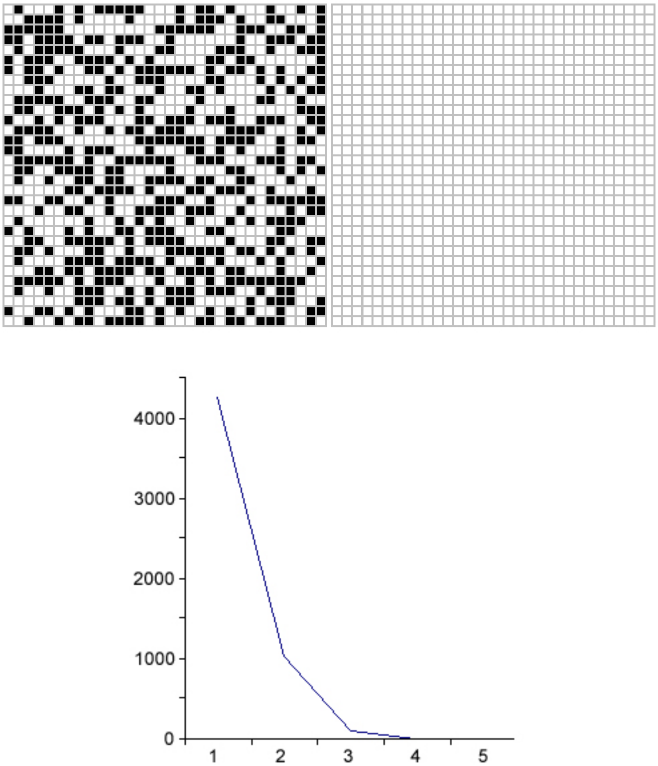

Fig. 2. Two configurations on the upper-left at t = 1 (left) and t = 4 (right) for rule 7788. All initial configurations lead to a homogeneous state of "dead" empty cells. Note that only a part of the CA configurations is shown in these images. The bottom curve is a time series for rule 5566 showing the number of "alive" cells (y-axis) for each generation (x-axis). After only four generations, eall cells are "dead".

Periodic Dynamics Class. Class II is associated with limit cycles in the phase space. Almost all configurations lead to a stable state with nested structures, except for some oscillating patterns. This stabilization process creates a periodic system. Figure 3 illustrates examples of such dynamics.

Chaotic Dynamics Class. Class III is associated with chaotic behaviors which refer to unpredictable space-time behaviors. Each configuration exhibits some rare stable patterns that survive only few generations and then are destroyed by the surrounding chaos. This stabilization process leads to an apparently random sequence, but this sequence is characterized by some statistical stability over time. Figure 4 illustrate examples of such dynamics.

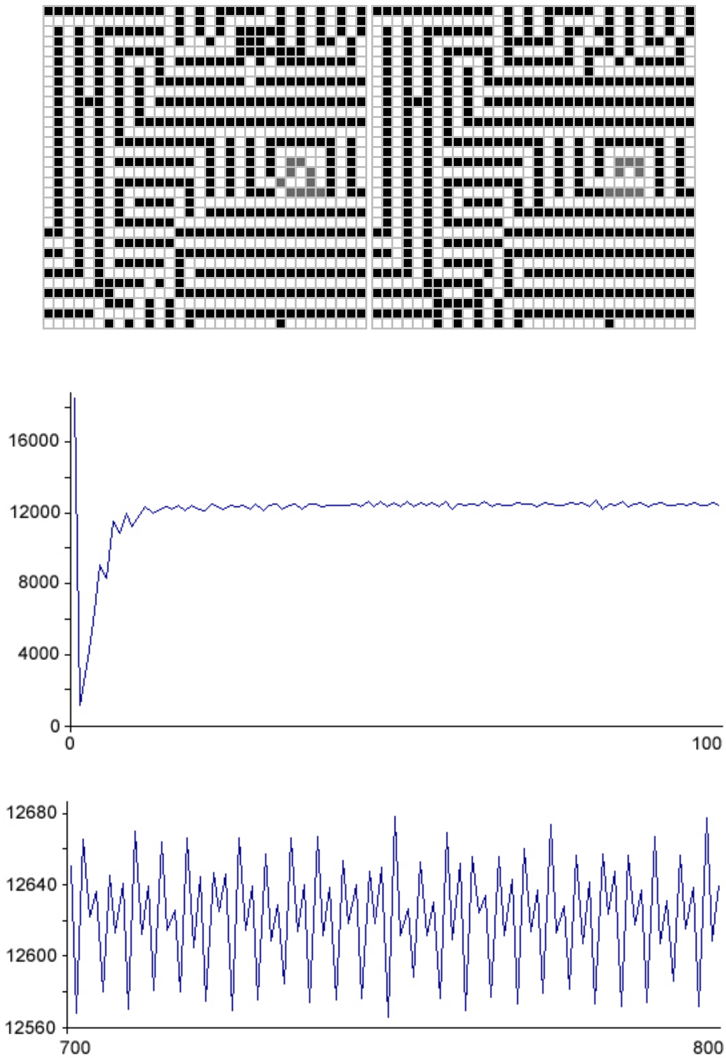

Fig. 3. Two configurations on the top at t = 59 (left) and t = 60 (right) for rule 5613. The cellular automata space becomes fixed after transitory configurations except for some oscillating pattern (in gray). Note that only a part of the CA configurations is shown in these images. The bottom curves are time series for rule 1616 showing the number of "alive" cells (y-axis) for each generation (x-axis). After a short transitory phase (upper curve), the CA oscillates between a small number of states (lower curve).

Complex Dynamics Class. Class IV is associated with complex behaviors characterized by long transients. The stabilization process leads to complex configurations that include both fixed and periodic structures. Some of these periodic patterns can propagate in the cell matrix (i.e. gliders). This emergent dynamical behavior is a sign that potentially indicates the support of universal computation. Figure 5 shows the

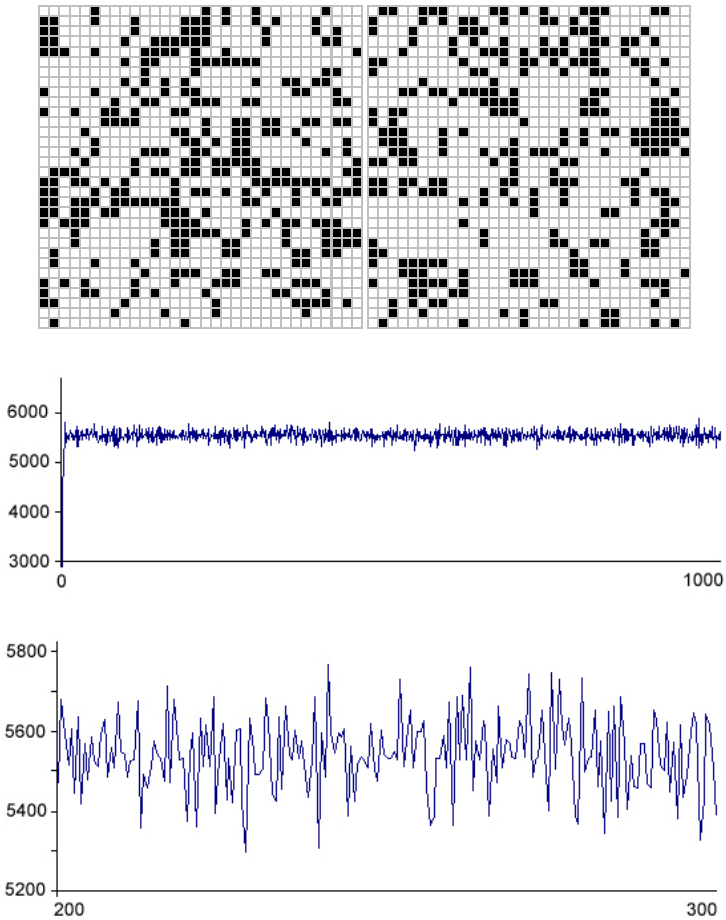

Fig. 4. Two configurations on the top at t = 10 (left) and t = 20 (right) for rule 1122. This rule exhibits a typical example of chaotic dynamics. Any emerging pattern is rapidly destroyed by the fluctuations of the environment. Note that only a part of the CA configurations is shown in these images. The bottom curves are time series for rule 1122 showing the number of "alive" cells (y-axis) for each generation (x-axis). After a short transitory phase (upper curve), the CA shows a typical chaotic behavior (lower curve).

most famous example of such dynamics, that is Conway's rule [8]. This CA has been extensively studied and considered as a metaphor of the emergence of life.

We verified that Complex CA, such as Conway's rule, are most likely to be found at a phase transition between ordered and chaotic CA. However, in contrast with Christopher Langton's continuous progression across the different regimes in his one dimensional CA study [10, 13], the behavioral structure of the Generalized-Life space is complex rather than linear. It is composed of homogeneous areas separated by smooth or sharp phase transitions [4]. The existence of these phase transitions between ordered and chaotic dynamics and between infinite and limited growth, as

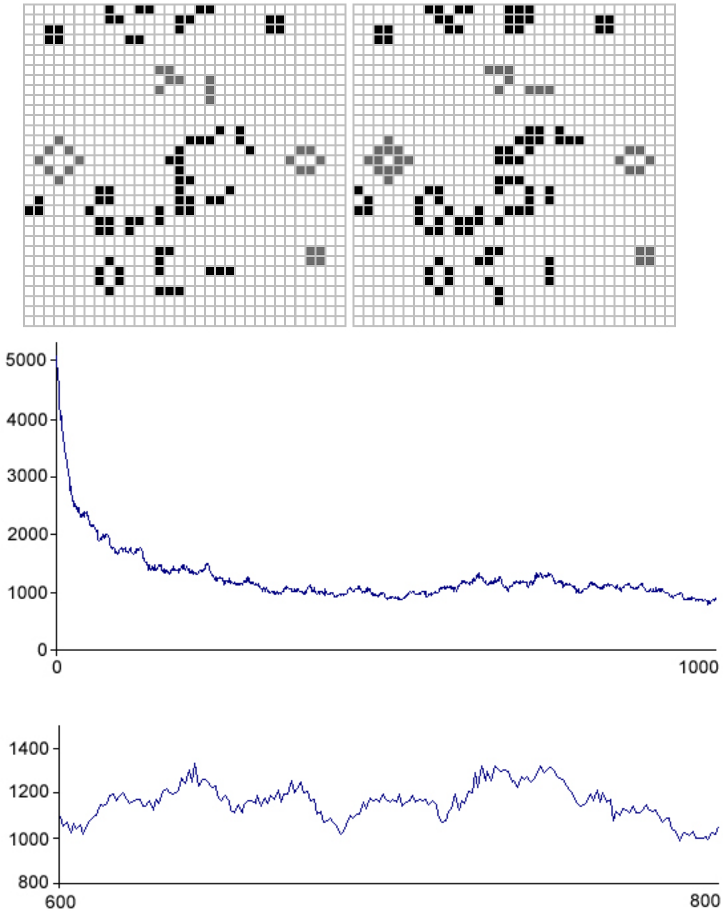

Fig. 5. On the top, two consecutive configurations beginning at t = 302 (left) for rule 2333. In gray, some typical fixed and periodic patterns. A glider is moving in the center at the top of the matrix. Note that only a part of the CA configurations is shown in these images. The two bottom curves are time series for rule 2333 showing the number of "alive" cells (y-axis) for each generation (x-axis). After a long transitory phase (upper curve), typically thousands of generations, the CA stabilizes with a majority of "dead" cells and some rare fixed and periodic patterns. The bottom curve shows a typical time series during the transitory phase. This type of curve seems to be a good signature of complex systems dynamics.

well as the location of complex CA in the vicinity of these transitions globally confirms the "edge of the chaos" hypothesis.

4 Discussion

The previous results show that after an initial variation, the behavior of the CA evolves toward a global statistically-stable state over time. This stabilization process leads to four cases: fixed for Class I, cyclic for Class II and chaotic for Class III. The complex Class IV CA seem to delay this stabilization thanks to the computational properties of the stabilization rule. Norman Packard argued first on the relationship between these dynamical behaviors and computational capability in CA [11]. Since, there has been a continuing effort to study this hypothesis [12–14]. Evidence has been shown that some class IV CA support universal computation in contrast with CA from other classes [15]. One property considered is the amount of memory required for producing these dynamics. The idea is that ordered or cyclic behaviors require memory in proportion to the nature and length of the pattern it repeats, while an ideal random behavior uses no memory to produce its information. In contrast, a theoretical Universal Turing Machine must have its storage space enlarged as needed. In the stabilization rule, the memory capability depends mainly on the E_b and E_h parameters. This rule (1) can be rewritten without any behavioral change:

$$\text{if } (S_t = 0 \;\&\; N_t \leq F_b \;\&\; N_t \geq F_h)\; S_{t+1} = 1 \tag{2a}$$

$$\text{else if } (S_t = 1 \;\&\; N_t \leq E_b \;\&\; N_t \geq E_h)\; S_{t+1} = S_t \tag{2b}$$

$$\text{else } S_{t+1} = 0. \tag{2c}$$

This reformulation shows that the (2b) part of the stabilization rule can memorize the previous state of the current cell while parts (2a) and (2c) are necessary for implementing basic logical functions such as AND, OR and NOT.

Another point of discussion is the obvious relationship between the *variation-stabilization* principle and the Darwinian *mutation and natural selection* principle. Our hypothesis is that biological evolution is a particular form of the variation-stabilization principle that occurs at a phase transition between ordered and chaotic regimes. In this framework, the DNA computing capacity seems to be a necessary advantage. More generally, evolution paradigms such as gradualism, punctuated equilibrium and natural drift, rather than being contradictory alternatives, could be interpreted as different forms of the variation-stabilization principle. As with our CA experiment, if the system is within the transition closer to the ordered regime, it leads to gradual evolution. If the system is within the transition closer to the chaotic regime, we have more randomness in the evolution dynamics. More studies must be conducted in order to validate this hypothesis.

The last important question we want to address here is the relationship of our study with the concept of "emergence," which is widely used in the sciences of complexity. Some effort has been made to formalize "emergence", but a consensus on a clear definition is still distant [16]. In our approach, a phenomenon at level L_n is *emergent* with respect to the lower-level L_{n-1} when it arises as a result of the interactions of L_{n-1} structural elements but not deductible from the properties of these elements. A well-known example in our CA experiment is the "glider": a periodic pattern discovered by John Conway. Gliders have been also found in other Class IV CA [4, 17] and there is evidence of their relationship with the universal computation capacity [15]. The fact is that it is practically impossible to deduce their global properties by just looking at their underlying structural elements (i.e. CA cells). The reason is a *causality break* due to the very high number of non-linear interactions between these structural elements. The observation of the two levels can not be made simultaneously. One can observe the global "patterns" level, but cannot observe in details the local behavior of the matrix cells at the same time. We think that this must be related to the *principle of complementarity* originally formulated by Niels Bohr in quantum mechanics [18]. In other words, the emergent properties represent the "wave-like interpretation" of the phenomenon which is not observable in the "particle-like interpretation" at a lower level. The *duality* of this two interpretations is necessary to have a complete description of the phenomenon.

5 Conclusion

We have introduced the variation-stabilization principle as a tentative outline for a general model of evolution in physical systems. We presented an experiment with the Generalized-Life CA that illustrate this principle and locate complex dynamics at the transition between ordered and chaotic regimes. We suggested that biological evolution takes its root in the evolution of physical systems as a particular case of the variation-stabilization principle that occurs at the transition phase between ordered and chaotic regimes. More research must be conducted to validate this theory. First, one could argue that the Generalized-Life CA represents a hierarchical system of only two levels: the cell matrix itself and the observed emergent patterns. This is true, and one research direction is to study the variation-stabilization principle in a more realistic and multi-level model such as the one we have used in cosmological experiments [19, 20]. A second complementary direction is to study the validity of the variation-stabilization principle in species dynamics using a virtual ecosystem such as Lifedrop [21]. Finally, another important direction is to study the relationship between the variation-stabilization principle and the second law of thermodynamics.

References

1. Darwin, E.: Zoonomia or, The Laws of Organic Life, 3rd edn., vol. 1. J. Johnson, London (1801)
2. Prigogine, I., Stengers, I.: Order out of Chaos, Man's New Dialogue with Nature. Bantam Books, New York (1984)
3. Smolin, L.: The Life in the Cosmos. Oxford University Press, New York (1997)
4. Magnier, M., Lattaud, C., Heudin, J.C.: Complexity Classes in the Two-dimensional Life Cellular Automata Subspace. Complex Systems 11, 419–436 (1997)
5. Wolfram, S.: Universality and Complexity in Cellular Automata. Physica D 10, 1–35 (1984)
6. Langton, C.G.: Computation at the edge of chaos: Phase transitions and emergent computation. Physica D 42, 12–37 (1990)
7. Heudin, J.C.: Modeling Complexity using Hierarchical Multi-Agent Systems. In: 6th International Workshop on Data Analysis in Astronomy, Erice (2007)
8. Gardner, M.: The fantastic combinations of John Conway's new solitaire game "Life". Scientific American 223, 120–123 (1970)
9. Bays, C.: Candidates for the game of life in three dimensions. Complex Systems 1, 373–400 (1987)
10. Langton, C.G.: Life at the edge of chaos. In: Artificial Life II, SFI Studies in the Sciences of Complexity, vol. 10, pp. 41–91. Addison Wesley, Reading (1991)

11. Packard, N.H.: Adaptation toward the edge of chaos. In: Kelso, J., Mandell, A., Shlesinger, M. (eds.) Dynamic Patterns in Complex Systems, pp. 239–301. World Scientific, Singapore (1988)
12. Langton, C.G.: Computation at the edge of chaos: Phase transitions and emergent computation. Physica D 42, 12–37 (1990)
13. Mitchell, M., Hraber, P.T., Crutchfield, J.P.: Revisiting the edge of chaos: Evolving cellular automata to perform computations. Complex Systems 7, 89–130 (1993)
14. Crutchfield, J.P., Packard, N.H.: Symbolic dynamics of noisy chaos. Physica D 7, 201 (1983)
15. Berlekamp, E., Conway, J.H., Guy, R.: Winning ways for your mathematical plays. Academic Press, London (1982)
16. Kubik, A.: Toward a Formalization of Emergence. Artificial Life 1, 41–65 (2003)
17. Heudin, J.-C.: A new candidate rule for the game of two-dimensional life. Complex systems 10, 367–381 (1996)
18. Bohr, N.: Causality and Complementarity. Philosophy of Science 4, 289–298 (1937)
19. Heudin, J.-C.: Complexity classes in three-dimensional gravitational agents. In: Artificial Life VIII, pp. 9–13. MIT Press, Sydney (2002)
20. Torrel, J.C., Lattaud, C., Heudin, J.C.: Studying complex stellar dynamics using a hierarchical multi-agent model. In: 6th International Workshop on Data Analysis in Astronomy, Erice (2007)
21. Métivier, M., Lattaud, C., Heudin, J.-C.: A Stress-based Speciation Model in LifeDrop. In: 8th International Conference on Artificial Life, pp. 121–126. MIT Press, Sydney (2002)