Self-Reproduction of Worms in Asynchronous Cellular Automata

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***Abstract*— This paper proposes a new self-reproductive model for worms in asynchronous cellular automata, in which a variety of worms can be self-reproduced based on the shape-encoding mechanism. By dealing with interplays among worms properly, they can self-reproduce in parallel. Furthermore, self-reproduction of a worm accompanies leaving the shape information, which avoids the overcrowding of worms on cellular space. Experiments show that a space usually results in dominance by only one type of worms due to space competition, even more than one type of worms on a space in the initial, which to some extent displays the characteristic of artificial evolutionary in our self-reproductive model.**

***Index Terms*— Self-reproduction, worms, Asynchronous, Self-timed cellular automata, Interplays**

I. Introduction

Self-reproduction is one of the basic characteristics in nature. Von Neumann [1] was the first man proposed using cellular automata (CAs) to build self-reproducing model. He designed a 29-state two-dimensional cellular space endowed with properties of both computational and constructional university. Codd et al. [2] reduced cell states into 8-states for the purpose of reducing complexity of von Neumann's model. Langton [3] was enlightened by Codd's periodic emitter, leaving out the property of universality, and devised the well-known Langton's loop to perform self-reproduction. Morita [4] proposed the shape-encoding mechanism that a variety of objects can achieve self-reproduction in a simple way. Furthermore, he designed a self-reproduction model in a reversible cellular space [5]. Overcrowding of objects (i.e., worms and loops) can be avoided by utilizing branching and splitting mechanism, which gives different branching signals to offspring, effectively dealing with collisions among worms. Based on this research, Sayama [6] proposed a new self-replicating cellular automata model allowing worms to transmit genetic information to others when colliding against each other, which may give rise to their variation. To some extent, it was an artificial evolutionary system on CAs.

Most often encountered in this frame works are synchronous CAs, in which all cells are updated simultaneously in discrete time step. Although easy to analyze, they may actually cause artifacts [7], [8], such as false correlations between cells and spurious attractors. Furthermore, since biological systems in nature are filled with asynchronous timing mode, it is sensible to study self-reproduction under asynchronous updating scheme. However, construction self-reproduction on ACAs is considered to be more difficult and complex since more unpredictable interplays need to be considered. Takada [9] proposed the ability to cope with deadlock caused by collisions between loops with an arbitration mechanism in a self-timed cellular automaton (STCA), a type of asynchronous cellular automaton (ACA). We [10] proposed a triggered self-reproductive model in STCA. Collisions caused by interplays between self-reproductive loops can be transformed into triggering the new round self-reproduction of the collided loop, avoiding unpredictable interplays in ACAs.

This paper proposes a novel self-reproductive model for worms in self-timed cellular automata, a variety of worms can self-reproduce in parallel. By utilizing the so-called shape-encoding mechanism, the entire self-reproductive process of a worm is directed by signals transmission directly, which self-inspects a worm to generate signals dynamically, interpreted the information carried by signals to construct correspondingly. Unlike a loop, a worm is not a closed curve but with a head and a tail. Thus, the mechanism to deal with interplays among worms need to be different from the mechanisms in [9], [11]. If an arm of a worm senses an obstacle preventing it to advance, it immediately withdraws without trial and error. This is induced by the idea that self-reproduction of a worm accompanies retracting its shape, which avoids the overcrowding of worms. Furthermore, our model exhibits an evolutionary process. Experiments show that a space results in dominance by only one type of worms due to space competition, even there is more than one type of worms in the initial.

The rest of this paper is organized as follows. Section II briefly presents the self-timed cellular automaton, after that section III describes self-reproduction of worms in parallel. Section IV shows experiments. This paper finishes with conclusions in Section V. The complete set of the transition rules used in this paper is shown in Appendix.

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II. Asynchronous Self-timed Cellular Automata

A self-timed cellular automaton (STCA) [12] is a two-dimensional asynchronous CA arrays consisting of identical cells, each of which is with von Neumann neighborhood consisting of four non-diagonal neighbors. Each cell in STCA is partitioned into four parts corresponding to its direct neighbor of the cell. For example, if each partitioned cell state is encoded by 1 bit, then the state of a cell is in 1 of 16 states encoded by 4 bits. Each cell undergoes transitions in accordance to transition function that operates on its four bits and the nearest part of each of its four direct neighbors. The transition function is depicted as follows:

$f : (a_N, a_E, a_S, a_W, b_N, b_E, b_S, b_W) \rightarrow (a'_N, a'_E, a'_S, a'_W, b'_N, b'_E, b'_S, b'_W)$,

We assume that dummy transitions are avoided, then: $(a_N, a_E, a_S, a_W, b_N, b_E, b_S, b_W) \neq (a'_N, a'_E, a'_S, a'_W, b'_N, b'_E, b'_S, b'_W)$ where $a_N, a_E, a_S, a_W, b_N, b_E, b_S, b_W, a'_N, a'_E, a'_S, a'_W, b'_N, b'_E, b'_S, b'_W \in \{0, 1\}$ and prime attached to bit state denote the respective state after the transition has take place. When the bit pattern matches the left-hand side of a transition rule, the cell will undergo a transition; otherwise the cell remains inactive if there is no transition rule whose left-hand side matches the cell's bit pattern. Moreover, transition rules on an STCA are rotation symmetric, thus each of the rules has four rotated analogues.

Since a transition on a cell may change bits of neighboring cells, two neighboring cells undergoing transitions simultaneously may write different values in shared bits. To prevent such a situation, we adopt checkerboard updating scheme to iterate cells in our experiments, which is an alternative stochastic updating scheme. Cells are divided into two disjoint sets, "even" and "odd". Two cells from one of the sets cannot be adjacent to be updated. The cells have a uniform updating probability p, by which "even" cells are updated, then "odd" cells, and so on, not violating the restriction. For convenience we count a cycle of updating"even" and "odd" cells as one time step (t = 1). STCAs tend to be very suitable for expressing the functionality of computational elements by less transition rules than conventional cellular automata with the same functionality. Less transition rules translates in simpler cells, which may be of help when eventually realizing the model at nanometer scales [13].

III. Self-reproduction of worms on STCAs

A worm is a wire with a head and a tail, as is shown in Fig.1(a). A head is an end cell of a wire to which signals flow, and a tail is an end cell from which signals flow. Since unsheathed path can simplify self-reproductive structures [14], thus we adopt it as signals transmission path. Fig.1(b) gives an example to display such data path. A signal consists of a sequence composed of two states. The partitioned states of each cell and the function of signals are listed in TABLE.I and TABLE.II, respectively. Transition rules used for our model are listed in Appendix.

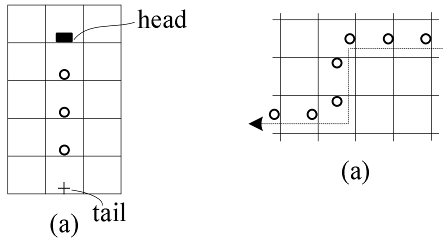


Figure 1. (a) An example of a worm structure with a head and a tail. (b) Data path used to transmit signals. Dashed arrow represents the transmission direction of signals.

A. Self-reproductive worms with shape-encoding mechanism

Various shapes of worms can be self-reproduced based on the so-called shape-encoding mechanism. An initial signal transmits from a tail of a worm to its head, as is shown in Fig.2(i)-(ii). After its arrival at the worm head (Fig.2(iii)), two construction arms are generated to form a T-junction (Fig.2(iv)). Meanwhile, a notify signal is generated to inform the worm ready to encode its form. It transmits into the worm tail (Fig.2(v)). When arriving at the worm tail, a trace signal is produced (Fig.2(vi-vii)).

The trace signal encodes a cell in front of it into corresponding construction signal. If a cell left in the straight path, a forward signal is produced; similarly, a leftward or rightward construction signal is generated if a left path or right path is encoded. Fig.2(viii)-(ix) gives an example of encoding a straight path. Note that the encoding process accompanies retraction of its tail. When a construction signal arrives at a T-junction, it is copied and transmitted into the two construction arms (Fig.2(x)-(xi)), which makes these branches have the same shape. The construction signals transmit along the construction arms. After arriving at the arm end, they are decoded and executed to extend the arms one cell forward, to the left, or to the right, according to the contents of the signals (Fig.2(xii)-(xiv)).

When the trace signal reaches the T-junction (Fig.2(xv)), it means the encoding process is finished. Then, two verify signals are produced (Fig.2(xvi)). The function of the verify signal is to verity whether a construction is successful. If succeed, a worm head is formed (Fig.2(xvii)-(xix)). Meanwhile, a cut-off signal moves into the direction of the T-junction (Fig.2(xx)). When both of the two split signals reach the branching point, the umbilical cord is cut off (Fig.2(xxi)-(xxii)). After that, a tail is formed in the new offspring with an initial signal in its body. Then each of the new offspring continues to self-reproduction in parallel (Fig.2(xxiii)).

B. Interplays among worms

Since biological systems in nature are filled with asynchronous timing mode, it is sensible to study self-reproduction under asynchronous updating scheme. Due

TABLE I.
SYMBOLS FOR THE STATES OF CELL PARTITION

State	0	1	2	3	4	5	6
Symbol	blank	○	●	▬	+	-	*

TABLE II.
STATES OF PARTITION PAIRS AND THEIR FUNCTIONS

Name	States of partition pairs && their symbols	Function
Worm head	3-0: #▮	An end cell of a worm to which signals flow
Worm tail	4-0: #▮	An end cell of a worm from which signals flow
Initial signal	4-4: ++	Initiate self-reproduction in a worm
Notify signal	5-1: ○ı	Inform a worm ready to encode its form
Create arms	2-4: +●	Create construction arms
Trace signal	0-2: ●#	Trace and encode a shape
Construction signals	1-1: ○○	Advance construction arm straight ahead
	1-2: ●○	Advance construction arm leftwards
	2-1: ○●	Advance construction arm rightwards
Arm end	6-0: #*	The end of construction arm
Dead end	3-3: ▮▮	Mark the blocked construction arm
Verify signal	2-2: ●●	Verify whether a worm is formed
Split signal	4-2: ●+	Cut off umbilical cord
Form a tail	5-5: ıı	To form a tail in a new offspring
	1-4: +○	

A pair of states is ordered as if they move in the counterclockwise. For brevity, we use # represent blank state

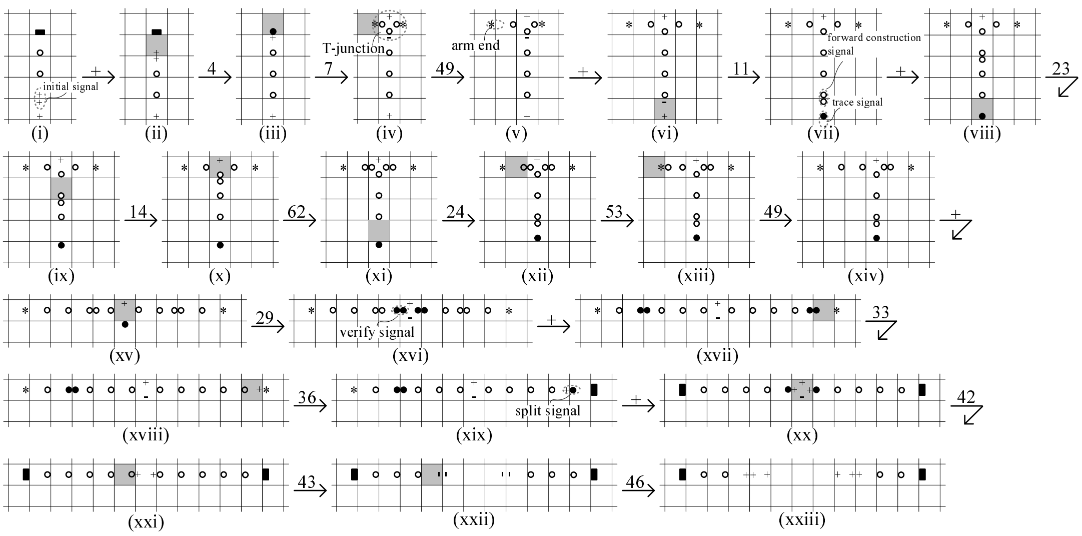


Figure 2. Displaying self-reproducing process of a worm. The numbers listed on arrows are transition rules in Appendix. "+" represents more than one transitions of cells lead to the next configuration. Due to asynchronous timing scheme, this is only one case to update cells.

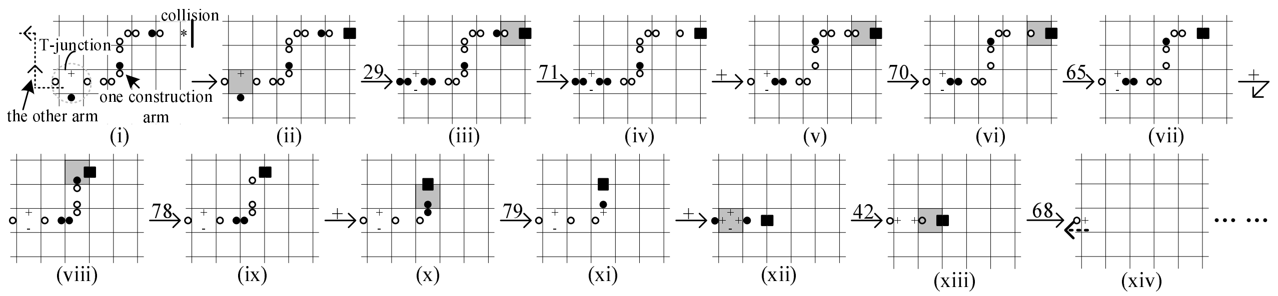


Figure 3. An example of withdrawing a failure arm. During withdrawing, all the following construction signals are deleted by it. When both of the two split signals arrive at the T-junction, the failure arm is erased from the space, while the other one continue to self-reproduce.

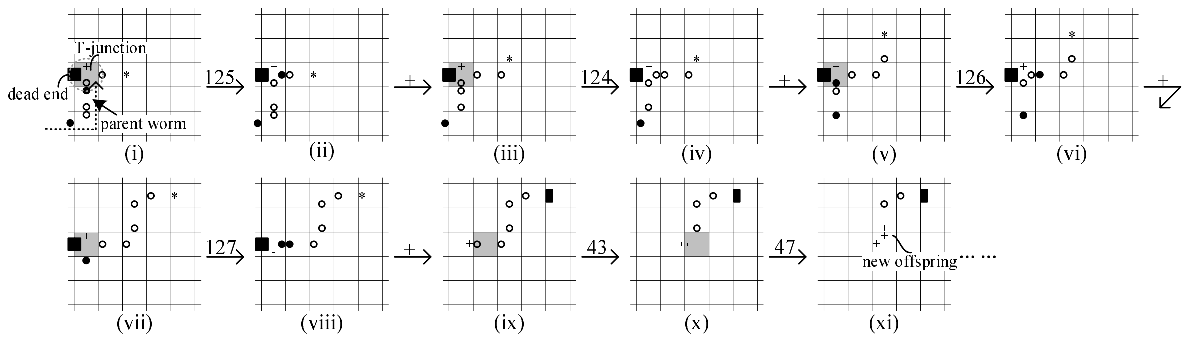


Figure 4. A dead end pads at a T-junction, which does not affect construction of the other arm. Few steps later, the new offspring is formed to continue self-reproduction, while the failure arm is erased from the space.

to asynchronous updating, interplays among worms are unpredictable and unavoidable. Key to achieve reliable reproduction is to deal with deadlocks caused by collisions. Especially the unsheathed self-reproductive structure, collisions are even complex, which tend to occur the situation of twisted collisions [15].

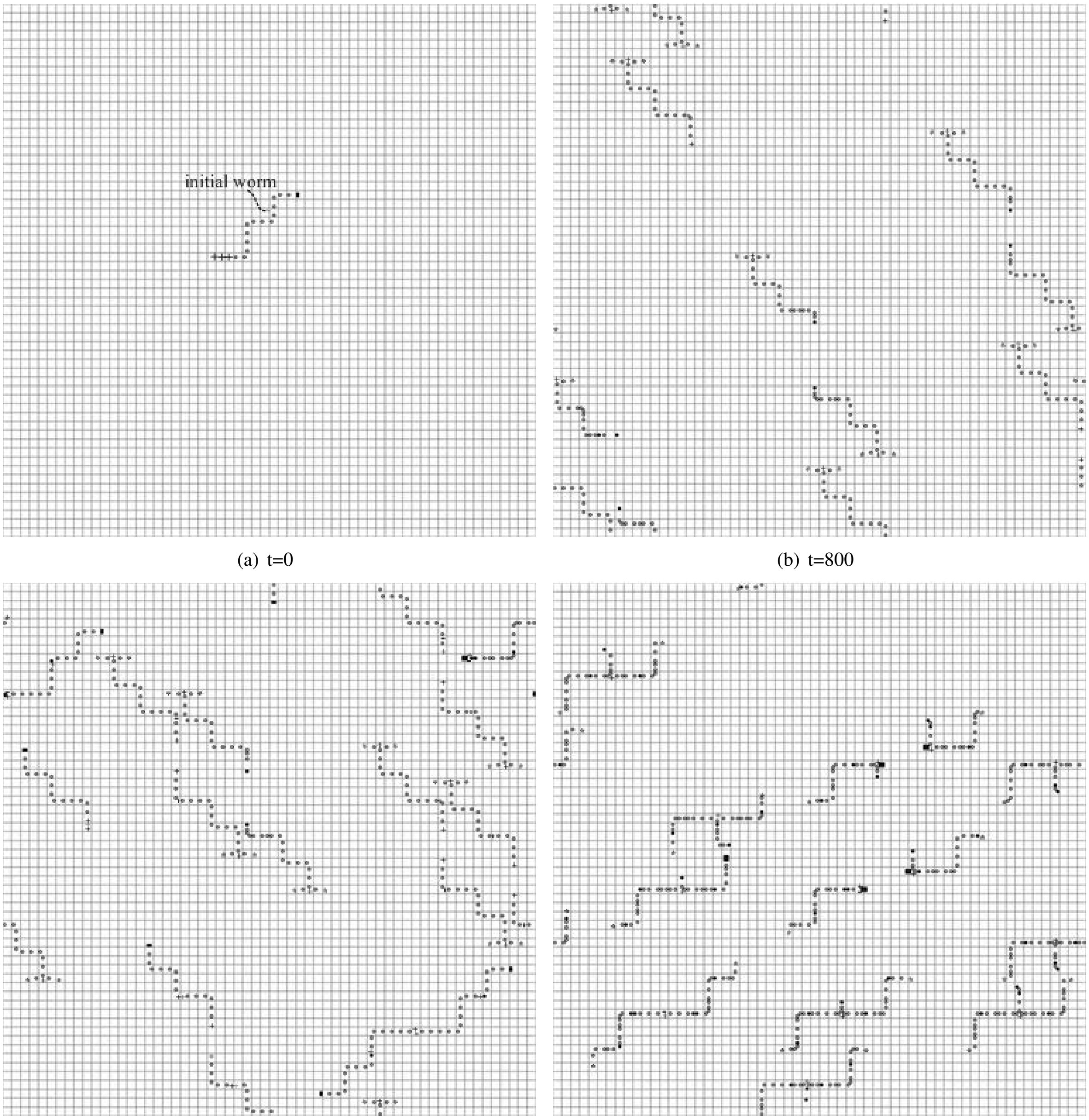
The collision of an arm with an obstacle causes the arm end to become a dead end, as is shown in Fig.3(i)-(ii). Then all the following construction signals transferred on the arm are deleted by it (Fig.3(iii)-(ix)). When meeting a verify signal (Fig.3(x)), it makes the signal turns into a split signal (Fig.3(xi)). Like the above mentioned self-reproducing process, an umbilical cord will be cut off (Fig.3(xii)-(xiii)). After that, the right part construction arm is erased from the space, while the left offspring is formed to continue the new round self-reproduction (Fig.3(xiv)).

Furthermore, if one of the two construction arms from a worm fails to continue and patches at the T-junction, like in Fig.4(i), it does not affect self-reproduction of the other arm. As is shown in Fig.4(ii)-(vi), construction signals encoded by its parent worm pass the T-junction. When the trace signal finishes encoding process, a verify signal is generated (Fig.4(vii)-(viii)). Few steps later, a new offspring is formed alongside erasure the failure arm on the space (Fig.4(ix)-(xi)). Similarly, if both of the two construction arms fail to self-reproduce, construction signals will be deleted at T-junction. Rules 82-84 are used for this purpose. After that, they will disappear from the space by the rules 85-86.

IV. Experiments

We now verify the validity of our STCA model through experiments. Our experiments are subject to the condition that worms self-reproduce in parallel in finite cellular space with periodic boundary condition. Secondly, worms never die and ever continue trying to extend their arms to place offspring.

Fig.5 shows an initial worm with irregular shape self-reproducing on a cellular space. As self-reproducing growing, some child worms are produced on the space. It is worth noting that the space configuration of offspring may be completely different at different time step, i.e., no matter at t=800, 3650 or 5000. Still, worms can not be very overcrowded on the space. This is due to the fact that an encoding process accompanies retracting its worm tail. If both of the two arms extended from its parent worm fail to continue, they disappear from the space. Therefore, self-reproduction of worms under our mechanism presents a characteristic of dynamics. Furthermore, Fig.6 shows self-reproduction of two worms with irregular shapes on a cellular space. In the initial, both of the two worms produce their offspring in parallel. As iterations continuing, competition for space among worms becomes more and more intense. As a result, the worms with shape “S” evolve to disappear, left space for the other shape worms to self-reproduce, as is shown in the Fig.6(d). This is because that the “S” shape worm is larger than the other shape one, which needs more space to place its offspring. By utilizing our mechanism, a worm does not self-reproduce by trial and error. Especially in the fierce space competition, the larger the worm is, the



(a) t=0 (b) t=800 (c) t=3650 (d) t=5000

Figure 5. The self-reproductive process of an initial worm on 60×60 cellular space. The child worms are produced in parallel dynamically.

less superiority it has to reproduce successful. Obviously, the larger worms are eventually erased from the space in this experiment.

V. Conclusions

This paper proposes a new self-reproductive model for worms in asynchronous self-timed cellular automata. Based on the shape-encoding mechanism, a variety of worms can be self-reproduced. Reliable self-reproduction in parallel can be achieved by dealing with collisions among worms properly. Self-reproduction of a worm accompanies losing the shape information, which avoids overcrowding of worms on cellular space. Moreover, a space usually results in dominance by only one type of worms, even though more than one type of worms on a space in the initial, displaying an evolutionary process. An evolutionary process constructed on CAs is completely emergent and self-organized one, instead of maintaining operations form outside, like artificial evolutionary systems in [16]–[18].

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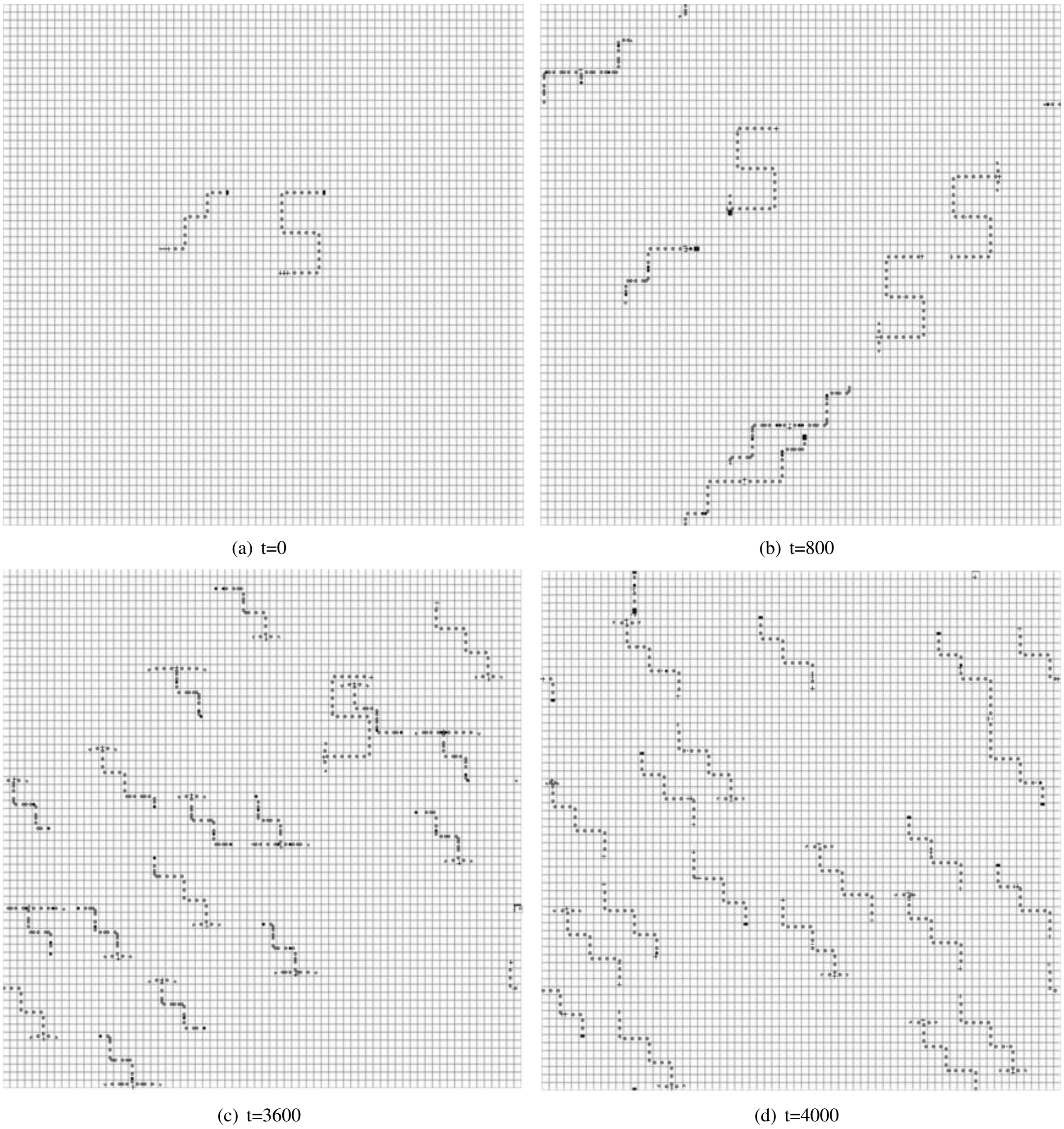

Figure 6. Self-reproduction of the two initial worms on 70×65 cellular space. They produce offspring in parallel. After a few steps, worms with "S" shape disappear from the space left only for placing offspring of the other shape worms.

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APPENDIX

Transition rules for our self-reproductive model are listed below, with their rotational symmetry equivalents left out.