Externally Controllable and Destructible Self-Replicating Loops

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Abstract. Self-replicating loops presented to date are essentially worlds unto themselves, inaccessible to the observer once the replication process is launched. In this paper we present a self-replicating loop which allows for user interaction. Specifically, the user can control the loop's replication and induce its destruction. After presenting the design of this novel loop, we delineate its physical implementation in our electronic wall, the *e-wall*.

1   Introduction: Cellular Automata and Self-Replication

The study of self-replicating machines, initiated by von Neumann over fifty years ago, has produced a plethora of results over the years [1]. Much of this work is motivated by the desire to understand the fundamental information-processing principles and algorithms involved in self-replication, independent of their physical realization [2, 3]. The fabrication of artificial self-replicating machines can have diverse applications, ranging from nanotechnology [4], through space exploration [5], to "intelligent" walls—the latter of which shall be discussed herein.

One of the central models used to study self-replication is that of cellular automata (CA). CAs are dynamical systems in which space and time are discrete. A cellular automaton consists of an array of cells, each of which can be in one of a finite number of possible states, updated synchronously in discrete time steps, according to a local, identical interaction rule. The state of a cell at the next time step is determined by the current states of a surrounding neighborhood of cells. The cellular array (grid) is n-dimensional, where $n = 1, 2, 3$ is used in practice; in this paper we shall concentrate on $n = 2$, i.e., two-dimensional grids.

A major milestone in the history of artificial self-replication is Langton's design of the first self-replicating loop [6]. His 86-cell loop is embedded in a two-dimensional, 8-state, 5-neighbor cellular space; one of the eight states is used for so-called core cells and another state is used to implement a sheath surrounding the replicating structure. Byl [7] proposed a simplified version of Langton's loop, followed by Reggia *et al.* [3] who designed yet simpler loops, the

smallest being sheath-less and comprising five cells. More recently, Sayama [8] designed a structurally dissolvable loop, based on Langton's work, which can dissolve its own structure, as well as replicate.

All self-replicating loops presented to date are essentially worlds unto themselves: once the initial loop configuration is embedded within the CA universe (at time step 0), no further user interaction occurs, and the CA chugs along in total oblivion of the observing user.

In this paper we present a self-replicating loop which allows for user interaction. Specifically, the user can control the loop's replication and induce its destruction. These two mechanisms are explained in the next section, followed in Section 3 by their hardware implementation in our electronic wall, the *e-wall*. Finally, we present concluding remarks in Section 4.

2   Loop Design and Operation

Contrary to previous loops, which self-replicate continually, the novel one presented bellow is idle *unless externally activated.*

We consider a two-dimensional, five-neighbor cellular space, with seven basic states per cell (Figure 1; the CA's state-transition rules are given in the Appendix). Our loop, based on the minimal loop of Reggia called UL06W8V [3], comprises four cells. As long as no external input is provided, the loop is inert, continually undergoing a four-time-step cycle (Figure 2).

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0: empty component
1: building component
2: east-moving signal
3: north-moving signal
4: west-moving signal
5: south-moving signal
6: left-turn signal
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Fig. 1. The seven basic cellular states used for the idle loop. Replication necessitates additional states discussed ahead.
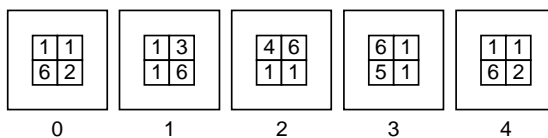

Fig. 2. The four-step idle cycle of the inactive loop.

The user activates the idle loop by providing an external input on one of its four cells (in Section 3 activation occurs by physically touching the e-wall). Activation of the cell leads to the appearance of state 7 instead of state 6 (Figure 3). The activated loop is now ready to self-replicate (if space is available) or self-destruct (if surrounding loops prevent replication).
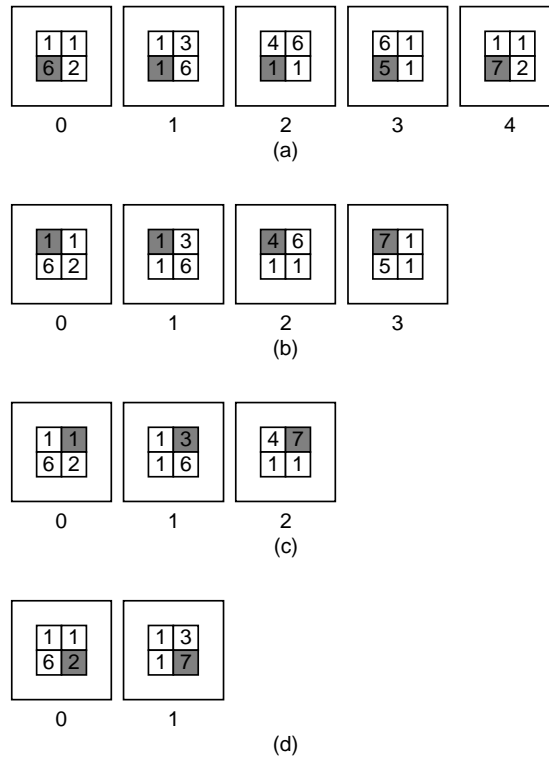
Fig. 3. Activating the idle loop by touching one of its four cells. Depending upon the cell touched, the appearance of state 7 (activated left-turn signal) takes between four (a) to one (d) time steps. In the figures above, the externally activated cell is shadowed.

When surrounded by empty space, the activated loop self-replicates; for example, if the lower-left cell is activated, the loop replicates eastward within eight time steps (Figure 4). Figure 5 presents the four possible eight-step replication processes, induced by activation of the respective cells. Replication requires eight additional cellular states (Figure 6).

When the loop's replication is blocked by another loop, the former initiates an eight-step destruction process (Figure 7); this process can occur in one of four directions, depending on the initially activated cell (Figure 8). While the mother loop can destroy the daughter loop, the contrary is impossible: when the daughter tries to replicate into the mother's space, both loops become idle within four time steps (Figure 9). This deactivation process is shown for all four directions in Figure 10.

The behavior of the loops can be described at a higher level by introducing what we call "macro-notation" (Figure 11). Using these macro symbols we can describe a 12-step process combining activation followed by self-replication (Fig-
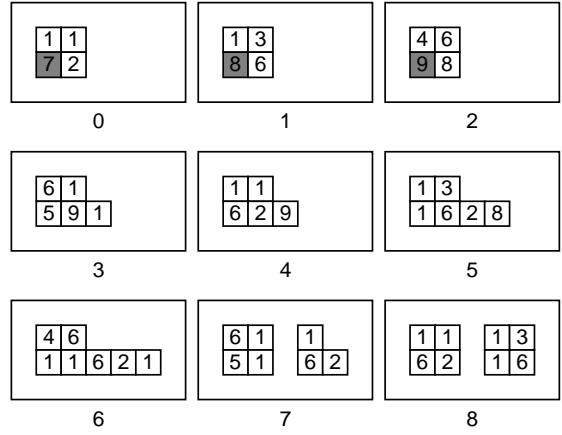
Fig. 4. When the lower-left cell is activated (touched), the loop self-replicates eastward within eight time steps.
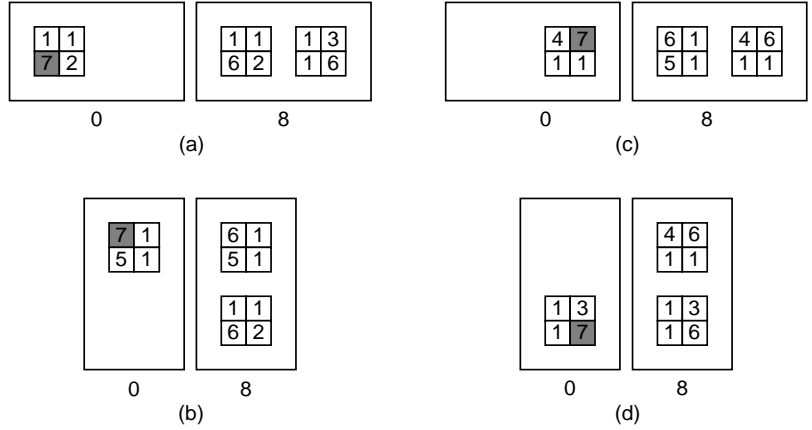

Fig. 5. The four possible activated cells (a-d) and the corresponding replication processes occasioned.

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 7: activated left-turn signal
 8: first east-branching signal
 9: second east-branching signal
10: first north-branching signal
11: second north-branching signal
12: first west-branching signal
13: second west-branching signal
14: first south-branching signal
15: second south-branching signal
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Fig. 6. The eight additional cellular states involved in the activation and self-replication process.
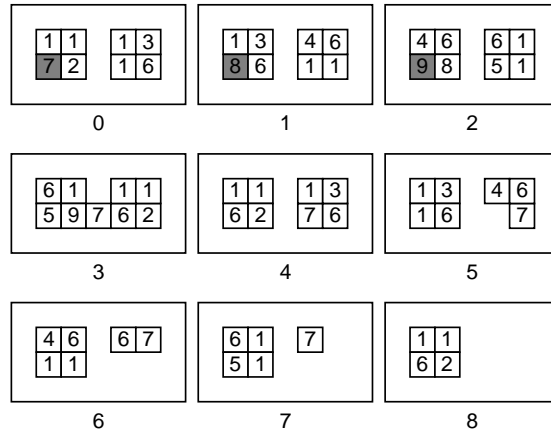
Fig. 7. Activating the lower-left cell results in a destruction process, since the loop is blocked by another loop and thus cannot self-replicate eastward.
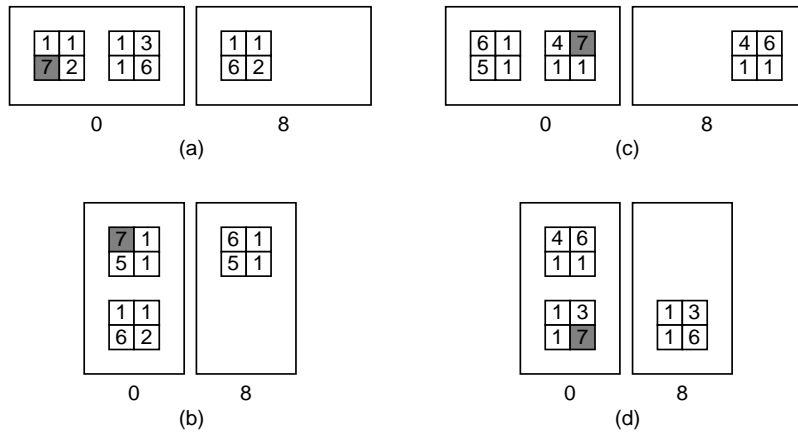

Fig. 8. The four possible activated cells (a-d) and the corresponding destruction processes occasioned.
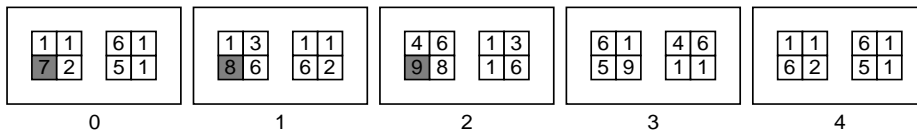

Fig. 9. Daughter deactivation: When the activated daughter loop (left) tries to replicate into the mother loop's (right) space both loops become idle.
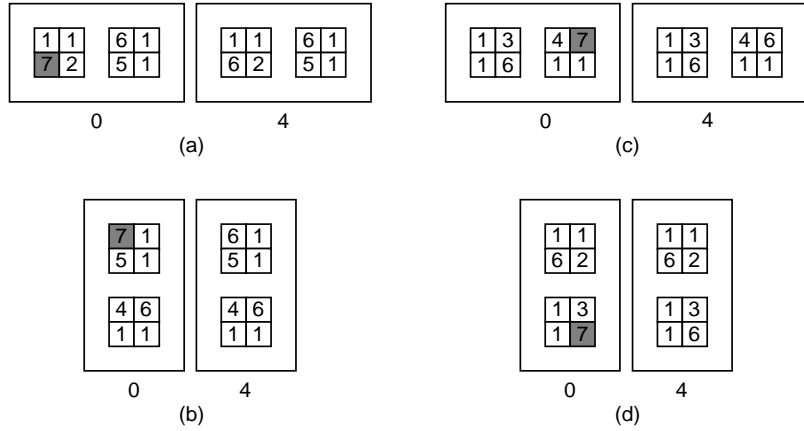
Fig. 10. The four possible activated cells (a-d) and the corresponding deactivation processes occasioned.

ure 12). Three successive 12-step activation-plus-replication processes followed by a single 12-step activation-plus-destruction process are depicted in Figure 13. This kind of macro description allows one to observe and study behavioral patterns at a higher level, similarly to Langton's replicating "colony" [6].
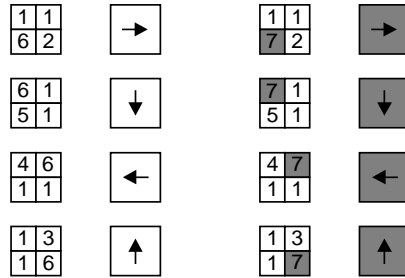

Fig. 11. Macro notation: Idle and activated loops, with their corresponding macro symbols.

3   Physical Implementation: The E-wall

We have physically implemented the five-neighbor CA described above in a two-dimensional electronic wall—the *e-wall*[1]—which is an undergoing project in our
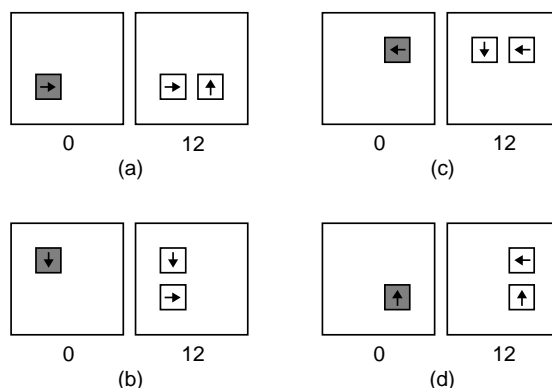
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[1] Patent pending.

Fig. 12. A macro depiction of the 12-step activation-plus-replication process, shown for the four possible cell activations (a-d).

lab (Figure 14). The e-wall is ultimately intended as a self-repairing display medium, capable of interacting "intelligently" with the user and recovering from faults. In our implementation, each CA cell corresponds to a cell in the wall. The physical cell includes: (1) an input device, (2) a digital circuit, and (3) an output display.

The cell's outer surface consists of a touch-sensitive panel which acts like a digital switch, enabling the user to click on the cell and thereby activate self-replication or destruction (Figure 15).

The cell's internal digital circuit is a field-programmable gate array (FPGA), configured so as to implement: (1) external (touch) input, (2) execution of the CA state-transition rules necessary for loop replication, and (3) control of the output display. This latter is a two color light-emitting diode (LED) display, made up of 128 diodes arranged as an 8×8 dot-matrix, each dot containing a green and a red LED. The display allows the user to view a cell's current state (of the sixteen possible) and whether it is in activated or deactivated mode.

4   Concluding Remarks

We presented an interactive self-replicating loop wherein the user can control the loop's replication and induce its destruction. We then described the loop's physical implementation within our electronic wall, or e-wall. The ability to interact with a CA universe—a little-studied issue—is of fundamental import where cellular devices are concerned: one must be able to enter input and to view the output if any practical application is envisaged [1]. Our work herein is but a first step in the domain of interactive cellular replicators, an issue which we believe will play an important role in the future of such devices.
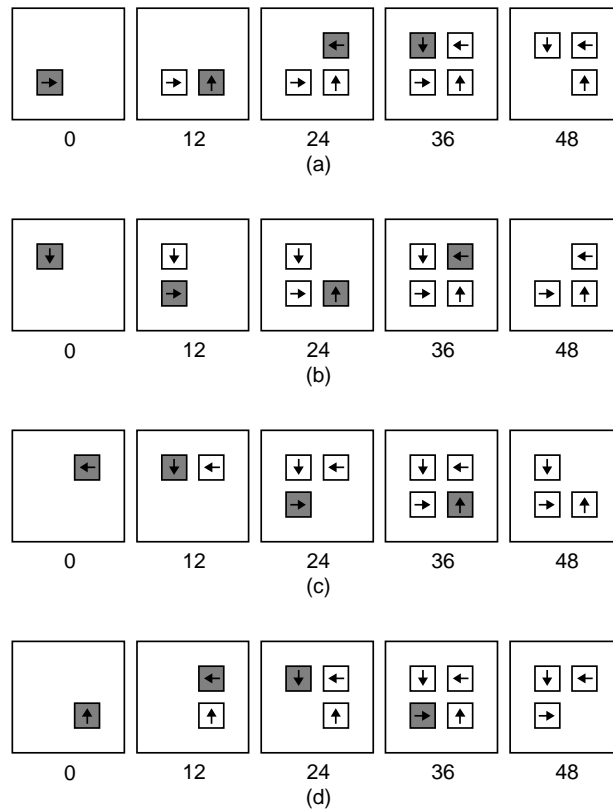
Fig. 13. A macro depiction of three successive activation-plus-replication processes followed by an activation-plus-destruction process, shown for the four possible cell activations of the initial loop (a-d). The loop appearing at time step 36 destroys the original loop after 12 additional steps.

References

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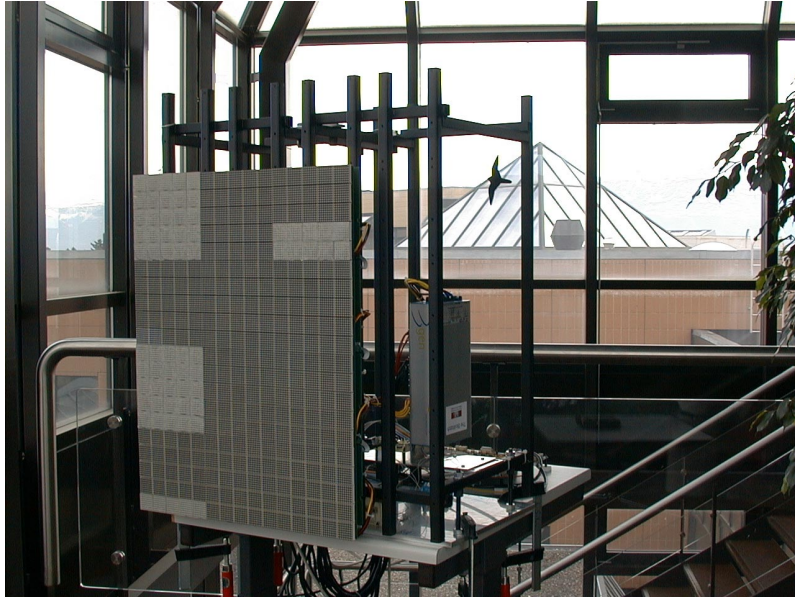
Fig. 14. The e-wall used to physically implement our loop (Photograph by A. Badertscher).
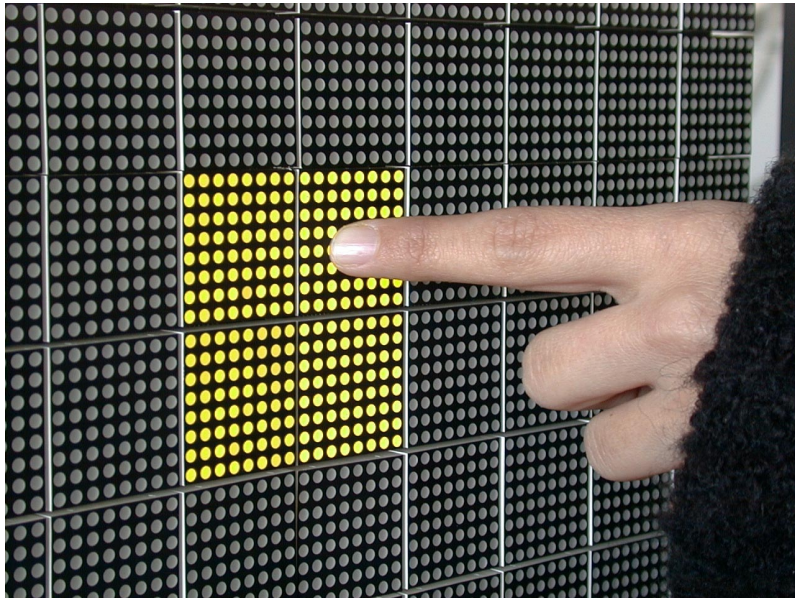

Fig. 15. Touching a cell in order to activate the loop (Photograph by A. Badertscher).

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Appendix: Specification of the CA State-Transition Rules

The state-transition rules of the CA implementing the externally controllable and destructible self-replicating loops are given in Figure 16. In this figure, C, N, E, S, and W correspond to the current states of the cell and of its neighbors to the north, east, south, and west, respectively; $C+$ is the state of the cell at the next time step. There are 3 sets of rules in the figure: (1) 108 rules independent of the activation of the cell ($A = \mathrm{X}$), (2) 4 rules when the cell is inactive ($A = 0$), and (3) 4 rules when the cell is activated ($A = 1$).

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C,N,E,S,W   ->C+    C,N,E,S,W   ->C+    C,N,E,S,W   ->C+    C,N,E,S,W   ->C+

A=X
0,0,0,2,0   -> 1    1,0,3,8,0   -> 4    5,6,0,1,0   -> 6    7,3,0,0,1   ->10
0,0,0,2,1   -> 3    1,4,1,0,0   -> 5    5,6,9,0,0   -> 6    7,0,0,1,4   ->12
0,0,3,0,0   -> 1    1,4,10,0,0  -> 5    5,6,11,0,0  -> 6    7,0,1,5,0   ->14
0,0,3,1,0   -> 4    1,1,0,0,5   -> 2    5,6,0,14,0  -> 6    8,1,6,0,0   -> 9
0,4,0,0,0   -> 1    1,12,0,0,5  -> 2    5,6,1,15,0  -> 6    8,6,0,0,9   -> 9
0,4,1,0,0   -> 5    2,0,0,0,6   -> 6    5,7,1,0,0   -> 6    8,0,0,0,2   -> 2
0,0,0,0,5   -> 1    2,0,1,0,6   -> 6    6,1,2,0,0   -> 1    9,4,8,0,0   -> 5
0,1,0,0,5   -> 2    2,0,8,0,6   -> 6    6,3,0,0,1   -> 1    9,1,1,0,5   -> 2
0,0,0,0,8   -> 1    2,1,9,0,6   -> 6    6,0,0,1,4   -> 1    9,0,0,0,2   -> 2
0,0,0,0,9   -> 8    2,11,0,0,6  -> 6    6,0,1,5,0   -> 1    10,6,0,0,1  ->11
0,0,0,10,0  -> 1    2,13,0,0,6  -> 6    6,3,2,0,1   -> 1    10,0,0,11,6 ->11
0,0,0,11,0  ->10    2,1,0,0,7   -> 6    6,3,0,1,4   -> 1    10,0,0,3,0  -> 3
0,0,12,0,0  -> 1    3,0,0,6,0   -> 6    6,0,1,5,4   -> 1    11,10,0,0,5 -> 2
0,0,13,0,0  ->12    3,1,0,6,0   -> 6    6,1,2,5,0   -> 1    11,1,0,2,1  -> 3
0,14,0,0,0  -> 1    3,10,0,6,0  -> 6    6,12,2,0,0  -> 1    11,0,0,3,0  -> 3
0,15,0,0,0  ->14    3,11,0,6,1  -> 6    6,3,0,0,14  -> 1    12,0,0,1,6  ->13
1,0,0,0,2   -> 2    3,0,0,6,13  -> 6    6,0,0,8,4   -> 1    12,0,13,6,0 ->13
1,0,0,3,0   -> 3    3,0,0,6,15  -> 6    6,0,10,5,0  -> 1    12,0,4,0,0  -> 4
1,0,4,0,0   -> 4    3,0,0,7,1   -> 6    6,3,0,0,8   -> 8    13,0,0,2,12 -> 3
1,5,0,0,0   -> 5    4,0,6,0,0   -> 6    6,0,0,10,4  ->10    13,0,3,1,1  -> 4
1,0,0,0,9   -> 9    4,0,6,0,1   -> 6    6,0,12,5,0  ->12    13,0,4,0,0  -> 4
1,0,0,11,0  ->11    4,0,6,9,0   -> 6    6,14,2,0,0  ->14    14,0,1,6,0  ->15
1,0,13,0,0  ->13    4,0,6,0,12  -> 6    6,0,2,0,1   -> 0    14,15,6,0,0 ->15
1,15,0,0,0  ->15    4,0,6,1,13  -> 6    6,3,0,1,0   -> 0    14,5,0,0,0  -> 5
1,0,0,2,1   -> 3    4,0,6,15,0  -> 6    6,0,1,0,4   -> 0    15,0,3,14,0 -> 4
1,0,0,2,14  -> 3    4,0,7,1,0   -> 6    6,1,0,5,0   -> 0    15,4,1,1,0  -> 5
1,0,3,1,0   -> 4    5,6,0,0,0   -> 6    7,1,2,0,0   -> 8    15,5,0,0,0  -> 5


A=0
2,1,0,0,6   -> 6    3,0,0,6,1   -> 6    4,0,6,1,0   -> 6    5,6,1,0,0   -> 6


A=1
2,1,0,0,6   -> 7    3,0,0,6,1   -> 7    4,0,6,1,0   -> 7    5,6,1,0,0   -> 7
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Fig. 16. CA state-transition rules.