Interaction Based Evolution of Self-Replicating Loop Structures

Keisuke Suzuki and Takashi Ikegami

General Systems Sciences,
The Graduate School of Arts and Sciences,
The University of Tokyo,
3-8-1 Komaba, Tokyo, 153-8902, Japan
{ksk, ikeg}@sacral.c.u-tokyo.ac.jp

Abstract. We propose an ecosystem of self-replicating cellular automaton loops by designing new rules for interactions between individual loops. The loops interact competitively with each other, from which a hypercycle-like network emerges. A spiral structure is seen to emerge from this model with five species. This spiral allows the formation of larger loops at the bounaries between different species. Unlike the single species case, our model allows larger loops to live for long periods of time, and they can replicate in spite of their necessarily lower replication speed.

1 Introduction

The study of self-replicators using 2-dimensional cellular automata (CA) originated in J.von. Neumann's universal constructor[1]. His self-replicator can construct structures that can be coded on a description tape, which is analogous to biological reproduction. By extending von. Neumann's original studies, we would like to understand how new replicators can come out and how different replicators can interact with each other. In particular, evolution isn't caused passively by random mutation but is caused actively by other replicators. The latter interactive and deterministic aspect of evolution is stressed by, e.g.[2, 3]. Here, we consider about the evolution caused by only the interaction between replicators. As mentioned in [4], von. Neumann's model allows for increases in both functional and structural complexity. However, in our model we consider only structural complexity, i.e. the shapes of replicators. Without any explicit fitness function, replicators irreversibly change their shapes over time, which we call "evolution". Recently, Sayama has studied the evolution by interaction with his cellular automata replicating system[5]. In his model, while replicators can change their shape, no open-ended evolution appears. It is difficult for more complex replicators to emerge, because simpler self-replicators, which are smaller, can replicate faster than larger ones. This leads to the dominance of small replicators. In another of Sayama's models[6], which uses shape-encoding worms, more divergent forms can replicate but these become fragile against interactions.

In this paper we propose an improved self-replicating CA model which allows larger loops to evolve due to the spiral formation via the interaction between loops. In section 2, we introduce the present model. The rules governing interaction between loops are presented in section 3. In sections 4 and 5 we discuss our results. In particular, macroscopic spirals are seen to emerge, with larger loops found at the boundaries between spirals.

2 Shape-encoding Loop

To allow the evolution of self-replicators, we use the shape-encoding loop model, which was designed by Morita and Imai[7]. Our model has a greater number of cell states, and new state transitions. It is defined on a two-dimensional, five-neightbor cellular space, and self-replicators are given by configurations of cell states on the space.

2.1 States of Cells

129 cell states are used in this model. There is a unique "background" (inactive))cell state. The remaining 128 states are used to compose self-replicating pattens as shown in Fig. 1
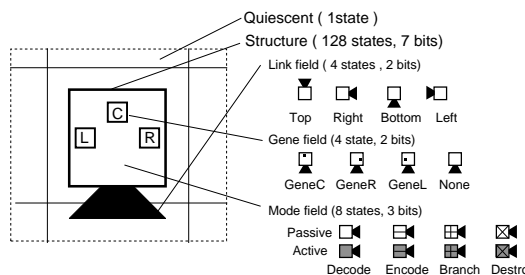

Fig. 1. An illustration of cell states. Three different fields are classified by function. The Link field (4-states) represents a cell direction, which is drawn as a filled trapezoid in the following figures. The Gene field (4-states) stores shape infomation for constructing new loop strutures, which are drawn as the three inner squares. The Mode field (8-states) represents special conditions used for self-replication, which are drawn as lines and colors in the outer squares.

2.2 Self-replication Process

The shape infomation of replicators is coded in their gene fields. The construction of daughter loops follows this shape infomation. Unlike Langton's loops, each gene field is read only once during the construction of a daughter loop. As a result, the shape of self-replicators can be varied and complex.

Here, we demonstrate the self-replication process in four stages: "Finding corner", "Encoding shape", "Expanding arm" and "Withdrawing arm" (Fig.2). A loop of size N is in the finding corner stage when it has one 'branch-active' (ba) state and N-1 'decode-passive' (dp) states. The ba state is transferred to its neighbouring cell in the anti-clockwise direction. When the ba cell reaches the first corner, it first turns into the 'decode active' (da) state and then turns into the 'branch-passive' (bp) state. Then the second 'encoding shape' stage begins. Here, the 'encode' state is transferred to all connected cells beginning with the cell connected to the first corner. As a result, the replicator's shape information is encoded througout the loop, before returning to the corner bp state. In Fig.2, the shape information may be read as "LCLLCC". In the third stage, which we call the expanding arm stage, new cells are successively added to the corner bp state. These new cells are called the expanding arm, and the shape information is sent from the parent cell, through the arm, to make a new (child) replicator. Finally, in the 'withdrawing arm' stage, the 'destroy-passive' state is created which removes the expanding arm cells until it reaches the first corner cell. When it reaches the corner, it turns the bp state already at the corner into the ba state, beginning the next replication cycle. In the next section, we define a transition rule for interactions between self-replicating worms.
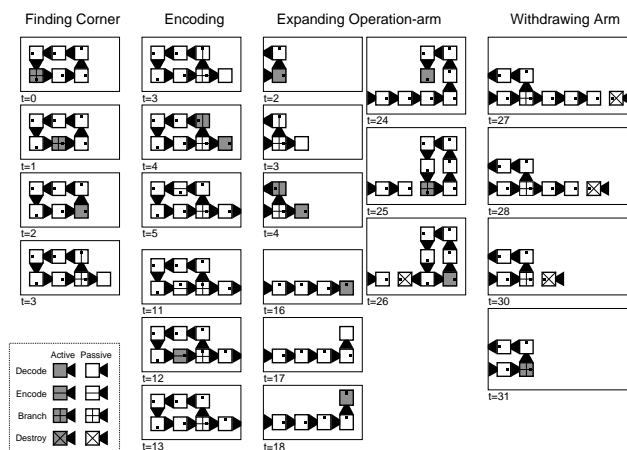

Fig. 2. Self-replicating processes of a 6-cell loop. An arbitrary loop structure can be replicated by the same process

3   Competitive Interaction

We define new rules for the interaction between self-replicating loops. Following the Evoloop model, we introduce dissolution cell states. Here, we use the destroy-active mode which is not utilized in normal self-replicating processes.

This destroy-active mode only emerges on a site where collision occurs between two loops and unlike the destroy-passive mode, it dissolves any type of cell, not just arm cells. Also, we can introduce a notion of "species" by adding a new index field. Species are defined as cells having the same value in this field.

We organize the competition between different loop species by introducing a hypercycle-like interaction. For example, the species S_2 is superior to S_1 but inferior to S_3(Fig3). The competitive interactions between the different species yield a variety of different self-replicators on the CA space, which have not been studied in previous self-replicating CA models. .
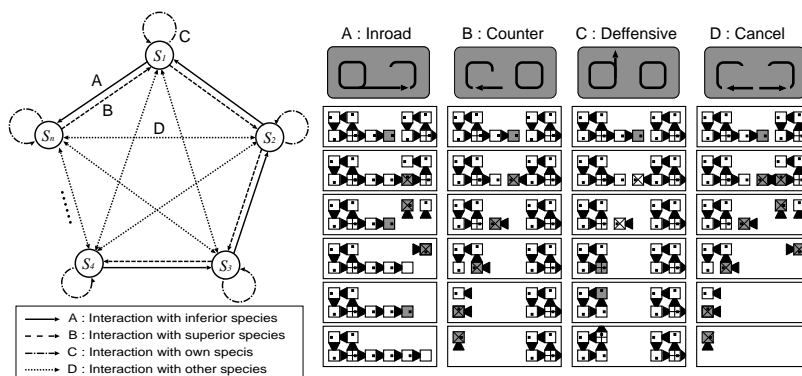

Fig. 3. Competitive interactions between species are illustrated in the left figure. Each species has exactly one superior and one inferior species. The strengths of interaction are given by the four collision styles depicted in the right figure. When the arm of a loop on the left side collides with a loop on the right, only the right-hand loop is destroyed by the 'Inroad' interaction, only the left loop is destroyed by 'Counter', both of them survive in 'Defensive', and both of them are destroyed in 'Cancel'.

4   Dynamics of Self-replicating Loops

We now report on the dynamics of interacting self-replicating loops. Two main observations can be made. First, a spiral structure emerges from this system, which is not unexpected. Second, larger replicating loops with longer life times evolve at the boundaries between species.

4.1   Spiral Structures

On the boundary regions between species, loops of the superior species can clear space for their replication because they can succesfully invade loops of the inferior species. Consequently, the global dynamics of these self-replicators forms spiral structures, as shown in Fig.4. This kind of structure was often seen in the study of other spatial models where multiple elements interact(see e.g. [8]).
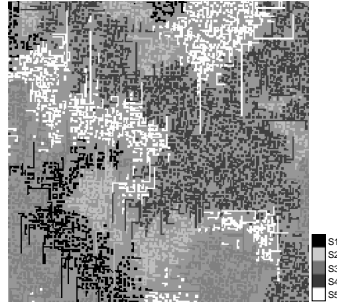
Fig. 4. A spiral structure produced by five interacting species in 200 ×200 cell space. The spiral rotates in a counter-clockwise direction

In the Evoloop model, larger replicators cannot survive for long periods of time, because smaller ones can replicate themselves faster, quickly spreading out in the CA space. Like Evoloop systems, most of the CA space is dominated by loops of minimal size, because they can replicate faster and spread out more quickly. However, we can also observe larger loops frequently emerging on the boundary between species as shown in Fig.5. Various kinds of shapes can exist in a region of inferior species. Although most loops cannot copy themselves, some loops can replicate correctly and breed locally.
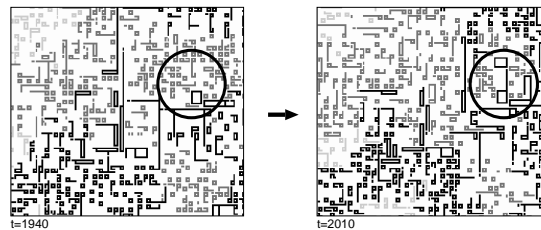

Fig. 5. Larger loops emerge on a boundary with an inferior species. The loops with a medium gray tone are of an inferior species to the loops in black. After 70 steps, the emergent larger loop (circled) sustains replication, invading the inferior species

### 4.2 Analysis of Self-replicating Loop Structures

To understand how the spiral structure can generate larger loops, we compare the multi-species competition model with the single-species models. Fig.6 shows the frequency distribution of replicating loops for the competition model, and each of the 4 interaction types used individually. The initial condition for the competition case is a random arrangement of the five species over a 400×400 cell space. Only four-cell loops exist at the initial time step. For the other cases

shown in Fig.6, only a single species which interacts with itself via the particular interaction is used. The results are accumulated over 10000 time steps. It is easy to see that the full competition model produces the largest loops(e.g. larger than 50 cell sizes). The competition model can provide enough space for replication at the boundary, but the single species models cannot do this.
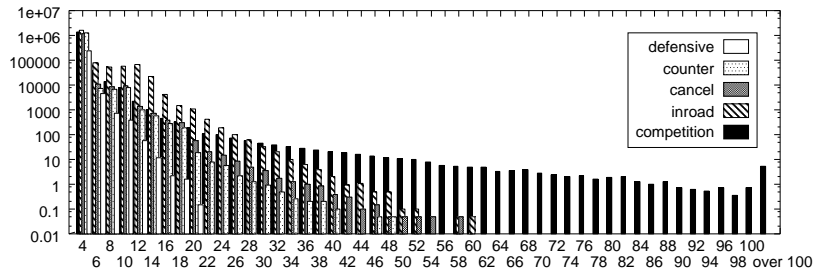

Fig. 6. Frequency histogram of loop sizes. A vertical bar represents the total number of loops of a particular size observed during 10000 steps. The initial state only includes loops of size 4. The CA space has 400×400 cell sites. Loops larger than size $\sim$50 only emerge in the competition model

Fig.7 shows that both the population of the loops and the boundary length between regions of different species oscillates globally. The length of the boundary to the inferior species rises soon after the loop population increases, and the boundary length to the superior species rises after that. The frequency of larger loops increases whenever a significant length of boundary to an inferior species arises.
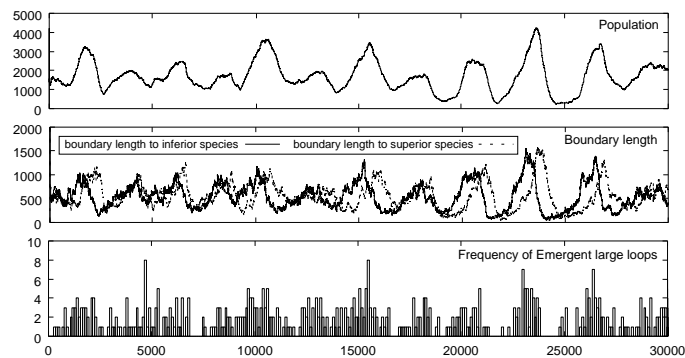
Fig. 7. Dynamics of one species in a five-species competition network. Fluctuations of the loop population (top) seem to be accompanied by changes in the boundary length (middle). The number of larger loops (size $\geq$ 20) loops increases whenever the length of the boundary to the inferior species increases(bottom)

Though larger loops can emerge, these loops vanish when they interact with other loops. Fig.8 shows the plot of lifetimes of loops according to their length. For the stability of loops on interaction, the 'Counter' and 'Defensive' interaction rules generate long lived loops, in contrast to the 'Inroad' and 'Cancel' rules. The 'Counter' and 'Inroad' rules are assymmetric interactions that generate relatively large loops. On the other hand, the 'Cancel' and 'Defensive' rules generate only small loops. The competition interaction can develop loops with both larger size and longer lifetimes.
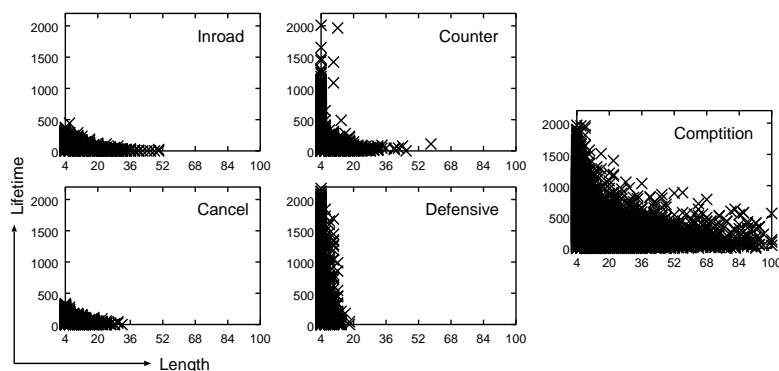
Fig. 8. Life time plots of loops interacting to each of the four interactions, and the full competition network, plotted as lifetime versus loop length. Because of the relative unstability of the inroad and cancel rules, they cannot generate long-lived loops. The distribution found in the competition model shows the existence of many large loops with long lifetimes.

5   Discussion

In this paper, we showed that introduction of species and competition between them enhances the evolvability of self-replicating loops. It is reported that hypercycle formation gives an evolutionary advantage as it leads to resistance against parasites[8]. We also insist that hypercycle formation indeed enhances evolvability. The ability for loops to clear sites is important for the existence of larger loops. How long these large loops can survive depends on the type of interaction between loops(e.g. the degree of loop destruction involved) Fig.8 reveals that more stable interactions (i.e. "Counter" and "Defensive) lead to many long lived loops. The coexistence of different interaction types leads to large loops with longer lifetimes.

There are many problems left to address. We have to allow both left and right interaction with loop arms, and also allow both clockwise and counter-clockwise loops. Then we expect that not only the size but the shape of loops can more easily evolve.

One of our future projects is to observe information flow from the microscopic to the macroscopic level, and vice versa. Flow from the microscopic to the macroscopic level is easier to observe. It is clear that properties of replicators (e.g. genetic information such as size and form) can affect the global behavior of the ecology (e.g. spiral waves). What is more interesting is to see how macrocsopic structure can affect the information at the microscopic level. For example, it would be interesting to see the emergence of different replicators reflecting the spatio-temporal macroscopic ecological pattern. Introducing a food-web structure may be another way to see information flow from the macroscopic to the microscopic level(see e.g. [9]).

Acknowledgements

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