

Characterization of Multispecies Living Ecosystems With Cellular Automata

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Abstract

A multispecies artificial ecosystem is formulated using cellular automata with species interactions and food chain hierarchy. The constructed finite state automaton can simulate the complexity and self-organized characteristics of the evolving multispecies living ecosystems. Numerical experiments show that a small perturbation or extinction event may affect many other species in the ecosystem in an avalanche manner. Both the avalanches and the extinction arising from these changes follow a power law, reflecting that the multispecies living ecosystems have the characteristics of self-organized criticality.

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1 Introduction

The modelling of artificial life is very important to the understanding of the origin of life and its evolution, thus the studies using computer simulations are of both scientific importance and practical applications. Since Langton (1986) relaunched the field of artificial life, the possibly universal aspects of living systems have been investigated by exploring the artificial chemistry acting on artificial molecules in terms of rule-based cellular automata (CA). Langton (1986) carried out numerous CA simulations with a parameterization scheme allowing the relationship of Wolfram's classes cataloged the rules that generates different classes of dynamics. Since then there have been many extensive studies about artificial life. However, the understanding and studies of artificial life is still at very early stage.

Artificial life simulations using cellular automata have received much of interests in the community

of artificial life and evolutionary computing. Conway's game of life has popularized this area of research. However, most of the existing simulations of CA is about the evolutionary and classification of one single species, and this has demonstrated the complexity and richness of simple rule-based systems. Interestingly, multispecies models have begun to attract much attention (Sole and Manrubia, 1996; Amaral and Meyer, 1999). In order to study the ecological effect and the interaction among different species, a multispecies system of artificial life should be explored in detail. It can be expected that the behavior and characteristics of multispecies living system could be very different from that of single species cellular automata.

The aim of this paper is to present some new results using a multispecies system of artificial life with cellular automata. By numerical experiments, we will find how the interactions among different species affect the evolution behavior and self-organization as well as species extinction events. This paper is organised as follows. In the next sections, we describe how to construct the cellular automata for the multispecies living systems, we then implement the systems and give some numerical simulations. Based on the numerical simulations, the complexity and entropy of the evolving living systems are measured, and the self-organized criticality is tested. The possible reason of extinction behavior of the living systems is also explored. The implications of the multispecies interactions will be also discussed.

2 Rule-Based Cellular Automata for Multi-Species Living Systems

Cellular Automata (CA) is a finite-state machine on a regular lattice. The input to the machine is the states of all machines in its neighborhood, the change of its state is based on the rules or transition

functions. The states of all machines in the lattice are updated synchronously in discrete time steps. Each cell evolves according to the same rules which depend only on the state of the cell and a finite number of neighboring cells, and the neighborhood relation is local and uniform. One classic example is Conway's game of life where one takes a neighborhood consisting of the nearest 8 cells to a cell on a 2-D cellular automata. Its transition function for the local automaton for two states (1 and 0, or alive and not alive) is as follows: If 2 or 3 neighbors of a cell are alive (or 1) and it is alive at present, then it is alive at next state; If 3 neighbors of a cell are alive and it is currently not alive, its next state is alive; the next state is not alive for all the other cases. Even with these simple rules, an universal computational machine can be constructed on an infinite 2-D grid, which is capable of emulating the computing power of any Turing machine or digital computer.

The present model is an extension of the combined version of the Sole-Manrubia model (1996) and Amaral-Meyer food chain model (1999). The next state for a cell is determined by the transition function in the general form

$$C_i(t+1) = H[\sum_j G_{ij}C_j(t) - \theta], \quad (1)$$

where H is the heaviside step function, and θ is the threshold. G_{ij} of the influence of cell j on cell i , $G_{ij} > 0$ or < 0 if j is the food or predator for cell i . The summation is over the nearest neighborhood. The multispecies cellular automata works in the following way:

1. The CA consists of M interacting species, when $M = 1$ it degenerates into the classic Conway's game of life and obeys the same simple rules.
2. Different species interacts with each other in a way of food chain hierarchy. Each species is label as a hierarchy level and for simplicity, we use the level i for species i with species $i - 1$ as the pray or food for species i and species $i + 1$ as its predator.
3. In the nearest 8 cells of to a cell of species i , if the number of predators is greater than the number of prays, and the cell is currently alive, then its next state is alive; If the number of the prays is more than the number of predators, then its next state is alive whether its present state is alive or not; If the predators are in the same number as the pray, the present state does not change.
4. If there is no predator or pray in the 8 neighborhood cells, then the transition function is the same as the single species Conway's cellular automata.

In the numerical simulations, the 2-D lattice is randomly initialized with the highest population of the lowest level of species $i = 1$. For a regular 100×100 lattice with $N=256$ species initialized this way, we can investigate the complexity, self-organization, species interaction and avalanche events.

To simulate the effect of species interaction and extinction, a small probability of extinction rate is also introduced into some species, the influence of the extinction of one species on the other species in the food chain model can be studied in some detail. In addition, by introducing some extra population in one species, one can control some other species in the food chain model and give important implications on the ecological effect in reality such as the rat control. A number of numerical experiments have also been investigated. Some trend and self-organized criticality is analyzed from the simulated results.

3 Numerical Experiments

By using the cellular automata described in the above section, we can simulate the behavior of multispecies living systems with multispecies interactions in a food chain hierarchy. In the rest of this paper, we present some results from a huge number of the numerical simulations and parametric studies. A typical initial configuration is shown in Figure 1.

3.1 Variation in Complexity and Entropy

For a population size $N = 100 \times 100$ with $M = 256$, the complexity of the cellular automata can be measured by its entropy S

$$S = - \sum_i p_i \log p_i, \quad (2)$$

where p_j is the probability of find the species i in the total population (Adami,1998). For a finite population size, p_i can be approximated by the fraction of samples n_i

$$p_i = \frac{n_i}{N}, \quad (3)$$

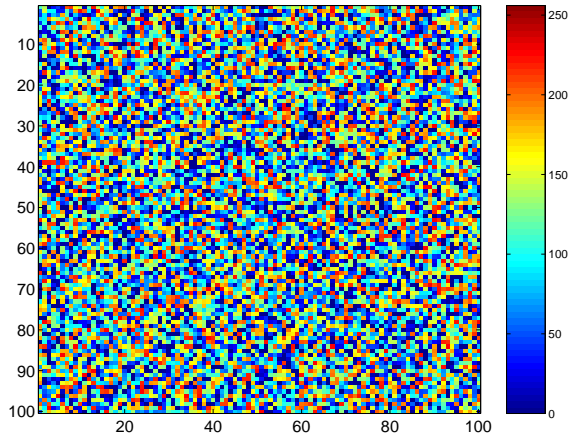


Figure 1: A random configuration of multispecies cellular automata

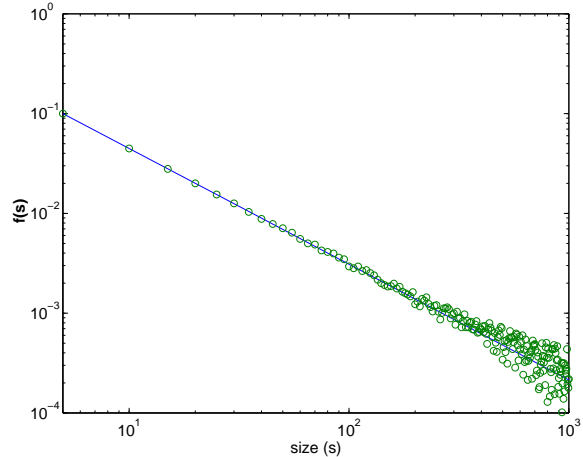


Figure 3: Self-organized criticality in multispecies living systems

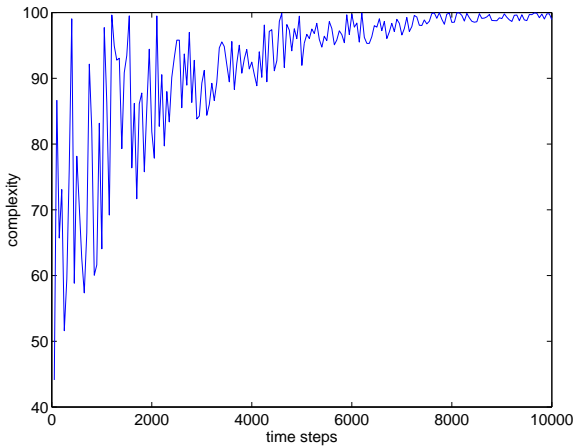


Figure 2: Variations of complexity versus time steps

so that

$$S = - \sum_i p_i \log p_i. \quad (4)$$

The variation of complexity of the 256-species cellular automata is shown in Figure 2.

It is clearly seen that the complexity varies significantly at the early stage of the evolution process, then it gradually relaxes to the equilibrium at long time, indicating that the living systems is in a quasi-steady state among different species.

3.2 Self-Organized Criticality

Based on the pioneering work by Adami (1995) on the self-organized criticality in living systems using the *Tierra* experiments and the subsequent

work by Newman et al (1997), there is a good reason to believe that self-organized criticality exists in the artificial living systems. In order to test whether the self-organized criticality exists in the multispecies living ecosystems, we introduce a small perturbation to ecosystem and measure the population changes affected by the perturbation or avalanche in population and species, this is because the ecosystem can form between all the competing and yet interconnected species. The change in response to any perturbation will enable this living to relax to a new equilibrium or the self-organized state. By tracing the 15000 avalanches obtained from numerical simulations on 100 x 100 lattice grid, the results are shown in the log-log plot in Figure 3.

This figure clearly show that the avalanches size distribution follows a power-law with the exponent $\gamma = 2.26 \pm 0.04$. This implies that the multispecies living ecosystem has the characteristics of self-organized criticality. This is consistent with the earlier work by Adami (1995). Our present work implies that the self-organized criticality could be universal in living systems.

3.3 Extinction

In the above numerical simulations, the changes or redistribution of populations of different species have been studied. There may not necessarily involve the extinction of some species. In some case, for example, when the initial population size for some species is very small and its predators are strong, the whole species could become extinct, and

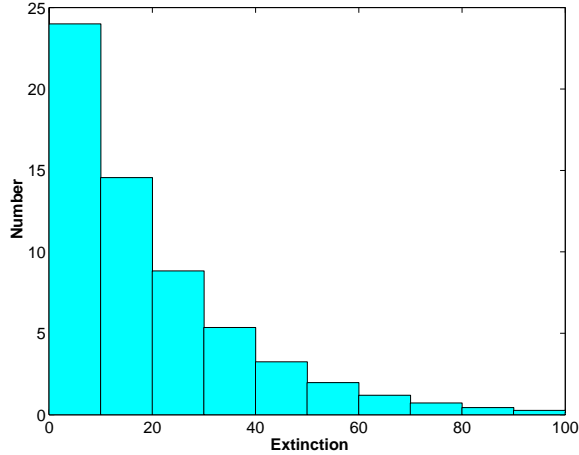


Figure 4: Extinction intensities at different time stage

the extinction of one species may influence other species in the food chain. To simulate this effect, we introduce an extinction probability $p_e = 0.01$ for a species at some level, say $i = 16$, in the food chain hierarchy. The extinction obtained from the numerical simulations is shown in Figure 4.

The extinction intensities at different time stages (100 time steps as a stage) follow a power-law with an exponent $\gamma = 2.05 \pm 0.1$, which implies that extinction is a self-organized phenomenon. This is consistent with the fitting data $\gamma = 1.7 \pm 0.3$ from the fossil record (Newman and Eble, 1999), and the extinction is a result of external change and species competition.

4 Discussion

The multispecies ecosystems of artificial life have been formulated in terms of 2-D cellular automata of the combined Sole-Manrubia type together with the Amaral-Meyer food chain model. By using the proper interactions between different species in the food chain hierarchy and the transition function, the finite state automaton can simulate the complexity of the evolving multispecies living ecosystem. Numerical experiments show that the complexity measured by the system entropy fluctuates at early stage of evolution, then it evolves to the self-organized or dynamic equilibrium state under certain conditions. By introducing the extra fraction of population or a small perturbation, the species population may be affected at different scales. The avalanches arising from these changes obey a power-law with the exponent $\gamma = 2.26$, re-

flecting that the multispecies living ecosystem has the characteristics of self-organized criticality.

On the other hand, in the case of one species in the margin of extinction, it can affect many species in the multispecies living systems and can lead some kinds of mass extinction. Numerical simulations also show that the extinction intensities follow a power-law form with the exponent $\gamma = 2.05$, thus indicating the species interaction and competition is the mechanism for the extinction under the action of external changes. Although the present modelling provides a lot of features about the complexity of the artificial living systems, much more work is clearly needed to investigate the system behavior such as how the different extinction mechanisms and transition rules affect the evolution of the multispecies living ecosystems.

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