Chapter 1

Spontaneous evolution of self-reproducing loops on cellular automata

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A simple evolutionary system "*evoloop*" implemented on a deterministic nine-state five-neighbor cellular automata (CA) space is introduced. This model was realized by improving the structurally dissolvable self-reproducing loop I had previously contrived after Langton's self-reproducing loop. 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 the loops spontaneously varied through direct interaction of their phenotypes, smaller individuals were naturally selected, and the whole population gradually evolved toward the smallest ones. This result shows that it is possible to construct evolutionary systems on such a simple mathematical medium as a CA space by introducing the mortality of individuals, their interaction, and their robustness to variations into the model.

1.1 Introduction

This article gives an affirmative answer to the question 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.

In this article, a simple evolutionary system "*evoloop*" implemented on a deterministic nine-state five-neighbor cellular automata (CA) space is introduced. This model was realized by improving the structurally dissolvable self-reproducing (SDSR) loop I had previously contrived[12] after Langton's self-reproducing (SR) loop[6]. 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, besides a slight modification of initial structure of the loop.

The experiment with the *evoloop* 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. This result shows that it is possible to construct evolutionary systems on such a simple mathematical medium as a CA space by introducing the mortality of individuals, their interaction, and their robustness to variations into the model. This implies that, in the future, we will be able to create extraordinary large-scale evolutionary systems in a fine-grained superparallel machine environment by using a very simple algorithm with neither explicit management of living individuals nor generation of random numbers for stochastic mutation of genotype.

1.2 Former works

Langton's SR loop[6] is one of the most famous models of self-reproduction on CA. It was implemented on a simple eight-state, five-neighbor CA space. Fig. 1.1 shows the manner of self-reproduction of the SR loop. This loop contains several signal states '4' and '7' in its Q-shaped tube 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 ability halts because of a shortage of space. Langton's SR loop was such a useful model in studying self-reproduction on CA that various modifications were invented after it[2, 3, 4, 8, 10, 14, 15].

After this SR loop, I previously contrived the SDSR loop capable of structural

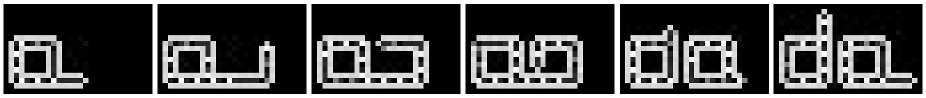


Figure 1.1: Self-reproduction of Langton's SR loop.

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[12]. The dissolving state was granted with an ability to travel along a tube and dissolve neighboring structures so that once 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 through collision of two or more normal 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.

1.3 Evoloop: an evolving SDSR loop

1.3.1 Reconstructing the state-transition rules

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. Thus even a slight fluctuation such as a one-site discrepancy in propagation of signals could easily ruin the self-reproductive process of the loop. For example, when the form of the arm of the SDSR loop is altered by force during its self-reproductive process, it cannot reproduce any self-reproductive offspring; it either generates a dissolving state (Fig. 1.2, left) or falls into a sterile structure (Fig. 1.2, right). 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 rigidness of rules seems to have prohibited evolution of the SDSR loop.

Figure 1.2: What happens if the form of the arm of the SDSR loop is altered by force during self-reproduction.

To resolve this problem, it was necessary to make the self-reproductive mechanism described by the state-transition rules more “adaptable.” The word “adaptability” used here means a degree of the variety of situations in which structures in the CA space can retain their regular operations. To enhance the adaptability of the state-transition rules, 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 signals. 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, and (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. In addition, 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.

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 signal ‘7’s 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 reassigned to ‘3’, ‘4’, and ‘5’ in new rules. These reassignments made it much easier to refine the state-transition 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*.” Fig. 1.3 depicts general behaviors of refined phases of the self-reproductive process of the *evoloop*. Mechanisms concerned with phase 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. The complete state-transition rule set of the *evoloop* is presented in the other literature[11, 13].

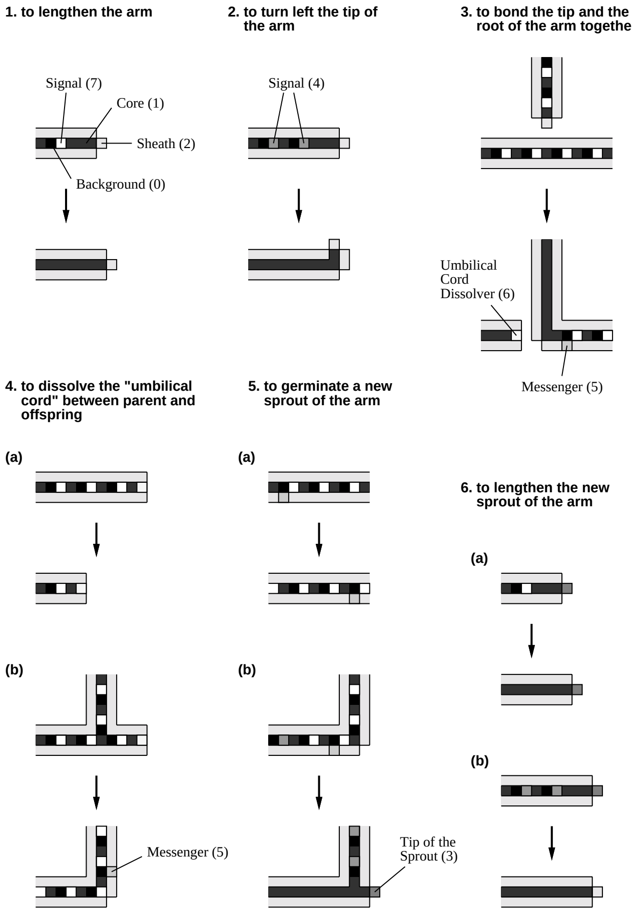


Figure 1.3: Behaviors of six functional phases of the self-reproductive process of the *evoloop*. **3.** When the tip of the arm collide with the middle of the arm, they will bond together, and both an umbilical cord dissolver '6' and a messenger '5' will emerge after several transient configurations. **4.** The umbilical cord dissolver '6' will travel along the umbilical cord against the signals' flow, dissolving structures of the cord (a), and it will turn into another messenger '5' when it arrives the T-junction of the parent loop (b). **5.** The messenger '5', having been generated in the aforementioned phases, will be trailed on the sheath by a signal '4' or '7' traveling along the tube (a), and it will begin to wait at the corner for a signal '4' arriving. When a signal '4' arrives there, it will germinate a new sprout there, while the messenger '5' will disappear (b). **6.** The growth of a new sprout will be stimulated by signal '7's (a), and the sprout will be changed into an ordinary arm by a couple of signal '4's (b).

Self-reproduction of the *evoloop* is shown in Fig. 1.4. Since the sprout of the *evoloop* is explicitly stimulated to grow by signal '7's contained in its body, the length of its umbilical cord is longer than that of the SR/SDSR loop. Thus, the colony of the *evoloop* looks a little sparse than that of the SR/SDSR loops. In the shown case, the loop contains thirteen signal '7's in its body. Hereafter the number of signal '7's in a loop will be used as a label of "species" of that loop.

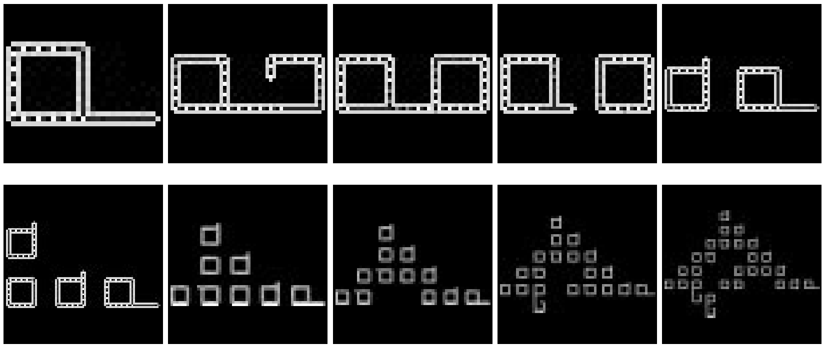


Figure 1.4: Self-reproduction of the *evoloop* of species 13 (i.e., a loop that has thirteen signal '7's). Each picture is scaled differently to the size of the colony.

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. Fig. 1.5 shows, for example, a takeover of the arm happening between 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.

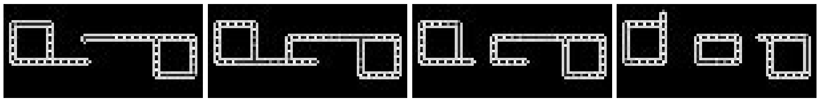
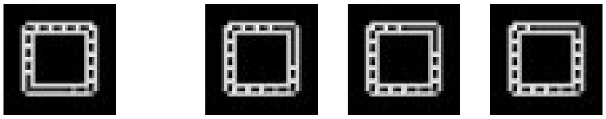


Figure 1.5: Takeover of the arm caused by collision of two *evoloops*.

1.3.2 Modifying the initial structure

To examine evolvability of the *evoloop*, I carried out several preliminary experiments of breeding *evoloops* in finite spaces. The results indicated that the *evoloop* actually has some evolvability, because in some cases the loop evolved to that of larger species, and in other cases it generated some variants that lost their self-reproductive ability but became capable of reproducing smaller offsprings than themselves. However, self-reproductive smaller species could not emerge yet in these preliminary experiments.

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 signals into its offspring if the form of its arm was altered by some collisions with other structures during the self-reproductive process. This capability of signal injection may be affected by the order of signals in the loop. Based on this idea, I looked for new genotypes of the *evoloop* 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 *evoloops* with slightly modified genotypes (shown in Fig. 1.6) have a stronger self-reproductive ability. The function of these genotypes is exactly the same as before, while only the order of signals differs. In the new genotypes, signal '4's are located near the front of a signal stream instead of its end. These genotypes seem convenient for a loop to inject more signal '7's into its offspring than before when some collision happens to itself. It must be noted that such genotypes were not viable without the new state-transition rules implemented in this study. 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 signal '7's in front of signal '4's. According to this naming manner, the old loop should be called n-*evoloop*.



n-*evoloop* 2-*evoloop* 3-*evoloop* 4-*evoloop*

Figure 1.6: 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).

1.4 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.

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.

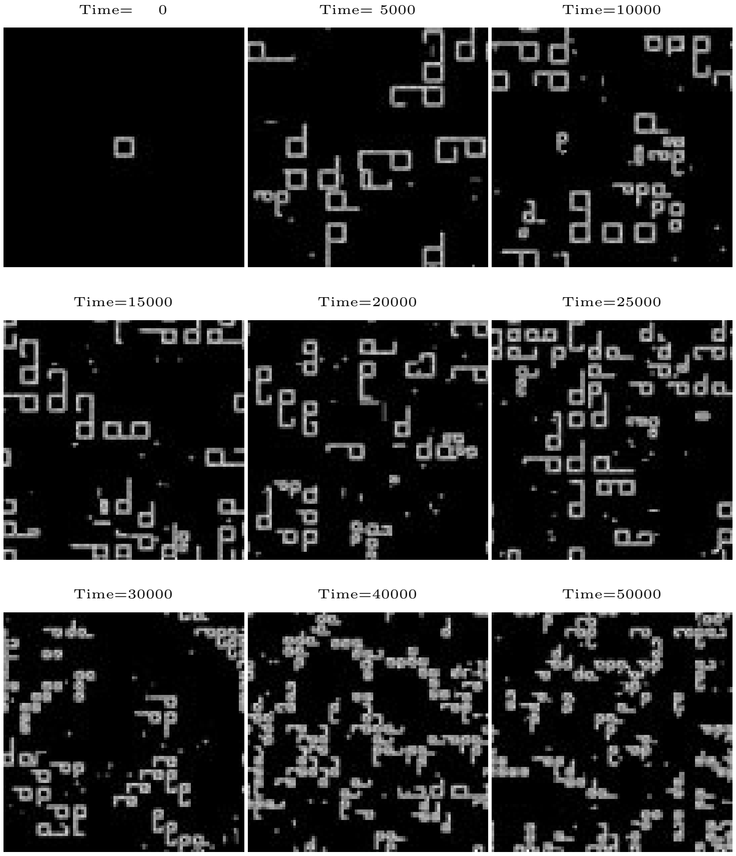


Figure 1.7: Temporal development of configuration of the evolutionary process of 2-*evoloops*. The ancestor is of species 13. The space is of 200 × 200 sites with periodic boundary conditions.

Fig. 1.7 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 all the space. Then, self-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 itself, 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. 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.

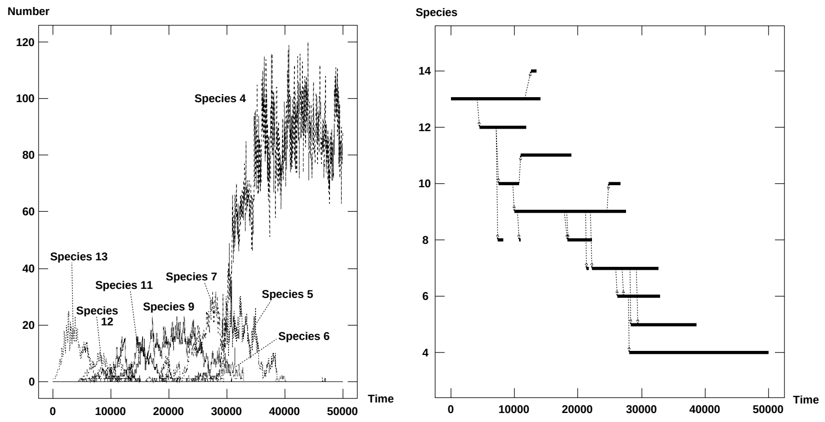


Figure 1.8: Temporal development of numbers of living *evoloops* (left) and their genealogy (right) in the shown case.

Fig. 1.8 shows temporal development of numbers of living loops and their genealogy in the aforementioned case. It is clearly observed from 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 occuring 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 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, unpredictable conditions as well as by difference of fitness 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[7, 9]. A main reason 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.

1.5 Discussion

We may derive from this study some insights on the evolvability of artificial evolutionary systems. Fig. 1.9 shows a rough analogy between the development of digital organisms made by computer programs[1, 5, 7, 9] and the development of self-reproducing loops on CA including the *evoloop*. Behaviors of these artificial systems are classified here into three categolies: self-reproductive, competitive, and evolvable; the last category is further divided into two: adaptive to physical environment and adaptive to other individuals.

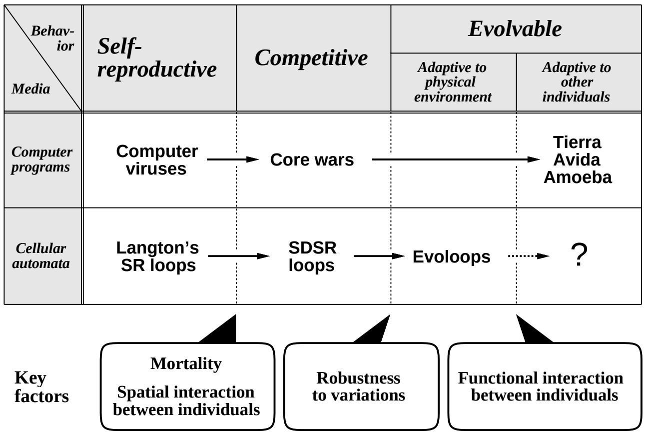


Figure 1.9: Analogy between the development of digital organisms made by computer programs and the development of self-reproducing loops on CA.

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*[9] met with success by making both its instruction set and its addressing mode quite robust to genetic operation such as mutation and recombination of program codes. This factor also forms the main difference between the SDSR loop and the *evoloop*. Of course, as noted above, the *evoloop* 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 *evoloop*, it would be expected to have some characteristics inherited from the *evoloop*, 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.

Finally, from a biological viewpoint, the results obtained in this study can be regarded as a unique example of evolution in which variation occuring on phenotypes by their direct interaction consequently leads to variation of genotypes. 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 anscestral 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.

For details of the *evoloop* refer to the other literature[11, 13], some of which can be retrieved from `http://necsi.org/postdocs/sayama/sdsr/`. This site carries several simulator software packages and color movies of acting loops too, which would be helpful for readers in understanding the behaviors introduced in this article.

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