Introduction of Structural Dissolution into Langton's Self-Reproducing Loop

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Abstract

The phenomenon of death, or disappearance of life, has two aspects. One is failure in the function of life and the other is dissolution of the structure of life. In order to examine the significance of the latter aspect, the author contrived a "structurally dissolvable self-reproducing (SDSR) loop" by introducing the capability of structural dissolution into Langton's self-reproducing (SR) loop in which death as functional failure has already been installed. To be more specific, a *dissolving state* '8' was introduced into the set of states of the CA, besides other modifications to Langton's transition rules. Through this improvement, the SDSR loop can dissolve its own structure when faced with difficult situations such as a shortage of space for self-reproduction. This mechanism (disappearance of a subsystem of the whole system) induces, for the first time, dynamically-stable and potentially evolvable behavior into the colony of SDSR loops.

Introduction

This study is an attempt to introduce death as *structural dissolution* into Langton's self-reproducing loop (abbreviated as "SR loop" in the following) in which death as *functional failure* is already featured. While it was motivated simply by the author's desire to allow SR loops to continue with their characteristic behavior semi-permanently within finite memory space, it also creates a means to investigate the significance of a death-process for the dynamics of life.

What is life? How does a living system behave? To answer any of these basic questions, so far many kinds of behavior characteristic of life have been studied, such as self-reproduction, metabolism, physical motion, perception, learning, immunity, inheritance, evolution, emergent behavior of population, death, and so forth. According to these studies, life has been defined many times in many ways. We temporarily and simply define life here only via its behavioral aspects, as a complex system which adapts to and affects the external environment, and also has the capability of self-reproduction and evolution. Among these characteristics of life, it may be no exaggeration to say that death is one of the phenomena which are examined relatively less than the others.

What is death? What kind of behavior do we call death? At least we can say as a trivial definition that death is a state transition of a system from a living state to a non-living one. Though we also need definitions for the living state and the non-living state in order to complete this statement, we do not want to consider it too deeply here. For the time being, here we will define the living state to be a state in which a system functions correctly and shows the abovementioned behavior characteristic of life. "Death of life" as a state transition from the living state to the non-living caused by loss of sound function of the system is, for now, referred to as *death as functional failure* in this article.

In practice, however, there are many cases in which we view the cessation of life not only as functional failure but also by the disorganization of the physical structure of a system. Here, we shall refer to this, again for the time being, as *death as structural dissolution*. For example, all terrestrial creatures including human beings will be decomposed into organic compounds by their own function and other microorganisms after death due to functional failure, unless a special treatment for preservation is applied to their corpses. Moreover, it is clearly understood that in the engineering techniques represented by genetic algorithms, e.g., or in artificial ecosystem simulations like *Tierra*, death of an individual implies not only their functional termination but also removal of them from the memory space of computers. Thus, it is obvious that the value of death for a system in a finite environment would not only be functional failure, but in fact in the structural dissolution associated with it. However, death has never been discussed while drawing a distinct line between these two aspects.

Therefore, we aim here at elucidating the significance of death as structural dissolution by introducing it into a system in which it was previously absent, and chose Langton's SR loop for the subject matter. A new state '8' was introduced into the set of states of the CA, while states '0'–'7' and Langton's transition rules were

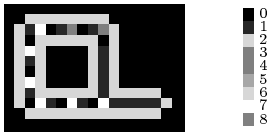

Figure 1: Configuration of Langton's SR loop. Six signal states '7' (each of which make the arm grow straight for one cell) and two signal states '4' (which make the arm turn left) are set in the 'Q'-shaped tube enclosed by sheath states '2'. The right chart indicates the correspondence between states of cells and shades of pixels in the figure. The following figures are also drawn according to this chart.

preserved in order to completely emulate the properties of the SR loop. Transition rules governing the behavior of the new state '8' were designed in such a manner as to give state '8' the meaning of a *dissolving state* which can propagate along the tube of the loop and dissolve the neighboring structure. Such an improved loop was termed "structurally dissolvable self-reproducing loop" ("SDSR loop".) Through experiments with the SDSR loop, several interesting phenomena never previously seen in the world of SR loops were observed.

This article consists of five parts: Review of Langton's SR loop, explanation of a concrete method for implementation of the SDSR loop, observation of results of experiments using the SDSR loop, several discussions about them, and a brief conclusion.

Langton's Self-Reproducing Loop

Langton's SR loop (Langton 1984) is one of the most famous models of self-reproduction constructed by means of cellular automata (CA). Langton invented it in order to reveal that universality of construction is not necessary for self-reproduction. The SR loop is implemented in an 8-state 5-neighbor CA. Its configuration is shown in Figure 1. Signal states '4' and '7' are set to float in the 'Q'-shaped tube enclosed by sheath states '2'. Signals propagate along the tube in the direction of the neighboring core state '1'. When a signal reaches the tip of a construction arm which is thrust outward from the loop, translation from genotype to phenotype will occur, such as straight growth or left turning of the arm. When the tip of the arm reaches its own root after it turned left three times, tip and arm bond together to form a new offspring loop, and then the connection between parent and offspring—which Langton called the "umbilical cord"—disappears. In such a way, the SR loop is ingeniously designed to reproduce itself in just 151 updates. This method of self-reproduction is shown in Figure 2. Since the specifications of the SR loop are described at length in Langton's paper, details are omitted here.

When the SR loop finishes self-reproduction, it will try to do the same again in the same way but rotated by ninety degrees counterclockwise. It repeats this action forever while there is enough space for self-

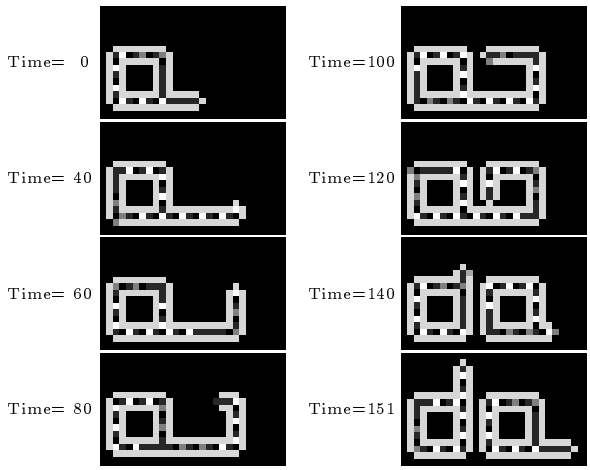

Figure 2: Self-reproduction of the SR loop. As signals in the loop propagate counterclockwise, copies of them are made and sent toward the tip of the arm. The arm grows through repetition of straight growth and left turning (time=40–100). When the tip reaches its own root after three left turns, they bond together to form a new offspring loop. Then the connection between parent and offspring disappears (time=120–140). In such a way, the loop reproduces its offspring which has a structure identical to its parent's in the right area, in 151 updates (time=151).

reproduction. If an area in which the loop wants to place its offspring is already occupied by others, it generates a new sheath fragment in the tube to obstruct the pathway of signals. Then, signals in the loop become extinct one after another, being absorbed by the obstacle fragment. Finally, only a circular tube filled with core states is left, by itself. The manner by which this proceeds is shown in Figure 3. Thus, death as functional failure is certainly present in the SR loop. However, it is not equipped with the capability of death as structural dissolution, except for partial dissolution: the disappearance of the umbilical cord.

A Structurally Dissolvable Self-Reproducing Loop

In order to accomplish at the same time the following two tasks—to completely emulate the abovementioned properties of the SR loop and to introduce the capability of structural dissolution, it was decided to introduce a new *dissolving state* '8' into the set of states of the CA, while exactly preserving the states '0'–'7' and all the transition rules proposed by Langton[1]. We expected that structural dissolution would be realized through propagation of this dissolving state along the tube of the loop. Details of this implementation are described in below.

[1] As we remark later, there is *one* exception to this complete preservation.

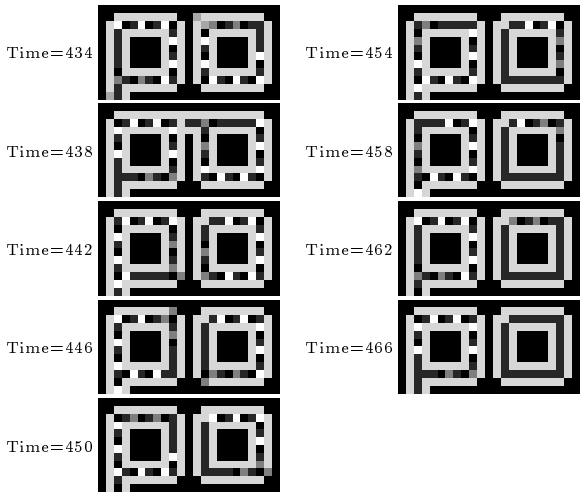

Figure 3: Death as functional failure of the SR loop. The right loop tries to thrust its arm to the left (time=438). Since the left area is already occupied by another loop, however, a sheath fragment is generated on the pathway of signals at the upper left part of the right loop (time=442). Signals propagating in the loop are absorbed one after another by the generated fragment (time=446–462). Eventually, all the signals have been extinguished, and only a circular tube filled with core states are left (time=466).

First, we need to address a technical problem inherent in the rules published by Langton, as those were limited to an *indispensable* rule set for simple self-reproduction only, while many situations ("neighborhoods") still remained undefined. We suppose that Langton implicitly assumed that the environment in which the loops would expand was itself infinite, so that the loops would not encounter any irregular situation not previously defined in the transition rules. However, if space is designed to be finite by imposing periodic, or free, boundary conditions at the edges, it is obvious that those inhabitants will eventually face the limitation of space and the appearance of irregular situations will cause their activities to halt. To avoid this inconvenience, before introducing the possibility of structural dissolution, the transition rules needed to be extended to redefine rules which had been left undefined in Langton's SR loop, by a natural extension of the ideas of Codd and Langton (Codd 1968; Langton 1984) as follows:

1. A background state '0' in the tube next to a core state '1' will turn to '1'. All other '0's will remain as is.
2. A core state '1' in the tube next to a signal state '7' will turn to '7'. Or, a '1' in the tube next to a signal state '6' will turn to '6'. Or, a '1' in the tube next to a signal state '4' will turn to '4'.
3. Signal states '4', '6' and '7' in the tube next to '0' will turn to '0'.
4. A sheath state '2' next to a signal state '3' will turn to '1'. Or, a '2' next to another '2' will remain as is.

Extensions 1, 2 and 3 define general rules for propagation of signals in the tube, and extension 4 defines general rules for the connection of two tubes. The criterion for judgment whether a cell is in the tube or not was taken to be whether at least two cells in the state '1', '2', '4', '6' or '7' are included in the four cells neighboring itself.

Second, a new *dissolving state* '8' was introduced into the set of states of the CA with the following transition rules:

1. A state '8' will unconditionally turn to '0'.
2. When neighboring an '8',
   (a) both background states and core states ('0' and '1') will turn to '8' if there is a sheath state or a signal state in the four cells next to themselves. This rule represents *infection* of dissolving states. Otherwise, they will remain unchanged.
   (b) a sheath state and several signal states ('2', '3' and '5') will turn to '0'. This rule represents dissolution of tube structure.
   (c) the remaining signal states ('4', '6' and '7') will turn to '1'. This rule represents dissolution of signals in the tube.

Owing to these rules, the dissolving state acquires the ability to propagate along the tube and dissolve a neighboring tube structure. The direction of propagation of a dissolving state is the same as that of the signals' flow in the tube, because, if it propagates against the signals' flow, it is blocked by the sequence of signals. This behavior of the dissolving state is shown in Figure 4.

Third, only *one* alteration was made in the transition rules inherited from Langton as follows:

$$\frac{\texttt{CTRBL I}}{\texttt{11152 2}} \longrightarrow \frac{\texttt{CTRBL I}}{\texttt{11152 8}}$$

Here, `CTRBL` and `I` stand for the states of neighbor cells and the image of transition, respectively. This alteration implies that the SDSR loop will generate a dissolving state in itself for the situation in which the SR loop will generate a sheath fragment in itself at the beginning of death process.

Fourth, finally, it was decided that all the rules left undefined after the above definitions are implemented are uniformly directed to the dissolving state '8'.

Via the previous definitions, once a site takes on the dissolving state, a continuous structure which includes that site will be extinguished quickly by the dissolving state propagating in the tube. Thus, the SDSR loop acquires the capability of structural dissolution in addition to self-reproduction.

The SDSR loop designed here can dissolve itself in the manner depicted in Figure 5. This can be regarded

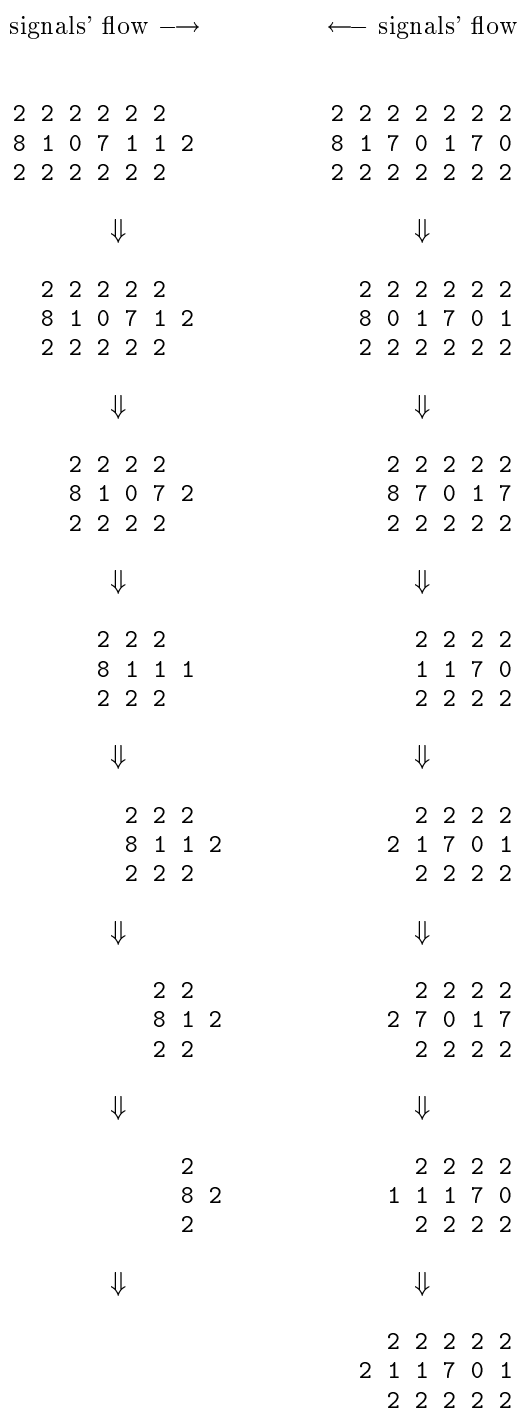

Figure 4: Behavior of the dissolving state '8'. Cells not explicitly specified are in background state '0'. When a dissolving state propagates in the same direction as the signal flows (left), it can completely dissolve the structure to the tip of the tube. However, when a dissolving state propagates against the direction of flow (right), it is blocked by the sequence of signals. For these reasons, a dissolving state will extinguish the tube structure along the same direction as the signals' flow.

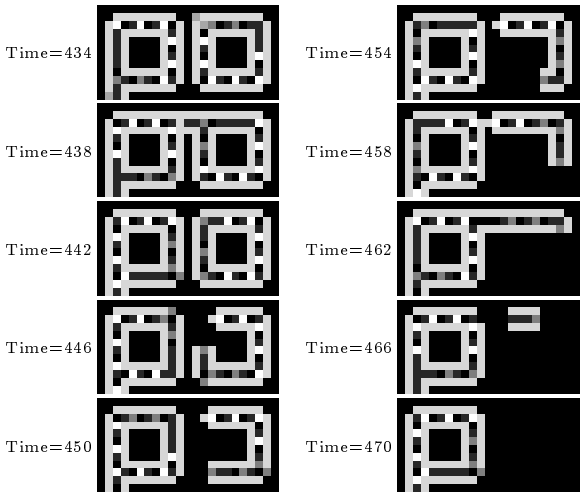

Figure 5: Death as structural dissolution of the SDSR loop. The right loop tries to thrust its arm to the left (time=438). Since the left area is already occupied by another loop, however, a dissolving state is generated on the pathway of signals at the upper left part of the right loop (time=442). The dissolving state propagates counterclockwise along the tube and dissolves neighboring sheaths one after another (time=446–462). Eventually, the structure of the right loop has been completely dissolved (time=466–470).

as a phenomenon similar to programmed death of biological cells, such as apoptosis. However, it is important to point out the fact that structural dissolution of the SDSR loop is programmed not in the genes of a living organism, but into the transition rules, the natural laws of the very world.

In addition, the SDSR loop also acquires some ability to overcome external difficulties. For example, when several obstacles are placed in front of the loop, it is possible that the loop eliminates them by dissolving its organ (i.e., the tip of the arm) together with obstacles and reproduces itself correctly, as shown in Figure 6. This can be regarded as a phenomenon similar to the cutting of a lizard's tail, or the vomiting of internal organs of sea cucumbers, that is, the action of disposing partial organs of an individual in order to overcome external difficulties and achieve survival of the individual.

Experiment

In this section, several experiments using SR loops and SDSR loops are reported. The SR loop is provided with the same extension of transition rules as the SDSR loop except for the rules concerned with the dissolving state '8'. All sites under undefined situations in the SR loop are set to remain as they are.

Self-reproduction in infinite space

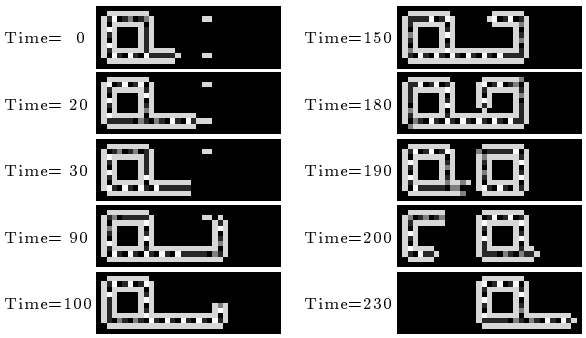

Figure 6: Structural dissolution of organs of the SDSR loop. Two sheath fragments are placed in the area in which the loop intends to reproduce its offspring (time=0). As the loop thrusts an arm, a dissolving state appears because of collision of a tip of the arm with a sheath fragment. The dissolving state extinguishes the fragment together with the tip (time=20–100). After the loop has managed to eliminate obstacles in such a way, it reproduces the offspring correctly into the right area (time=150–190). However, because the length of the arm is changed in the process of elimination of fragments, an inconsistent situation with the mechanism of the loop has developed in the parent, and the structure of the parent loop is consequently dissolved (time=190–230).

The first experiment is to breed loops with no restriction due to finite space. Figure 7 shows the development of the spatial distribution of SR loops and SDSR loops in infinite space, compared with each other. One generation takes 151 CA updates, which the loop needs for one complete self-reproduction.

The behavior of SDSR loops at the edge of the colony is identical to that of SR loops at the same location, because there is no deficit in space so that no dissolving states appear in the SDSR loops at that point. However, at the core of the colony, it is observed that many SDSR loops dissolve their own structure and provide new space for neighbor loops to reproduce themselves, while corpses of SR loops which died because of functional failure remain at the same location in the "control" world of SR loops. Thus the colony of SDSR loops appears more sparse.

Figure 8 shows the temporal development of the number of living individuals in the process of self-reproduction of both SR loops and SDSR loops. We can see from this figure that the number of living SDSR loops is much larger than that of living SR loops. Since SDSR loops can reproduce into the central area of the colony (which is filled with corpses in the world of SR loops,) they arrange themselves into the shape of a collapsing spiral. We can therefore estimate that the number of living individuals of SDSR loops approaches $O(\text{Generation}^2)$ as time proceeds, substantially different from the number of living individuals of SR loops, which is estimated to be $O(\text{Generation})$ as they can

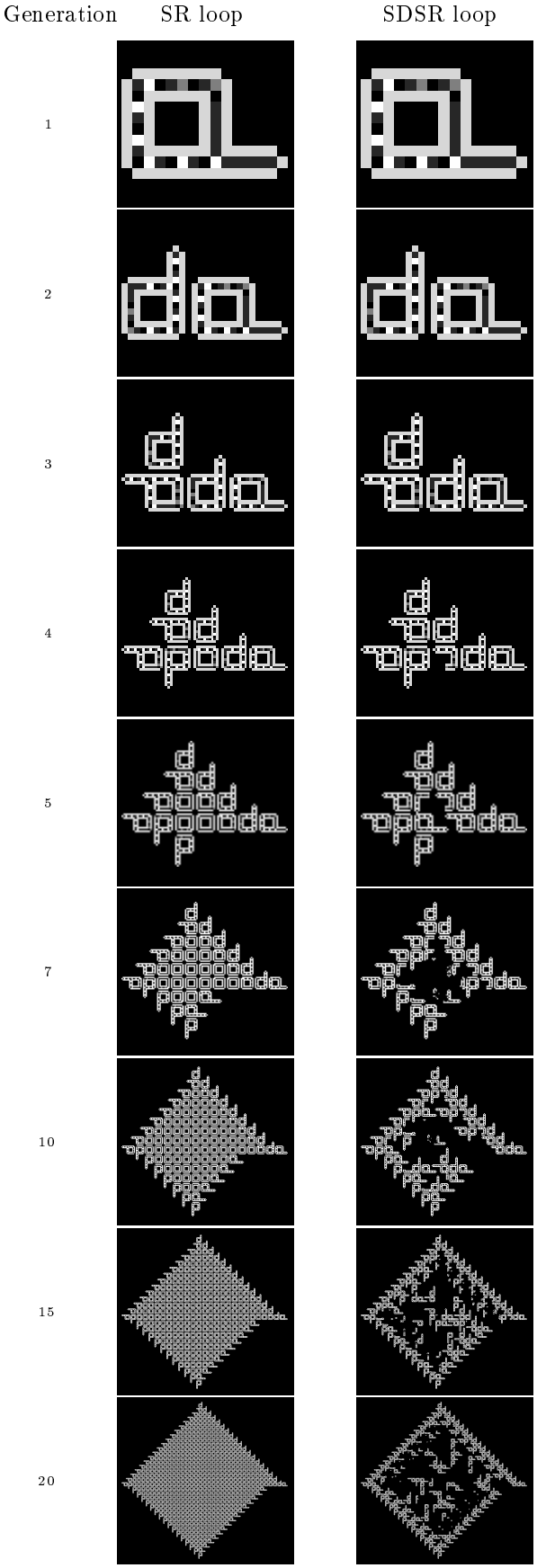

Figure 7: Development of spatial distribution of SR/SDSR loops in infinite space. Each picture is scaled differently to the size of the colony.

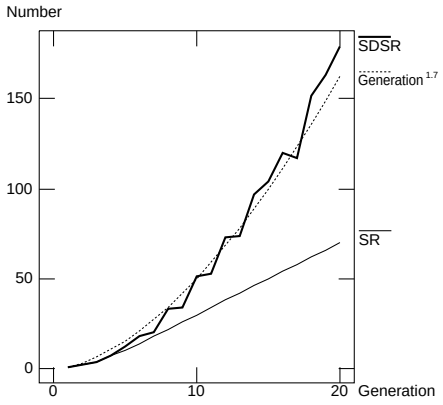

Figure 8: Development of the number of living loops in Figure 7. The curve of Generation$^{1.7}$ is drawn for reference.

reproduce only at the edge of the colony.

Self-reproduction in finite space

The second experiment involves breeding loops in *finite* space. Under this condition, the advantage of SDSR loops will become even more apparent than in the former experiment. Figure 9 shows the evolution of the spatial distribution of SR loops and SDSR loops in finite space, just as in Figure 7. The size of the space is restricted to 200×200 sites, where wrapping (periodic) boundary conditions have been applied in both x and y directions.

In the world of SR loops, when the opposite edges of the colony collide with each other due to the periodicity of space, the irregularity of the emerging situation leads to a failure of the loops' function, so that their self-reproductive behavior halts. Eventually, the entire space is filled with static patterns including corpses of loops. After that, no changes can happen in this world ever more. On the other hand, in the SDSR loops' world, as new regions, which can be used for self-reproduction of new loops, are produced continuously by structural dissolution, the self-reproduction of loops is actively maintained. Although SDSR loops have a probability of accidental extinction of species caused by structural dissolution, they continue self-reproduction for a significantly longer period longer of time, at least ten thousand generations in this experiment. Thus, there can be no doubt that SDSR loops have attained a semi-permanent state of dynamic stability, while SR loops tend to fall into a static state without living behavior.

In addition, we observed a number of *merged* loops, strange configurations shown in Figure 10, which were produced in the course of self-reproduction of SDSR loops. Because SDSR loops can continue their self-reproductive behavior for a long period owing to structural dissolution, they are faced many times by rare situations which can produce these merged loops by

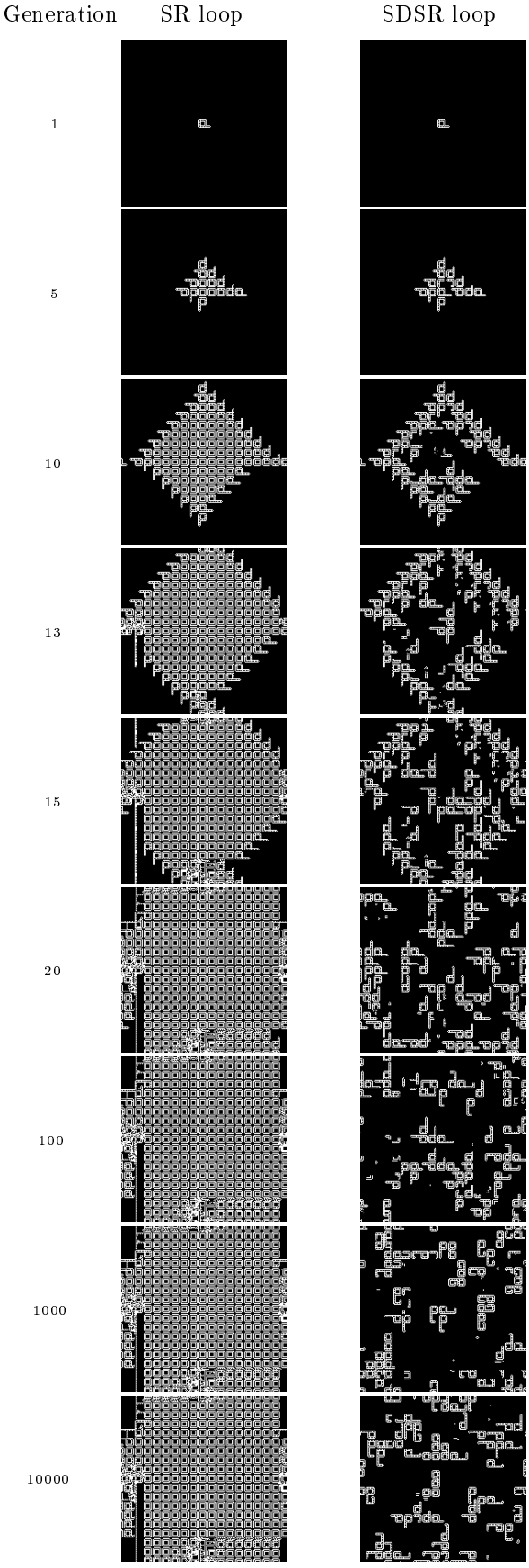

Figure 9: Development of spatial distribution of SR/SDSR loops in finite space. Each picture is scaled to 200×200 cells.

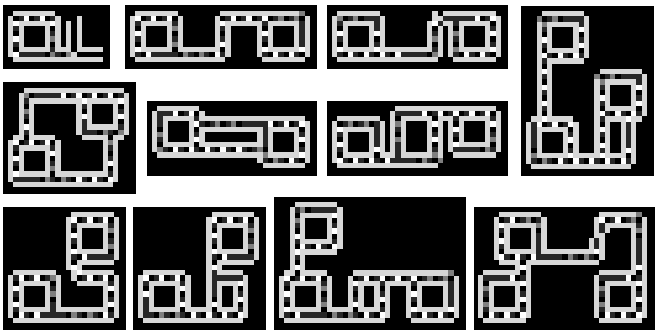

Figure 10: Examples of merged loops produced through the interaction of phenotypes of SDSR loops in the course of self-reproduction in Figure 9.

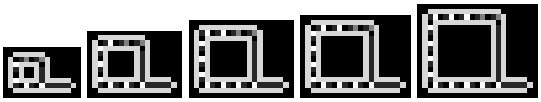

Figure 11: Examples of loops of different species. The name for each species is (temporarily) the number of signal states '7' contained in the loop of that species.

direct interaction of phenotypes. However, since they are generated by bonding arms of more than one loop, they are destined to lose their construction arms which are necessary for self-reproduction. In this sense, they can be regarded as corpses having lost the capability of self-reproduction because of functional failure.

Struggle for existence in finite space

The third experiment is to observe the struggle for existence among SDSR loops of different species in finite space. Even though Langton's loop contains exactly six signal states '7', we can construct loops of arbitrary size using extended transition rules, as long as no less than four signal states '7' are contained in the loop. Figure 11 shows examples of loops of different species.

When loops of two different species were placed and bred in the same finite space, we observed that in the SDSR loops' world one species drove the other into extinction in less than ten thousand updates. Figure 12 shows an example of competition between species 4 and 6. It is observed that small species generally fit this world better than big ones. This is a trivial result as the smaller the size of loops, the faster they can reproduce themselves (as the gestation time is shorter) and the slighter the damage due to structural dissolution for the entire colony.

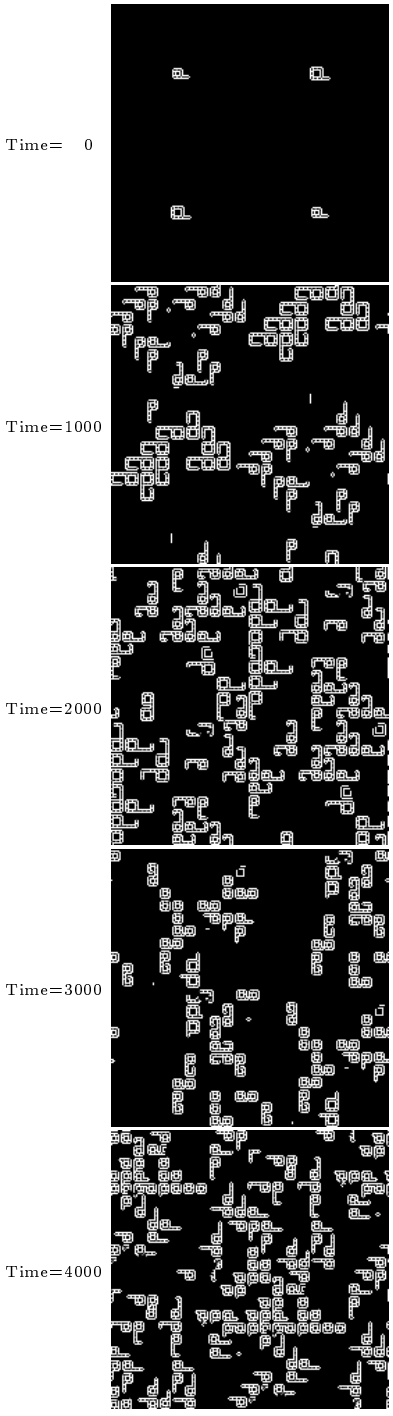

Figure 12: Example of struggle for existence between loops of species 4 and 6. At the beginning, loops of species 4 are placed in the upper left and lower right regions of the space, and loops of species 6 in the upper right and lower left regions (time=0). As time proceeds, loops of species 4 show that they are superior to those of species 6 (time=1000–3000). Eventually all loops of species 6 are exterminated (time=4000). Each picture is scaled to 200 × 200 cells.

Discussion

Significance of structural dissolution

In the previous sections, we compared the behavior of SDSR loops to that of SR loops. Both loops are identical to each other except for the rules concerned with the dissolving state '8'. As a result, SDSR loops show several unique phenomena never observed in the world of SR loops, such as (1) an ability to overcome external difficulties by means of organic dissolution, (2) significant increase in the number of living loops when bred in infinite space, (3) continuous self-reproduction in finite space, (4) production of many merged loops in the course of self-reproduction, and (5) competitive exclusion acting between loops of different species.

Because the phenomena (2), (4) and (5) can be regarded as by-products of (3), the substantial meaning of structural dissolution lies in (1) and (3). The difference between them is the level at which structural dissolution occurs: the organic, or the individual, level. Even though we usually view the latter as the cessation of life, the level of dissolution is actually not essential to the consideration of the behavior of the whole system. The important fact is that both (1) and (3) have a common point in being a phenomenon of *disappearance of a subsystem which becomes inconsistent with the environment.*

Thus, it is evident that structural dissolution functions as a kind of negative feedback mechanism. Resources having been owned by the dissolved subsystem will be re-utilized by the other subsystem. Repetition of such processes provides the whole system with dynamic and adaptive stability, and furthermore, probability of evolution. For instance, an individual can secure its living state by dissolution of partial organs, and a colony can continue its dynamic behavior by dissolution of individuals.

Strategic death based on structural dissolution

Note again here that the mechanism of structural dissolution in this study is not described in the "genes" of the loops, but rather is embedded in the transition rules which govern the dynamics of the CA. In contrast, as was pointed out by Todd (Todd 1993), if death is genetically programmed in individuals, those individuals are subject to being driven into extinction in the course of natural selection by the emergence of *immortal* individuals which have lost their genes of death. Still, many genes concerned directly with aging and death have recently been discovered and discussed in the field of molecular genetics. These discoveries teach us that death is effectively preprogrammed in real creatures by genetic means. What, then, should we conclude from the fact that genetic programs implying aging and death actually exist while avoiding being eliminated through natural selection?

We would like to offer the guess that death programmed by genetic means can be effective and remain in the population *if a primitive mechanism of structural dissolution is embedded in the basic laws of Nature,* such as the transition rules of CA adopted in this study. In other words, if the world is furnished with the rule that *everything will change sometime no matter how much you invest to preserve it,* the strategy of dynamic development of structures with positive dissolution of them will be more efficient than the strategy of static maintenance of fixed structures, and as a consequence death programmed in genes can be selected by living organisms. The other extreme of self-preservation is to force continuation of existence by constructing extra-strong structures in a static equilibrated system without dissolution, such as the structure of carbon atoms in diamond. However, such structures are generally simple, regular and static, and cannot be the source of complex and dynamic behavior characteristic of life. Because life is a structure which emerges in a system far from equilibrium, there may always be an essential probability of it changing its phase. Then, it is much more likely that strategic death has an advantage over other strategies and becomes the substantial characteristic of life.

Primitive evolution in SDSR loops' world

Before concluding this article, let us briefly consider here the evolvability of SDSR loops. The fact that both alteration of phenotypes caused by their direct interaction and competitive exclusion acting between loops of different species are observed in the world of SDSR loops suggests that the SDSR loop is potentially evolvable with mutations caused by the *interaction of phenotypes.* It is easy to imagine that, if a self-reproducing offspring different from its parent loop appears through a situation such as the merger of parent loops, and if it fits the laws of the world better than its parents, that it would spread through space and drive the parent species into extinction.

On the other hand, we usually think that the phenotype of life develops mostly according to its genotype, so that the evolution of life is caused by accidental changes which might occur to its genotype. This principle is based on the idea that a biological cell is regarded as a universal constructor which can control external/internal environments well and faithfully construct another cell according to DNA 'tapes.' Of course, this is almost certainly true with respect to sophisticated life forms such as eukaryotic organisms including human beings.

However, as mentioned by Langton (Langton 1984), there can be little doubt that life at the ancient dawn was *not* a universal constructor. At that time, the genotypes of living objects may have been physical structures at the *same* scale as their phenotypes, so that the genotype may have had some phenotypical character, and *vice versa.* Thus, it is very likely that evolution of life at that time was accomplished not only by change of genotypes but also by such environmen-

tal factors as direct interaction of phenotypes—in other words, such environmental factors could alter how the genotype is interpreted into a phenotype. Production of merged loops in the world of SDSR loops resembles the beginning of such a process of primitive evolution. Since both genotype and phenotype of the SDSR loop are configurations of the same scale which can affect each other, the SDSR loop (after some further development) will be a useful model for investigating the primitive evolution of life.

Conclusion

In this study, the SDSR loop which has the capability of structural dissolution was implemented through an improvement in Langton's SR loop. According to the results of several experiments using SDSR loops, remarkable behavior of dynamic stability and potential evolvability was observed, which has never been seen in the world of SR loops.[2]

We believe that, through the extension of rules given in this study, Langton's SR loop having been no more than a simple model of self-reproduction has begun to step toward an entity which could well contribute to the elucidation of the dynamics and history of life. With this conviction, we are now tackling the question *how the SDSR loop can be made to actually evolve*. This effort would represent the basis for the process of natural selection and evolution by means of a set of interacting *virtual state machines* embedded in CA, as foretold by Langton (Langton 1986).

Acknowledgments

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[2] A WWW server which provides information about the SDSR loop is open on the following place:

http://proton.is.s.u-tokyo.ac.jp/~sayama/sdsr/

This site contains color movies of SDSR loops in action which are inserted as figures in this article. They may be useful for the reader in helping to understand the behavior of SDSR loops.