

A New Structurally Dissolvable Self-Reproducing Loop Evolving in a Simple Cellular Automata Space

Hiroki Sayama

New England Complex
Systems Institute
24 Mt. Auburn St.
Cambridge, MA 02138
sayama@neeci.org

Abstract We constructed a simple evolutionary system, “evoloop,” on a deterministic nine-state five-neighbor cellular automata (CA) space by improving the structurally dissolvable self-reproducing loop we had previously contrived [14] after Langton’s self-reproducing loop [7]. The principal role of this improvement is to enhance the adaptability (a degree of the variety of situations in which structures in the CA space can operate regularly) of the self-reproductive mechanism of loops. The experiment with evoloop met with the intriguing result that, though no mechanism was explicitly provided to promote evolution, the loops varied through direct interaction of their phenotypes, smaller individuals were naturally selected thanks to their quicker self-reproductive ability, and the whole population gradually evolved toward the smallest ones. This result gives a unique example of evolution of self-replicators where genotypical variation is caused by precedent phenotypical variation. Such interrelation of genotype and phenotype would be one of the important factors driving the evolutionary process of primitive life forms that might have actually occurred in ancient times.

Keywords

cellular automata, evolution, self-reproduction, structural dissolution

1 Introduction

This article gives an affirmative answer to the question of whether it is possible to construct an *evolutionary process*—here I view this phrase as a process in which self-replicators vary and fitter individuals are naturally selected to proliferate in the colony—by utilizing and tuning up a simple deterministic cellular automata (CA) space. This study should move us closer to a representation of the process of natural selection and evolution by means of a set of interacting *virtual state machines* embedded in CA, as foretold by Langton [8].

CA are dynamical systems capable of representing extremely complex nonlinear phenomena where time, space, and states of sites are all discrete. They consist of identical automata (cells or sites) uniformly arranged on the lattice points of a D -dimensional discrete space Z^D , whose temporal development is formally represented by

$$s_{t+1}(z) = \Delta(s_t(z + z_0), s_t(z + z_1), \dots, s_t(z + z_{n-1}))$$

where $s_t(z) \in \Sigma$ is a state of an automaton located in coordinate $z \in Z^D$ at time t , Σ is a set of finite states each automaton may take, $\Delta: \Sigma^n \rightarrow \Sigma$ represents *state-transition*

rules, and $N = (z_0, z_1, \dots, z_{n-1})$ ($z_i \in Z^D$) is a *neighborhood template*. The function s_t , which maps coordinates to states, is referred to as a *configuration* of the CA at time t . The transition of states occurs simultaneously and uniformly to all sites in the CA space. CA with $D = 1, 2, 3$ have been studied so far; $D = 2$ for all CA discussed in this article.

To realize an evolutionary system on a simple CA space, I previously utilized Langton's self-reproducing (SR) loop and carried out a simple improvement—introduction of structural dissolution (a form of death) into the state-transition rules of Langton's CA [14]. I showed through experiments using the structurally dissolvable self-reproducing (SDSR) loop implemented there that the introduction of structural dissolution granted dynamic behavior and potential capability of evolution to the SR loop. However, the SDSR loop could not actually evolve yet in that stage.

In this article, I transformed the SDSR loop into an actually evolving one in a simple, deterministic nine-state five-neighbor CA space, by enhancing the adaptability (a degree of the variety of situations in which structures in the CA space can retain their regular operations) of the self-reproductive mechanism described by the state-transition rules, besides a slight modification of initial structure of the loop. The experiment with the improved loop, named “evolloop,” met with the intriguing result that, though no mechanism was explicitly provided to promote evolution, some evolutionary process emerged in the CA space, where loops varied by direct interaction of their phenotypes, smaller individuals were naturally selected thanks to their quicker self-reproductive ability, and the whole population gradually evolved toward the smallest ones. It is characteristic that in this result genotypical variation was caused by precedent phenotypical variation, which is quite different from the idea of mutation usually considered. It suggests that such interrelation of genotype and phenotype would be one of the important factors driving the evolutionary process of primitive life forms that might have actually occurred in ancient times.

2 Former Works

Langton's SR loop [7] is one of the most famous models of self-reproduction constructed by means of CA. It was implemented on a simple eight-state, five-neighbor CA space by modifying a periodic emitter that had been a component of Codd's automata [4]. Figure 1 shows the manner of self-reproduction of the SR loop. Names and functions of the states in Langton's CA are listed in Table 1. This loop contains several signal states 4 and 7 in its Q-shaped tube structure enclosed by sheath states 2. Each signal travels along the tube counterclockwise and splits into two identical signals at the T-junction of the tube. One of them circulates into the loop again and the other goes down toward the tip of a construction arm that is thrust outward from the loop. When a signal reaches the tip of the arm, 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 has turned left three times, the tip and the root bond together to form a new offspring loop, and then the connection between parent and offspring—which Langton called the “umbilical cord”—disappears. The SR loop reproduces itself in such a way in just 151 updates and will try to do the same again in the same way but rotated by 90 degrees counterclockwise, until its self-reproductive activity halts because of a shortage of space.

After this SR loop, I previously contrived the SDSR loop capable of structural dissolution (a form of death) as well as self-reproduction, where a new *dissolving state* 8 was introduced into the set of states of the CA while exactly preserving states 0–7 and all state-transition rules relevant to them [14]. The dissolving state was granted with an ability to travel along a tube and dissolve neighboring structures so that once

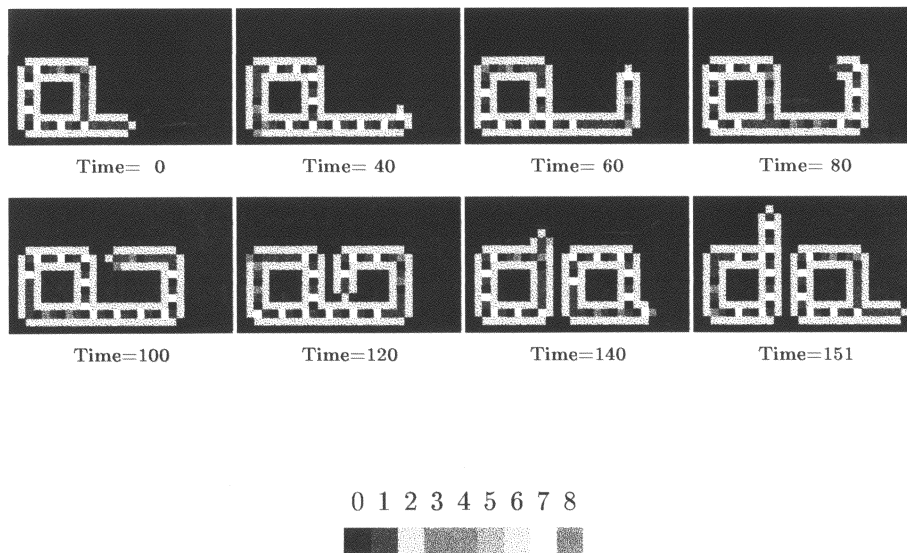


Figure 1. Self-reproduction of Langton's SR loop. The lower chart indicates correspondence between states of sites and shades of pixels in the figure. The following monochrome figures are also drawn according to this chart.

Table 1. Names (some of them are temporarily used only in this article) and functions of the states in the CA of Langton's SR loop.

Fundamental elements

State	Name	Functions
0	Background	The quiescent state of this CA
1	Core	To fill the tube of the loop and conduct signals in it
2	Sheath	To form the tube structure of the loop

Signals

State	Name	Functions	
3	Left indicator	To support left turning of the arm	
	Bonder	To support bonding of the two arms	
	Sprout generator	To support germinating of the offspring's new sprout	
	Sprout capper	To cap the tip of the offspring's sprout	
4	Gene	To keep genetic information of left turning of the arm and finishing of growth of the offspring's sprout	
	Umbilical cord dissolver	To dissolve the umbilical cord between parent and offspring	
5	Messenger	To point where the parent should germinate a new sprout	
	Sprout guide	To support growth of the parent's sprout	
	Messenger	To point where the offspring should germinate a new sprout	
6	Sprout guide	To support growth of the offspring's sprout	
	Sprout finisher	To finish growth of the offspring's sprout	
	7	Gene	To keep genetic information of straight growth of the arm and the offspring's sprout

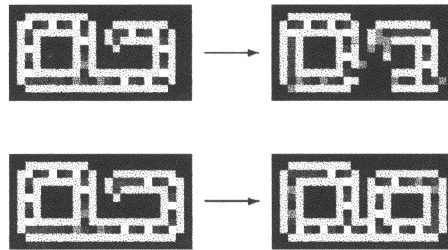


Figure 2. The results if the form of the arm of the SDSR loop is altered by force during self-reproduction.

a site takes on the dissolving state, a continuous structure that includes that site will be extinguished quickly. The SDSR loop shows several characteristic behaviors that were never seen in the SR loop world, such as continuous self-reproduction in finite space, production of many merged loops, competitive exclusion between loops of different sizes living in the same finite space, and so on. However, the SDSR loop could not actually evolve, which is the very problem resolved in the following sections.

3 Evoloop: An Evolving SDSR Loop

3.1 Concepts

Since natural selection acting among different kinds of loops has already been realized in the SDSR loop, what should be done next to realize the evolution of loops is to induce their variation. The approach often taken to induce variation in earlier artificial evolutionary systems is to fluctuate genomes of artificial organisms explicitly by using pseudo-random numbers or something like that. On the other hand, many sterile variants were produced in the experiment using SDSR loops that were carried out without any stochastic operation [14]. So, if we can make them stay and proliferate in the population, it should be possible to simulate all the essentials necessary for evolution on a completely deterministic system, which would greatly facilitate simplification of the model. I therefore decided that no stochastic mutation would be explicitly used in this study; specifically, induction of variation was achieved in implicit ways—through enhancing the adaptability of the self-reproductive mechanism of the SDSR loop and slightly modifying its initial structure. In this section, a new evolving SDSR loop called “evoloop” is implemented step by step, and its characteristic behaviors are observed.

3.2 Problem in the State-Transition Rules of the SDSR Loop

The reason the SDSR loop did not show any apparent evolvability is that its state-transition rules, which designated all mechanisms necessary for self-reproduction, were specialized only for a set of particular situations that appeared in an ordinary self-reproductive process of the original SR loop. Above all, functions of signals 3, 5, and 6 that were strongly related to germination of a new arm were strongly dependent on situations of their vicinity; thus, without more extension of the state-transition rules concerning these signals, even a slight fluctuation such as a one-site discrepancy in propagation of signals could easily ruin the self-reproductive process of the loop.

The CA space discussed here involves no stochastic operation such as random mutation of genotype; if the evolutionary process of loops occurred in such a deterministic universe, it should be driven by direct alteration added to phenotypes of offspring loops during self-reproductive processes. However, the SDSR loop cannot reproduce any self-reproductive offspring when the form of its arm is altered by force during its self-reproductive process; it either generates a dissolving state (Figure 2, upper) or

falls into a sterile structure (Figure 2, lower). In such cases, neither connection of the tip of the arm and its root nor dissolution of the umbilical cord between parent and offspring occurs correctly, because in these cases the location of genes near a bonding T-junction is different from the situation expected by Langton's state-transition rules. Such rigidity of rules seems to have prohibited evolution of the SDSR loop.

3.3 Reconstructing the State-Transition Rules

To resolve the problem of the SDSR loop mentioned above, it was necessary to make the self-reproductive mechanism described by the state-transition rules more "adaptable." The word "adaptability" used here intuitively means a degree of the variety of situations in which structures in the CA space can retain their regular operations (its quantitative evaluation will be done in Section 3.6).

To enhance the adaptability of the state-transition rules of the SDSR loop, I reconstructed mechanisms of its self-reproduction carefully, while keeping fundamental behaviors of signals as is. I first defined general rules concerned with sustenance of sheath structures and propagation of genes. Next, to clarify what behaviors must be realized in the state-transition rules for self-reproduction, I divided a self-reproductive process of the loop into the following six phases:

1. Lengthen the construction arm,
2. Turn the tip of the arm left,
3. Bond the tip and the root of the arm together,
4. Dissolve the umbilical cord between parent and offspring,
5. Germinate a new sprout of the arm,
6. Lengthen the new sprout of the arm.

Then, I manually refined each part of the state-transition rules relevant to each of the six phases to make it adaptable to a greater variety of situations than before.

On granting adaptability to the self-reproductive mechanism of the SDSR loop, some inadvertent complication of the old state-transition rules became a nuisance. Specifically, in the CA of the SR/SDSR loops, rules concerned with bonding of the tip and the root of the arm and germination of a new sprout of the arm in the parent loop were constructed in such a heuristic way completely dependent on some specific situations that they defied any modification. Ideally, the former mechanism should be improved to be able to bond the tip and the root whenever and wherever they meet, and the latter should be much simpler, like germination of a sprout in the offspring that had been realized in a relatively neat manner. In addition, since old rules had some redundancy in that the location of a new sprout of the parent's arm was pointed by a messenger 5 traveling on the sheath while that of the offspring's was pointed by a different messenger 6 traveling in the tube, these two mechanisms should be integrated into an identical one.

I conducted a thorough revision of the state-transition rules to fix these problems. For example, the mechanism for germination and growth of a new sprout was made to be identical in both parent and offspring. To equalize the length of the parent's sprout with that of the offspring, I let the sprout be explicitly stimulated to grow by all of gene 7s contained in the loop in any case. As a result, the length of the umbilical cord became longer than that in the SR/SDSR loops. For dissolution of such a lengthened umbilical cord, signal 6 was reassigned to be a special umbilical cord dissolver much more powerful than that in the old rules. Functions formerly possessed by signal 6 were

Table 2. Names and functions of the states in the CA of the evoloop.

Fundamental elements		
State	Name	Functions
0	Background	The quiescent state of this CA
1	Core	To fill the tube of the loop and conduct genes in it
2	Sheath	To form the tube structure of the loop
Signals		
State	Name	Functions
3	Left indicator	To support left turning of the arm
	Bonder	To support bonding of the two arms
	Sprout generator	To support germinating of the new sprout
	Sprout capper	To cap the tip of the sprout
	Sprout finisher	To finish growth of the sprout
4	Gene	To keep genetic information of left turning of the arm and finishing of growth of the sprout
	Sprout guide	To support growth of the sprout
5	Messenger	To point where the loop should germinate a new sprout
6	Umbilical cord	To dissolve the umbilical cord between parent and
	dissolver	offspring
7	Gene	To keep genetic information of straight growth of the arm and the sprout
Dissolving state		
State	Name	Functions
8	Dissolving state	To dissolve a contiguous structure of the loop

reassigned to 3, 4, and 5 in new rules. New functions of the states in this improved CA are listed in Table 2. Due to these reassignments, the state-transition rules became more feasible to modify; thus I could easily refine the rules to make them keep their regular operations in a greater variety of situations. After these above-mentioned operations, a dissolving state 8 was introduced into the set of states of the CA in the same way as in the SDSR loop.

I eventually obtained a new loop that was extremely resistant to fluctuation of environmental conditions with neither increase in number of both states and neighborhood sites of the CA nor alteration of the basic structure of the loop. I named this “evoloop.” Figure 3 depicts general behaviors of refined phases of the self-reproductive process of the evoloop. Mechanisms concerned with phases 3, 4, 5, and 6 are reconstructed this time from scratch, while those concerned with 1 and 2 are exactly the same as in the SR/SDSR loops. Detailed mechanisms of phases 3–6 are depicted in Figures 4–7 with descriptions on their workings. How to construct a complete state-transition rule set of the evoloop is shown in the appendix.

3.4 Basic Behaviors

Self-reproduction of the evoloop is shown in Plate 1. Since the sprout of the evoloop is explicitly stimulated to grow by gene 7s contained in its body, the length of its umbilical cord is longer than that of the SR/SDSR loops. Thus, the colony of the evoloop looks

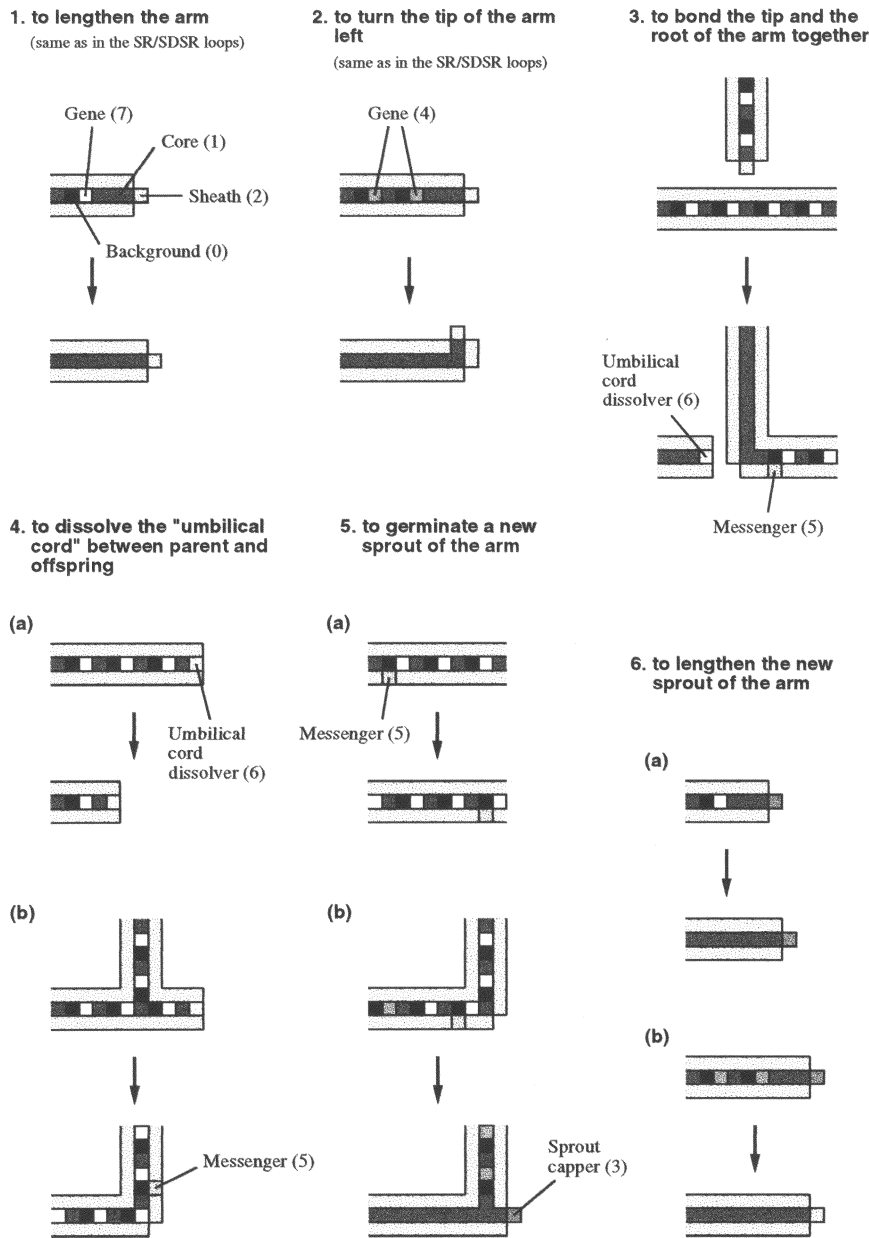


Figure 3. General behaviors of six phases of the self-reproductive process of the evoloop. Mechanisms concerned with phase 1 and 2 are exactly the same as those in the SR/SDSR loops, while those concerned with 3, 4, 5, and 6 are reconstructed from scratch (Figures 4–7).

a little sparser than that of the SR/SDSR loops. In this case, the loop contains thirteen signal 7s in its body. Hereafter the number of signal 7s in a loop will be used as a label of “species” of that loop.

It is remarkable that, owing to the adaptability enhanced above, some intriguing interactions of loops emerge in the evoloop world that have never occurred in the SDSR loop world. Plate 2 shows, for example, a takeover of the arm happening between

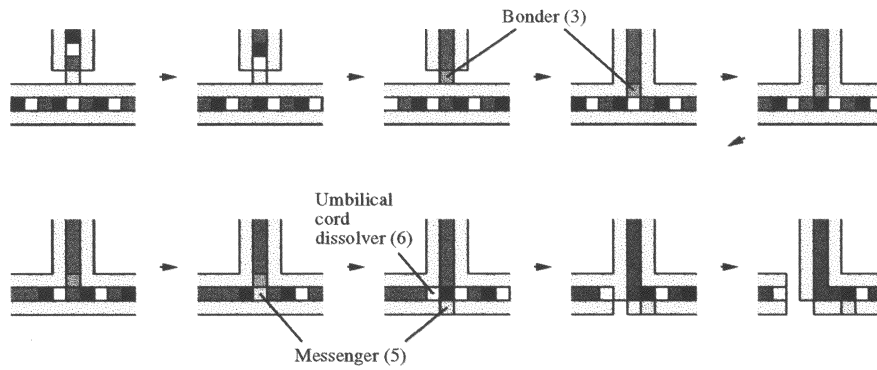


Figure 4. Mechanism of the phase to bond the tip and the root of the arm together in the evoloop. When a gene 7 hits the tip touching the middle of the arm, the sheath 2 having capped the tip turns into a bonder 3, while the gene 7 disappears. This bonder 3 moves onto the lower sheath and then waits there for another gene 7 to come from the parent loop. When a gene 7 comes into the junction point where the bonder 3 is waiting, it alters into a messenger 5. Next, the bonder 3 disappears, the gene 7 recovers through the messenger 5, an umbilical cord dissolver 6 appears out of the messenger 5, and the messenger itself goes through onto the outside sheath. The messenger 5 begins to travel along the sheath structure being trailed by the gene 7 toward the next corner, while the umbilical cord dissolver 6 goes back toward the parent loop.

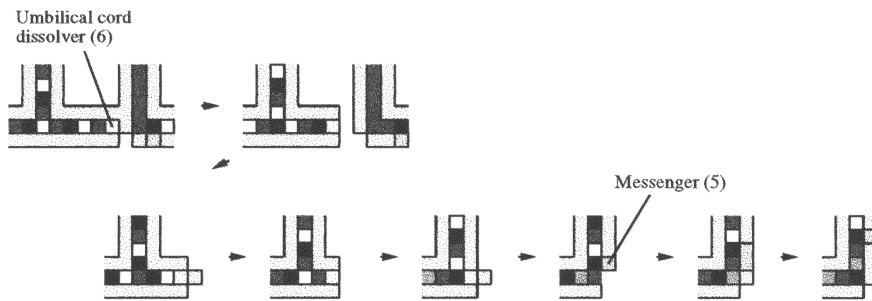


Figure 5. Mechanism of the phase to dissolve the umbilical cord between parent and offspring of the evoloop. The umbilical cord dissolver 6 breaks the connection of the cord and the offspring and begins to travel backward against the genes' flow, dissolving structures of the cord. When the dissolver 6 arrives at the T-junction (the root of the cord) in the parent loop, it generates a messenger 5 onto the sheath of the loop and itself disappears. The corner (which was formerly the T-junction) broken by the dissolver 6 is quickly repaired, and the messenger 5 begins to travel along the sheath being trailed by a gene propagating in the tube.

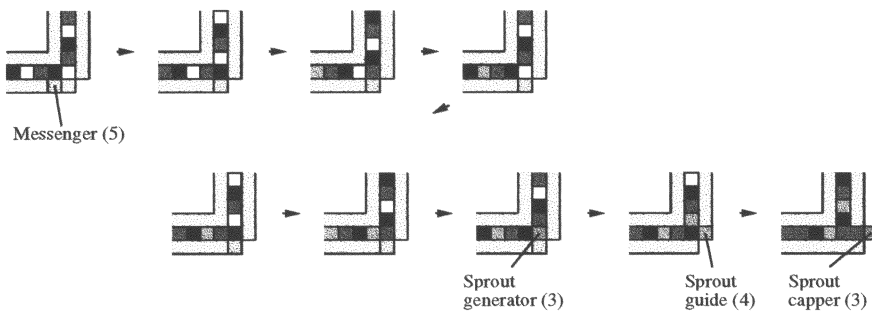


Figure 6. Mechanism of the phase to germinate a new sprout of the arm of the evoloop. When the messenger 5, having been generated in the aforementioned phases, arrives at the next corner, it begins to wait there for another gene 4. When a gene 4 comes into the corner where the messenger 5 is waiting, it alters into a sprout generator 3. Next, the gene 4 recovers from the sprout generator 3, a sprout guide 4 appears on the outside sheath out of the sprout generator 3, and the sprout generator itself and the messenger 5 disappear. The sprout guide 4 quickly turns into a new sprout of the arm capped by a sprout capter 3.

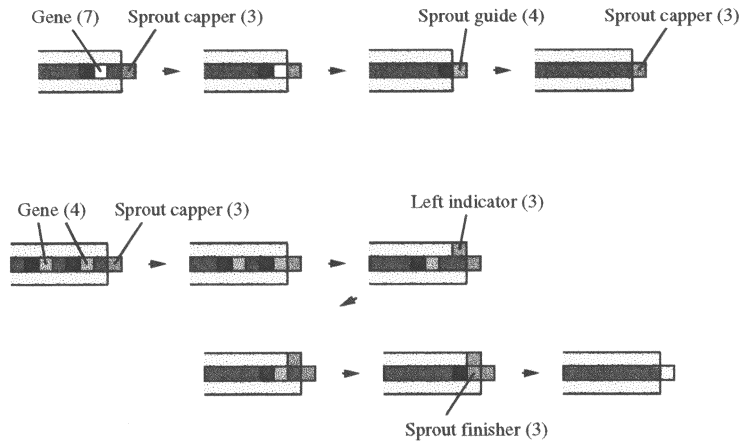


Figure 7. Mechanism of the phase to lengthen the new sprout of the arm of the evoloop. Upper: Growth of the sprout. This resembles the mechanism to lengthen the ordinary arm. When a gene 7 traveling in the tube structure hits the tip of the sprout, a sprout capper 3 having capped the tip turns into a sprout guide 4, and the gene 7 disappears. Then, the tip quickly becomes sheathed with a new sprout capper 3 and the sprout guide 4 disappears after one update; thus, the sprout becomes one site longer than before by a gene 7. Lower: Finishing of growth of the sprout. When the first gene 4 traveling in the tube structure hits the tip of the sprout, a left indicator 3 emerges on the left-hand sheath of the tip, and the gene 4 disappears. This left indicator 3 remains as is until the second gene 4 comes. When the second 4 comes into the tip of the sprout with the left indicator 3, it alters into a sprout finisher 3. Then, after one update, both the left indicator 3 and the sprout capper 3 turn into the ordinary sheath, while the sprout finisher disappears. Consequently, the sprout is changed into the ordinary arm by two gene 4s. Since the sprout is germinated by a gene 4 and changed into the ordinary arm by a pair of gene 4s, the length of the sprout becomes equal to the total number of gene 7s sandwiched between them.

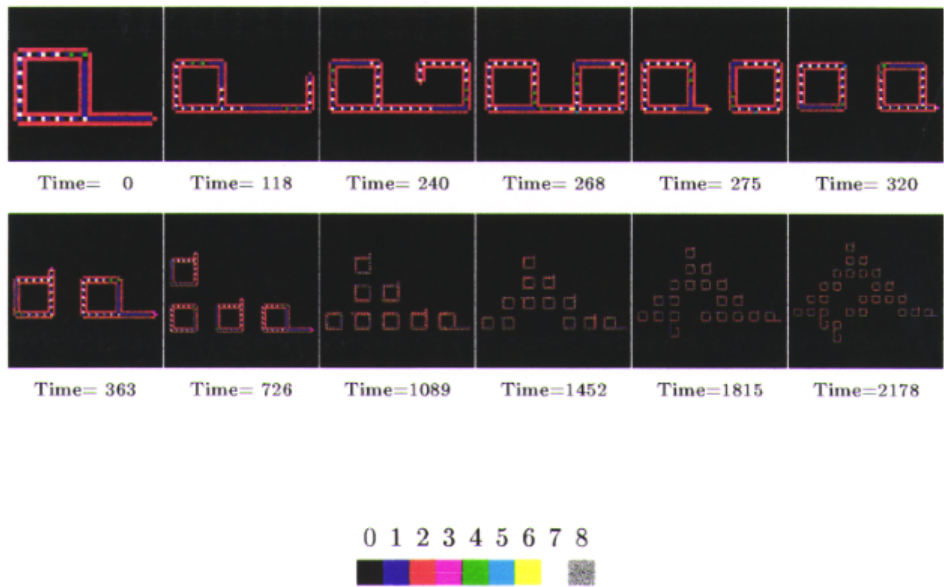


Plate 1. Self-reproduction of an evoloop of species 13 (i.e., a loop that has 13 signal 7s). Each picture is scaled differently to the size of the colony. The lower chart indicates correspondence between states of sites and colors of pixels in the figure. All color plates are drawn according to this chart.



Plate 2. Takeover of the arm caused by collision of two evoloops.

two evoloops. In this case, the right loop takes over the arm of the left loop, and consequently a small rectangular variant is produced between two loops. Due to the high adaptability of their self-reproductive mechanism, the parent loops as well as the produced variant can continue their self-reproductive activity after the accident. I expected such a direct interaction of phenotypes of evoloops to drive their evolution. Note again here that the state-transition rules of the evoloop have *no* explicit mechanism for evolution; they are merely composed of phases necessary for self-reproduction of loops.

3.5 Developing a Method of Observation

The evoloop world itself keeps no apparent information about the status of individual loops or interrelation among them, because all phenomena emerging in a space are generated only by local interactions of neighboring sites. All judgments—for example, which structure is living or dead, how genealogy of organisms is formed, when and where variation occurs—are left to the observer. This means that observation of such a world needs a considerable amount of computation for image processing in order to detect any meaningful information from the configuration of the whole CA space.

In this study, I developed another binary (two-state) CA system specialized for image processing that automatically identifies living loops in the space, and I embedded this system in the simulator software. To simplify computations involved in this process, I viewed all structures that contain an open square made of sheath 2 and signal 3 as being alive. Specifically, the configuration concerning only sheath 2 and signal 3 in the whole space is sent at some intervals to this “observer” binary CA as an initial configuration of active sites, and then the observer CA applies the following state-transition rule to the configuration until it reaches a fixed point: “An active site will remain if and only if neighboring exactly two other active sites, otherwise it will turn into a quiescent state.” Only a circular structure with no branch can survive this rule. In the evoloop world, such structures are only inner rectangles of loops, thus we can extract rough information about number and size of living loops in the space by this method.¹ After the configuration reaches a fixed point, number and size of squares are counted sequentially by the simulator software.

3.6 Evaluating the Adaptability

Comparing the adaptability of the evoloop with that of the SDSR loop is important for objective evaluation of models. The notion of adaptability has been used intuitively in this article as a degree of the variety of situations in which structures in the CA space can retain their regular operations. The regular operation of a structure can be defined here as a continuation of structure existing in the space without structural dissolution that will emerge in irregular situations. This definition suggests that the adaptability of a model can be roughly evaluated by measuring the average life expectancy (i.e., the average length of time from production to dissolution) of artificial organisms in the CA.

¹ Note that this method still involves some errors because it cannot exclude dead structures that contain square sheaths. In addition, when a structure contains two or more squares in itself (e.g., a loop that has just closed its arm), it is mistaken for two structures by this method.

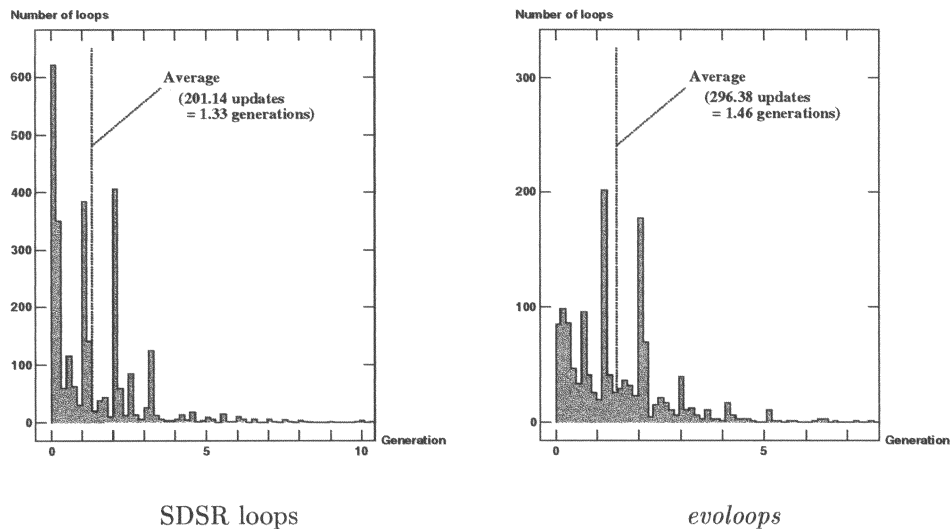


Figure 8. Histograms of distribution of lifetimes (lengths of time from production to dissolution) of SDSR loops (left) and evoloops (right) of species 6, being accumulated at scales of 25 updates. Both simulations were traced for 10,000 updates in a space of 200×200 sites with initial configurations populated by an ancestral loop of species 6. The lifetime of each loop having emerged in simulation was measured by the length of continuation of its 6×6 -site open square detected by the observer CA. These graphs are normalized so as to equalize total area of gray regions, which means total number of observed loops.

Based on this idea, I measured, using the observer CA mentioned above, lifetimes of all loops of species 6 that emerged during the first 10,000 updates of simulations of both SDSR loops and evoloops in a finite space of 200×200 sites with periodic boundary conditions. Initial configurations of both simulations were equally populated by an ancestral loop of species 6. The result is shown in Figure 8. These histograms indicate distribution of lifetimes of loops in both cases by accumulating them at scales of 25 updates. We can find a clear difference between SDSR loops and evoloops in these histograms. In the SDSR loop world (Figure 8, left), most lifetimes are of less than 25 updates, which means that these loops died immediately after their birth. On the other hand, in the evolloop world (Figure 8, right), immediate death of loops after birth is not so great, and most lifetimes are of 225–250 updates, which means that these loops died after they succeeded once in self-reproduction. Consequently, the average life expectancy of evoloops ($296.38[\text{update}]/203[\text{update/generation}] = 1.46[\text{generation}]$) is longer than that of SDSR loops ($201.04[\text{update}]/151[\text{update/generation}] = 1.33[\text{generation}]$). This result is considered to show quantitatively that the self-reproductive mechanism of the evolloop is certainly more adaptable than that of the SDSR loop.

3.7 Preliminary Experiments

To examine the evolvability of evoloops, I carried out several preliminary experiments of breeding evoloops of species 4 to 20 in finite spaces composed of 99×99 to 401×401 sites with periodic boundary conditions. Each run was traced for 50,000 updates. The results are shown in Figure 9. In these results it is indicated that the evolloop actually has some evolvability. For example, in some cases the loop evolved to that of a larger species (Figure 10, left), and in other cases it generated some variants that lost their self-reproductive ability but became capable of reproducing smaller offsprings than themselves (Figure 10, right). However, self-reproductive smaller species could not emerge yet in these preliminary experiments.

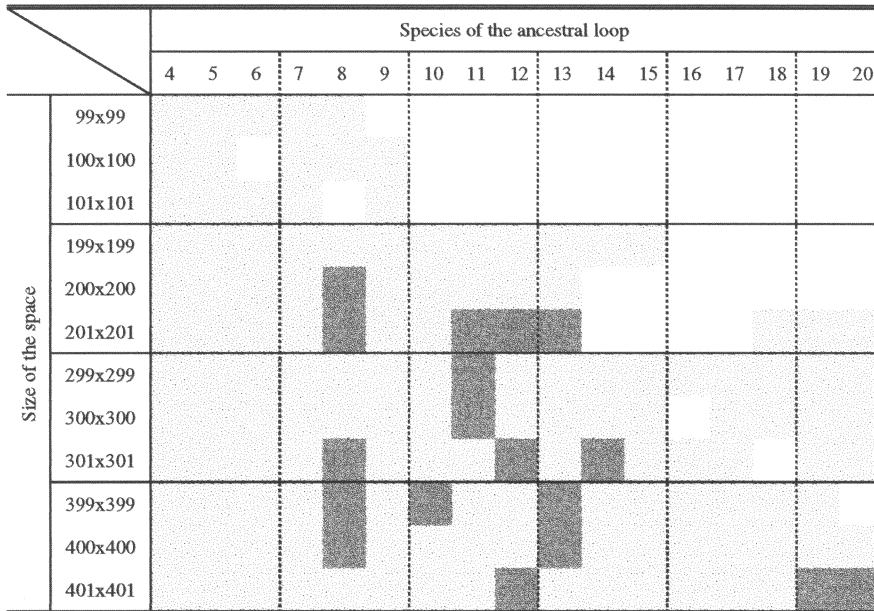


Figure 9. Results of preliminary experiments of breeding evoloops in finite spaces. The species of an ancestral loop ranges from 4 to 20, while the size of the space ranges from 99×99 to 401×401 sites. Spaces were given with periodic boundary conditions in all cases. Gray indicates that the self-reproductive activity continued dynamically for 50,000 updates in that case. Dark gray additionally indicates that the dominant species was changed to a larger one after 50,000 updates in that case. Blank means that the whole system fell into a fixed point or a short-period limit cycle before 50,000 updates.

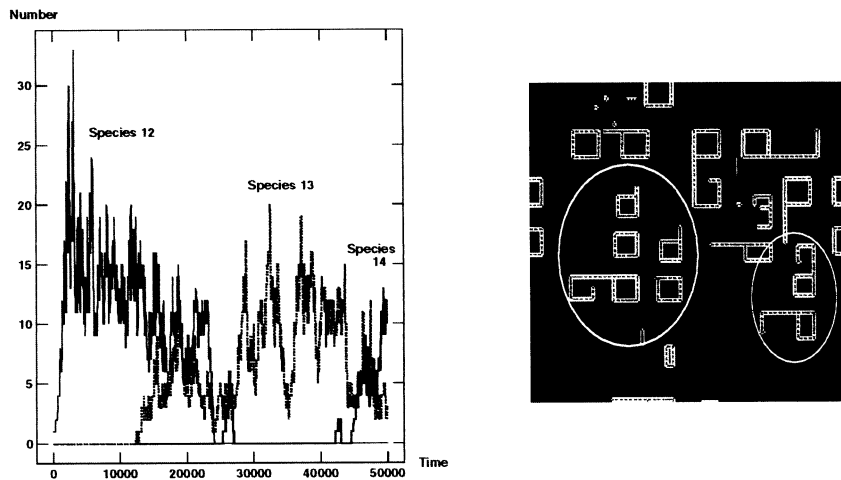


Figure 10. Evidence of the evolvability of evoloops observed in the preliminary experiments. Left: An example of evolution of the evoloop to larger species. Development of numbers of living loops is shown. The ancestor is of species 12. The space is composed of 201×201 sites. Right: An example of generation of variants that lost the self-reproductive ability but became capable of reproducing smaller offsprings (indicated by white circles). This is a snapshot taken in the run with an ancestor of species 15 and a space of 200×200 sites.

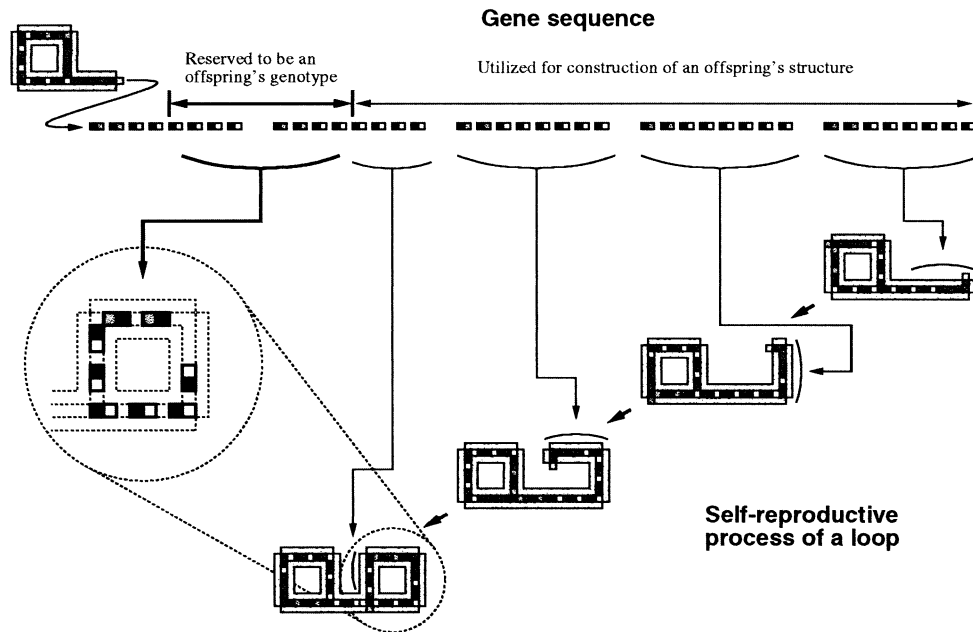


Figure 11. Manner of utilization of a gene sequence in a loop.

3.8 Modifying the Initial Structure

One explanation for why evolution toward self-reproductive smaller species did not emerge in the preliminary experiments would be that the loop in that stage did not have a mature capability of injecting enough genes into its offspring if the form of its arm was altered by some collisions with other structures during the self-reproductive process.

Generally, a genotype in a self-reproducing loop does not describe the whole shape of its phenotype, but does only an edge and a corner of the loop. The square formation of a loop emerges as a result of a repeated ontogenetic process of translating such genotypes into phenotypes. Mechanisms of closing an offspring loop, detaching offspring from parent, and germinating a new construction arm are all dependent on physical laws (state-transition rules) of the CA world, instead of being described in the genotype. Figure 11 shows a manner of utilization of a gene sequence in this process. A gene sequence of a little less than four repetitions of the genotype in the loop is used for construction of an offspring's structure, and genes contained in the subsequent region of the sequence are injected into the offspring to be its new genotype. This region can end up with genetic information that can be sufficient, insufficient, or even redundant, depending on the order of genes in the sequence. Therefore, it is likely that the order of genes will affect the self-reproductive ability of the loop.

Based on this idea, I looked for new genotypes of the evolloop that would have a stronger self-reproductive ability than before by examining various genotypical patterns. This effort by trial and error fortunately resulted in discovering that some evolloops with slightly modified genotypes (shown in Plate 3) have a stronger self-reproductive ability. The function of these genotypes is exactly the same as before, while only the order of genes differs. In the new genotypes, gene 4s are located near the front of a gene stream instead of its end. These genotypes seem convenient for a loop to inject more gene 7s into its offspring than before when some collision happens to itself. It must

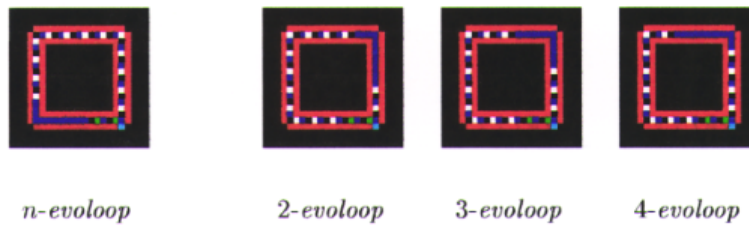


Plate 3. New genotypes of evoloops of species 13 that have a stronger self-reproductive ability. The right three loops have new genotypes of the strong self-reproductive ability in comparison with the original (leftmost one). These figures are standardized into a same state just before germinating a sprout for clarification of differences among genotypes.

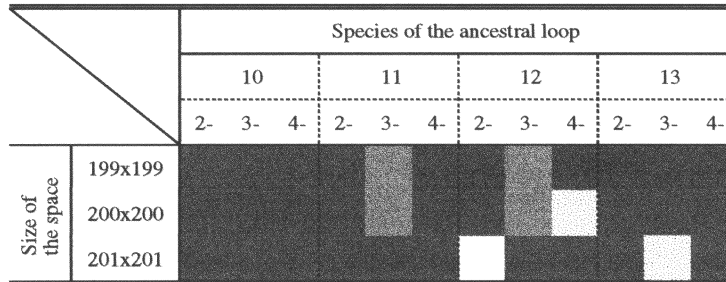


Figure 12. Results of full-scale experiments of breeding evoloops with new genotypes. The species of the ancestral loop range from 10 to 13, and 2-, 3-, and 4-evoloops were all examined. The size of the space ranges from 199 × 199 to 201 × 201 sites. Spaces were given with periodic boundary conditions in all cases. Dark gray indicates that rapid evolution of loops emerged in that case, while medium gray indicates gentle evolution of loops. Light gray means that evolution did not occur but the self-reproductive activity of loops continued for 50,000 updates. Blank means that the whole system fell into a fixed point or a short-period limit cycle before 50,000 updates.

be noted that such genotypes were not viable without the new state-transition rules implemented in this article.

In distinction from the old loop, these new loops with new genotypes are tentatively called 2-evoloop, 3-evoloop, and so on, by prefixing the number of gene 7s in front of gene 4s. According to this naming manner, the old loop should be called *n*-evoloop.

3.9 Results

I carried out full-scale experiments of breeding evoloops with new genotypes. The size of the space was decided, in consideration of both computing speed and feasibility of visualization, to be 199 × 199 to 201 × 201 sites. The loops of species 10 to 13 were selected to be ancestors as they were the largest species that rarely became extinct in the spaces of the aforementioned sizes. I examined 2-, 3-, and 4-evoloops.

These experiments resulted, in almost all cases, in evoloops varying through direct interaction of phenotypes, the whole population gradually evolving toward smaller species, and finally the space filled with the smallest one. All the results are shown in Figure 12.

A result using 2-evoloops of species 13 in a space of 200 × 200 sites is shown here for a typical example. In almost all other cases, behaviors of the whole system are qualitatively the same as this.

Plate 4 shows temporal development of configuration in the evolutionary process in that case. At first an ancestral loop is set alone in the center of the space. When simulation begins, the ancestral loop soon proliferates to all the space. Then, self-

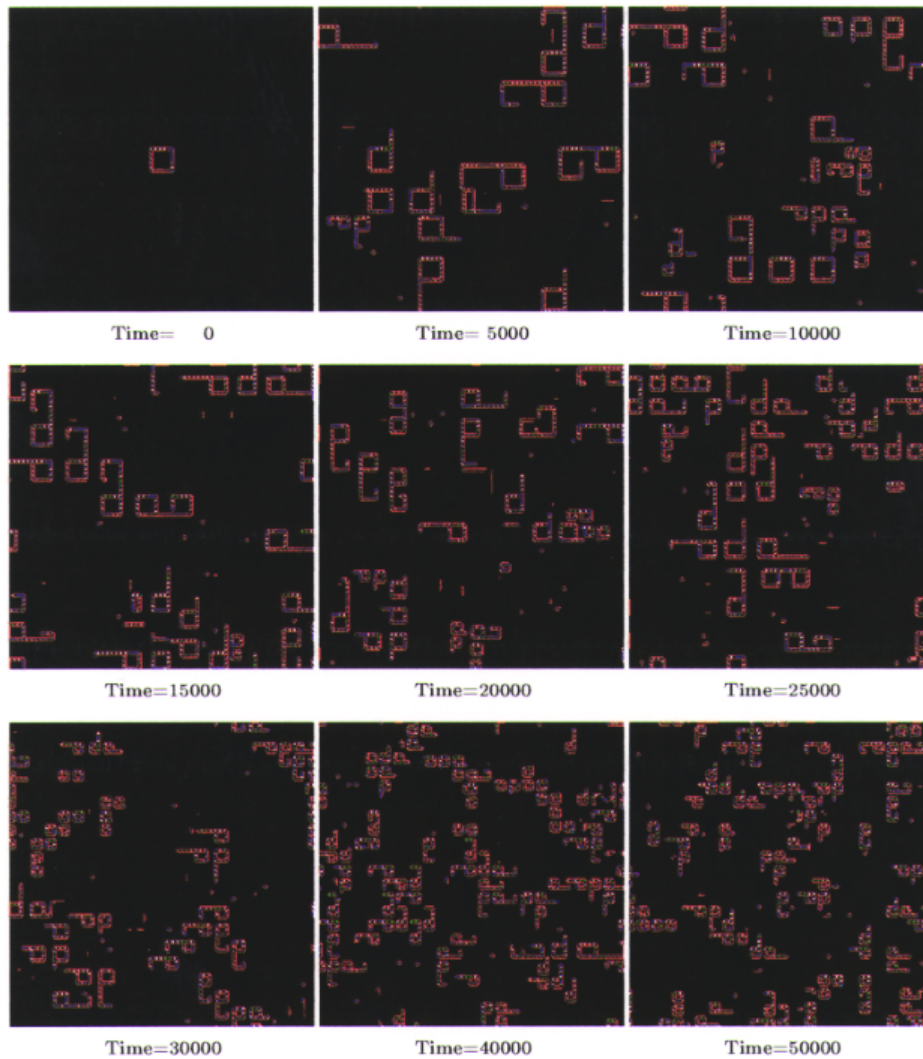


Plate 4. Temporal development of configuration in the evolutionary process of 2-evoloops. The ancestor is of species 13. The space is of 200×200 sites with periodic boundary conditions.

reproduction and structural dissolution of loops begin to happen frequently in the space, which produce various kinds of variants such as sterile loops, loops with two arms, loops not self-reproducing but reproducing smaller offsprings than themselves, and so forth. A self-reproducing loop of smaller species also emerges by accident from this melee, and once it appears, it is naturally selected to proliferate in the space, due to its quicker self-reproductive ability. Such an evolutionary process develops in the space as time proceeds, and eventually, the whole space becomes filled with loops of species 4, which is the strongest species in this world.

A principal cause of evolution in this world is direct interaction of phenotypes such as a collision of two loops or a crash of a loop into a debris structure, which may change the length of their construction arms. A typical example of such phenomena is shown in Plate 5. In this case, the length of the arm of a loop of species 9 (leftmost one) was altered by collision with another loop, which produced a little

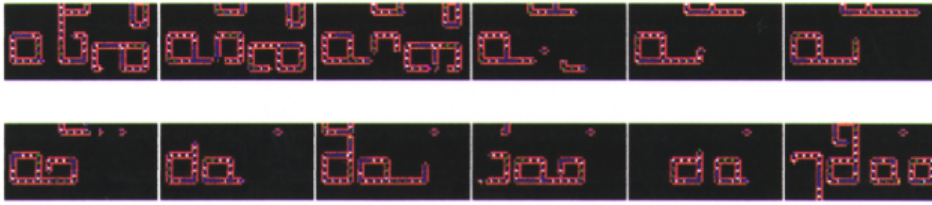


Plate 5. Example of variation of evoloops occurring through direct interaction of phenotypes.

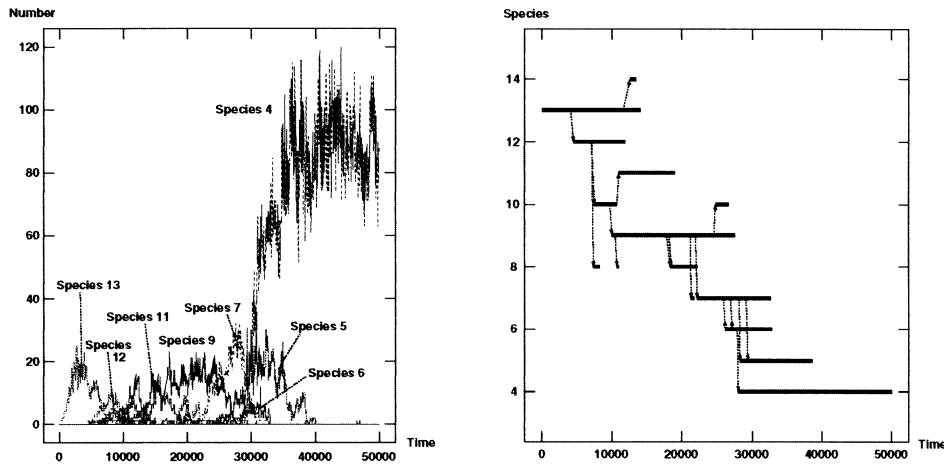


Figure 13. Temporal development of numbers of living evoloops (left) and their genealogy (right) in the case shown in Plate 4.

smaller rectangular variant. This variant generated an offspring of species 7, which fortunately had the capability of self-reproduction. It is quite characteristic of this evolutionary process that the variation in this world occurs first on the phenotype (not on the genotype) of the offspring being produced, consequently leading to alteration of the genotype. This manner of variation is in contrast to the idea of mutation we usually consider.

Figure 13 shows temporal development of numbers of living loops and their genealogy in the aforementioned case. It is clearly observed in these graphs that various species of evoloops are produced in the course of evolution, and species 4 finally exterminates the other species. The genealogy (shown on the right) indicates that variation occurring in this world has some tendency to move toward smaller species, but it also leads to larger ones in relatively low probability. Anyway, the whole system seems to evolve toward the smallest species 4 approximately in proportion to elapsed time. In addition, it is found in this genealogy that larger species sometimes exterminate an emergent smaller one that should, theoretically, have stronger power of self-reproduction. This indicates that selection in evolution of life can be affected to some extent by local, unpredictable² conditions as well as by difference of fitness values of competitive species.

Though the evoloops showed interesting evolutionary behaviors, we could not observe in their world either punctuated equilibrium of evolution or symbiosis of different species, which had been reported in other evolutionary systems [10, 12]. A main reason

² Here what I mean by “unpredictable” is that it cannot a priori be predicted before a simulation is carried out.

for this is that the evoloops have no ability to interact with each other in a functional way so that they cannot build complex relations by altering mutual fitness landscapes. In other words, the fitness landscape of evoloops is fixed throughout the run, where they merely adapt to a physical environment—a static space composed of a fixed number of finite sites.

4 Discussion

4.1 Evolution Driven by Direct Interaction of Phenotypes

The results obtained in this study can be regarded as a unique example of evolution in which variation occurring on phenotypes by their direct interaction consequently leads to variation of genotypes. In this sense, it may have some resemblance to Lamarckian evolution.

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

However, as noted by Langton [7], there can be little doubt that life at the ancient dawn was *not* a universal constructor, because the universal constructor must generally be made of an enormous number of components [4, 11, 18], which ancient life was unlikely to possess. At that time, genotypes of living objects may have been physical structures at the same scale as their phenotypes, so that the genotypes may have had some phenotypical character, and vice versa. Thus, it is very likely that the evolution of life at that time was accomplished not only by probabilistic change of genotypes but also by environmental factors such as direct interaction of phenotypes—in other words, such environmental factors could alter how genotype was interpreted into phenotype.

Since Langton's aim in inventing the SR loop was to create a model of primitive life forms in extremely small size that did not have the universality of construction/computation but were capable of self-reproduction, genotype and phenotype of the SR loop were both spatial structures of the same scale and had the potential to influence each other. This feature has been inherited by the SDSR loop and the evoloop. In the evoloop world, it actually happened that phenotypical interactions such as a collision of two loops altered their genotypical information, which consequently drove their evolution. This kind of evolutionary process emerging in the evoloop world would bear a close resemblance to the beginning of evolution of primitive life of small complexity, which might have actually occurred in the ancestral world. In such a world, organisms must have evolved not only by genetic mutation but also by interaction with the external environment, including other organisms.

4.2 Characteristics as Artificial Life Implemented on CA

The evoloop contrived in this article has several characteristics as a model of artificial life implemented on CA. The most important feature is that the evoloop is the first to realize an evolutionary process of self-replicators through both variation and natural selection in a CA space.

With respect to evolution of self-replicators on CA, Chou and Reggia's model [2] seems most successful. Their principal objective was, however, to observe the emergence of self-replicators out of a "primordial soup" rather than to realize their evolution, thus the evolutionary behavior obtained in their study was merely a repetition of a pro-

cess in which smallest loops emerged at first, they were intentionally made to mutate toward larger ones by external mutator states scattered over the space, and eventually they became extinct as they evolved to be too large. Thus, this evolutionary path always began at the optimum (smallest structure) of the fitness landscape and descended from there, which was somewhat unnatural.

On the other hand, the main focus of this study is on the evolutionary process itself. Here, the initial configuration was an empty space but a priori populated by a sole ancestral loop that had only a self-reproductive ability, and no explicit device was made to drive evolution of loops. From these points one may say that the evolutionary process that emerged in the evolooop world is produced by variation and natural selection spontaneously acting on the population of evolooops.

In addition, we can give it as another feature of the evolooop that the CA space used in this study has an extremely small complexity compared to other models. For example, Chou and Reggia's model mentioned above was constructed on a 256-state, nine-neighbor CA space; thus the size of the state-transition rules is $256^9 = 2^{72} \approx 5 \times 10^{21}$ when expanded into a form of a look-up table. Our CA is nine-state, five-neighbor, making the size of the rules $9^5 = 59049 \approx 6 \times 10^4$. This is probably the smallest complexity at the present time among the CA models proposed for simulating evolution of self-replicators.

4.3 Characteristics as an Artificial Evolutionary System

Here are some characteristics of the evolooop as an artificial evolutionary system evaluated through comparison with other evolutionary systems formerly invented. One of the most characteristic points of the evolooop is that it has no central operating system to maintain information about the activities of living individuals. Other evolutionary systems constructed so far [1, 10, 12] all needed rather complicated operating systems for identifying living or dead individuals, simulating their activities, inducing mutations to them, and so on. On the other hand, as for the evolooop, though it is provided with only simple physical laws that govern microlevel behavior of the universe, it can produce an evolutionary process in which genotype and phenotype of organisms definitely exist in the space and individuals vary and compete with each other through interactions among them. Thus the evolutionary process in the evolooop world would be considered as a completely emergent, self-organized one.

The other characteristic is that it does not involve any stochastic operation at all. There is no random flip of genetic information in the evolooop world, where all gene 4s and 7s emerge only by transcription of them at a T-junction of pathways and disappear only by either translation at a tip of an arm or structural dissolution. This indicates that the evolution of life can result from completely deterministic processes.

This feature may be analogous with the case that a CA-based model of Turing patterns [17] (patterns emerging on the surface of bodies of animals/plants produced by complex behavior of reaction-diffusion chemical systems) could spontaneously generate irregular patterns such as branching or breaking of zebra stripes by utilizing information implicitly lying in an initial configuration [19], while differential equation-based models for them could not generate such irregularity without operations being added explicitly from outside [9]. The important point common to the evolooop and the CA-based model of Turing patterns is that they are able to make use of disordered information hiding in low-level substructures as a seed of unpredictable behavior emerging at high-level superstructures, because in these models the subject phenomena are built from the most low-level elements in a bottom-up way, instead of being described directly in high-level formulae. This would be the main reason why the evolooop does not need any stochastic operation.

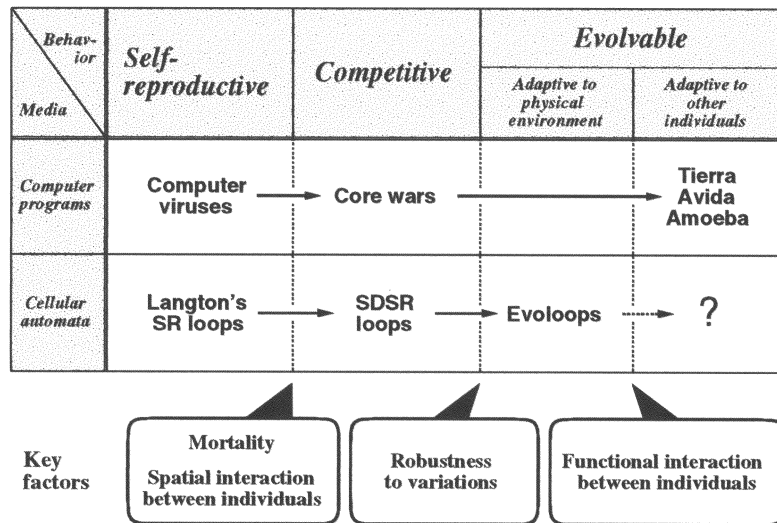


Figure 14. Analogy between the development of digital organisms made by computer programs and the development of self-reproducing loops on CA. Key factors common to both kinds of artificial systems in enhancing their behaviors are also shown at the bottom.

4.4 Evolvability of Artificial Evolutionary Systems

We may derive from this study some insights on the evolvability of artificial evolutionary systems. Figure 14 shows a rough analogy between the development of digital organisms made by computer programs [1, 5, 10, 12] and the development of self-reproducing loops on CA including the evolloop. Behaviors of these artificial systems are classified here into three categories: self-reproductive, competitive, and evolvable; the last category is further divided into two: adaptive to physical environment and adaptive to other individuals.

It would be possible to extract some factors common to both kinds of artificial systems in the same class of this analogy. The key factors to create competitive systems is obviously both mortality of individuals and spatial interaction between them. They are not sufficient, however, in advancing artificial systems to the evolvable class. The most important factor common to evolvable systems would be robustness of organisms to variations. For example, the famous evolutionary system Tierra [12] met with success by making both its instruction set and its addressing mode quite robust to genetic operations such as mutation and recombination of program codes. This factor also forms the main difference between the SDSR loop and the evolloop. Of course, as noted in the previous section, the evolloop is currently not in the same class as Tierra: It adapts only to a physical environment because it lacks a fourth key factor—functional interaction between individuals which causes emergence of diversity of digital organisms in Tierra.

If such a truly complex evolutionary system could be constructed on a simple deterministic CA space as a successor to the evolloop, it would be expected to have some characteristics inherited from the evolloop, as follows:

1. Evolution of life in such a system would be realized without any stochastic operations such as random mutation of genotypes.
2. There would be no need of a central operating system to maintain/evaluate information about the activities of all living individuals, since any particular

information about the individual organism is maintained on the configuration of the CA space where it resides.

3. Such a system would be intrinsically very suitable for massively parallel processing, since all behaviors of the system emerge from only local computations between neighboring sites.

These imply that, in the near future, we would be able to create extraordinary large-scale evolutionary systems on a fine-grained superparallel machine environment by using extremely simple algorithms, which would greatly advance our knowledge of both natural and artificial life. Such systems might also contribute well to the progress of the efforts to implement novel systems of parallel computation by using evolutionary CA, which are energetically studied these days [3, 6, 16].

5 Conclusion

In this article, I introduced the evolloop, a new self-reproducing loop model that evolves toward different forms through variation and natural selection in a simple deterministic CA space. This was implemented by two steps; first, the state-transition rules of the SDSR loop I previously proposed were fully rewritten so they could become more tolerant to fluctuation of environmental situations, and second, its initial structure was slightly modified to enhance their ability to catch a seed of variation. The evolloop displays quite intriguing evolutionary behaviors that the loops evolve toward smaller species, in spite of no stochastic mutation given. The result obtained in this study can be viewed as a special case of evolution where variation of phenotypes caused by their direct interaction gives rise to variation of genotypes. Such evolution might have actually occurred to ancient life forms of small complexity.

For a more detailed account of the evolloop as well as the SDSR loop, refer to the other literature [13, 15], which can be retrieved from the following WWW site:

<http://necsi.org/postdocs/sayama/sdsr/>

This site carries several color movies of acting loops too, which would be helpful for readers in understanding the behaviors introduced in this article. Software for simulation/visualization of the CA used in this study is also available from this site (for UNIX/MS-DOS machines only). The state-transition rule set of the evolloop is attached to these simulator software packages.

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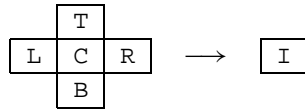
Appendix: State-Transition Rules of the Evolloop

The state-transition rules of the evolloop can be obtained by the operations below:

Table A1. Principal part of the state-transition rules of the evolloop.

CTRBL->I	CTRBL->I	CTRBL->I	CTRBL->I	CTRBL->I	CTRBL->I
00001->2	10202->1	11272->7	20172->2	21322->2	40125->0
00004->3	10211->1	11273->5	20202->2	21422->2	40162->0
00012->2	10212->1	11322->1	20203->2	21622->2	40212->0
00015->2	10213->1	11332->1	20205->2	21722->2	40215->0
00021->2	10221->1	11542->4	20206->5	22224->2	40222->1
00024->2	10224->4	11572->7	20207->3	22227->2	40232->1
00042->2	10227->7	11624->4	20212->2	22234->2	40262->6
00045->2	10232->4	11627->7	20215->2	22237->2	40312->0
00075->2	10241->4	12224->4	20221->2	22243->2	40322->1
00102->2	10242->4	12227->7	20222->2	22244->2	50002->5
00214->1	10243->4	12243->4	20223->2	22273->2	50012->5
00217->1	10251->1	12273->7	20232->3	22277->2	50021->5
00232->2	10252->7	12324->4	20242->2	22324->3	50023->2
01122->1	10254->3	12327->7	20245->2	22327->3	50024->5
01212->1	10257->7	12426->6	20252->5	30001->3	50027->5
01232->1	10271->7	12433->3	20262->0	30002->2	50042->5
01242->1	10272->7	12627->6	20265->0	30003->2	50072->5
01245->1	10273->5	20001->2	20272->2	30004->3	50202->2
01252->6	10512->1	20002->2	20275->2	30007->4	50205->2
01262->6	10542->4	20004->2	20312->2	30012->3	50212->5
01272->1	10572->7	20005->2	20322->2	30032->2	50215->2
01275->1	10621->1	20006->0	20342->2	30042->1	50242->5
01342->1	10624->4	20007->1	20345->2	30102->1	50272->5
01372->1	10627->7	20012->2	20372->2	30125->0	50312->0
01422->1	11112->1	20015->2	20412->2	30212->3	60202->2
01425->1	11122->1	20021->2	20422->2	30242->3	60212->2
01432->1	11124->4	20022->2	20442->2	30252->1	60222->0
01435->1	11125->1	20023->2	20512->2	30272->3	60242->2
01442->1	11127->7	20024->2	20542->5	30332->1	60272->2
01462->1	11162->1	20026->0	20572->5	31212->3	61222->0
01722->1	11212->1	20027->2	20612->5	31242->3	62224->0
01725->1	11213->1	20032->4	20621->2	31252->1	62227->0
01756->1	11215->1	20042->3	20642->5	31272->3	70102->0
01762->1	11222->1	20045->2	20672->5	32424->3	70112->0
01772->1	11224->4	20054->5	20712->2	32425->1	70122->0
10001->1	11227->7	20057->5	20722->2	32427->3	70125->0
10012->1	11232->1	20062->0	20772->2	32527->1	70162->0
10021->1	11242->4	20072->2	21122->2	32727->3	70212->0
10024->4	11243->4	20075->2	21222->2	40000->1	70215->0
10027->7	11252->7	20102->2	21223->2	40002->1	70222->1
10121->1	11254->3	20112->2	21224->2	40102->0	70232->0
10124->4	11257->7	20122->2	21227->2	40112->0	70262->6
10127->7	11262->6	20142->2	21232->3	40122->0	70312->0

1. Define the rules listed in Table A1 and their rotationally symmetric ones. Each situation *CTRBL* and its image *I* listed in the table is read as follows:



2. Let $8 \rightarrow 0$ with no condition.
3. To all the undefined situations in whose four neighbors (*TRBL*) there is at least one site in state 8, apply the following:
 - (a) Let $0,1 \rightarrow 8$ if there is at least one site in state 2,3,...,7 in its four neighbors (*TRBL*), otherwise let $0 \rightarrow 0$ and $1 \rightarrow 1$.
 - (b) Let $2,3,5 \rightarrow 0$.
 - (c) Let $4,6,7 \rightarrow 1$.
4. Clear up all the undefined situations by letting $0 \rightarrow 0$ and $1,2,\dots,7 \rightarrow 8$.

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