Development of a Two-Dimensional Replicator from a Single Non-Quiescent Cell in Cellular Automata Space

Perry W Swanborough

Abstract

Two hard problems in the origin of life question are identification of the structure of biology's ancestral replicator(s), and the emergence of replicators from a prebiotic environment. In the discipline of cellular automata (CA), not all CA abstractions of replication include any origin pathway to the replicating structures. In this work, an origin for the J. Byl (1989) CA replicator from an isolated non-quiescent cell is described. This origin pathway requires introduction of one oriented state and three other states, all of which permanently disappear from the subsequent replication process. Origin of the replicator and subsequent replication display three sequential and spatially-expanding domains of counter-clockwise rotation: the oriented state of a single cell rotates as the first replicator structure develops around it, followed by rotation of the 2x2 cell information loop as a replication cycle proceeds, and in subsequent cycles of replication, orientation of a parent replicator also rotates counter-clockwise as directions of replication are successively blocked by the replicator's children.

Keywords: origin of life, OOL, artificial life, cellular automata, replicator, complexity

Introduction

The origin of life (OOL) within a prebiotic world is a deep, unsolved problem in biology [6] for which there are many models and methods proposed as investigative tools. Cellular automata (CA) environments are one means of developing provisionally-useful abstractions of biological and biophysical phenomena, including replication. Two-dimensional abstractions of replication include [1], [2], [4]. A main motivating question in these and related studies is: what is the minimum threshold of complexity at which non-trivial replication is possible? This question immediately begs the question of how complexity in this context is defined and quantified [3]. A meaningful purpose of identifying the simplest-possible replicator is to approach the ideal of studying the phenomenon of replication itself, and not merely to study the replication behaviour of arbitrary replicating structures.

Intuitively obvious variables defining replication complexity include the size of a replicator (*e.g.*, the number of non-quiescent cells comprising a CA replicator structure), the size of the state-transition function required to support the replication process, and the size of the cell-state set [1]. The most transparent description of a state-transition function is a lookup table of all explicit state-transition rules - but is the length of a rule lookup table a meaningful quantification of complexity? Generally, a lookup table can be compressed in size by not explicitly listing default rules, and condensing many rules into one rule statement with a "wild-card" character (*) where possible, *e.g.,* in the rule-statement **5****** → **2**, the * state entries correspond to "don't matter" neighbour cell states, so in systems where this rule-statement applies, a **5** state at time t always transitions to **2** at time t+1. Is the reduced size of a so-condensed state-transition function a more relevant contribution to the quantification of complexity? Quantification of complexity is still an unresolved problem in many contexts [3].

I have studied abstractions of replication in cellular automata spaces as a means of thinking about homochirality in biology, *e.g.*, [8]. This work was best facilitated by study of look-up tables of all

explicit state-transition and state-preserving rules. Homochirality is a topic closely-related to the OOL problem, because it is so-far unknown how symmetry-breaking occurred within presumably racemic pre-biotic conditions to produce the ubiquitous chiral bias of biology observed today.

The objective of this study

Inspired by the inclusion of a mechanism for the emergence of replicators in [2], this work describes an origin mechanism for the J. Byl replicator [1]. Replication of the Byl structure is built on strong rotational symmetry, but the origin mechanism presented below (Figure 2) begins with an initial oriented state subject to the weak rotational symmetry which applies in [2]. Before presenting the result, brief descriptions of the Chou and Reggia [2] and Byl [1] systems follow:

The H-H Chou and JA Reggia CA replicators [2]

H-H Chou and JA Reggia developed a dynamic ecology of self-replicating structures including prebiotic emergence of minimal self-reproducing structures and subsequent development of a diverse size distribution of interacting replicators [2]. Chou and Reggia designed their system to incorporate a simple origin for the emergent replicators. In this system, the state-transition function of John Conway's Game of Life CA [5] is deployed as the initially-exclusive prebiotic physics, with each component of an initial random spatial distribution of unbound components {**>**, **V**, **<** , **^**, O, L} interpreted as an on-state, and empty cells (quiescent state) interpreted as the off-state. The Game of Life state-transition rules are defined by counts (not specific spatial distributions) of on-cells within cell neighbourhoods, so it can be readily recognized that Game of Life CA physics is achiral (in the sense that a neighbourhood and its mirror-neighbourhood both correspond to the same state-transition).

Wherever and whenever the 2x2-component configuration (O, O; L, **>**) appears, the status of the four components becomes *bound*. Chiral bound-component state-transition rules apply to bound components, while the unbound-component rules continue to apply for unbound components. The 2x2-cell configurations replicate under the chiral bound-component subset of the state-transition rules. Setting of a special bit to status * within the 2x2-cell structure enables replication of the structure. In Figure 9 of [2], exact replication of a 2x2-cell structure in isolation is illustrated.

The appeal of this system is that a replicating structure emerges by a conceptually simple process within an initially unstructured environment. The replicator incorporates some oriented states which rotate in accordance with rotation of the reference frame (*i.e.,* the directed state **^** within a structure rotates from **^** → **<** → **V** → **>** through counter-clockwise rotation of the structure within the cellular automata space, *i.e., weak* rotational symmetry applies).

Inspired by the inclusion of a mechanism for the emergence of replicators in [2], I considered the possibilities for simple origins of a *strong* rotational symmetry system of replicators, *i.e.*, the J. Byl replicator [1].

A strong rotational symmetry system of replicators: the J. Byl loop [1]

In the J. Byl loop, an internal 2x2 instruction loop of states (3, 3; 4, 1) rotates counter-clockwise as the state transition function is applied iteratively. Under the transition function, the instructions are simultaneously interpreted and copied so that an identical child is progressively constructed with its

own internal copy of the 2x2-cell instruction loop. To illustrate the rotation of the instruction loop under application of the state transition function, Figure 1 below shows a sterile loop. This loop instance lacks state 5 which is necessary for replication, so the instruction loop (3, 3; 4, 1) rotates unproductively (neither interpreted nor copied) indefinitely.

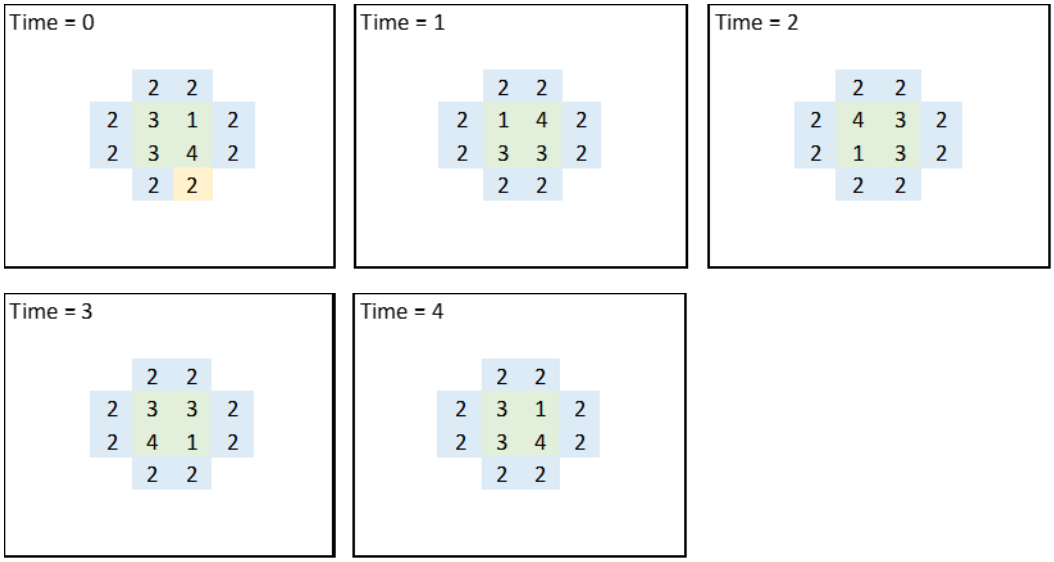
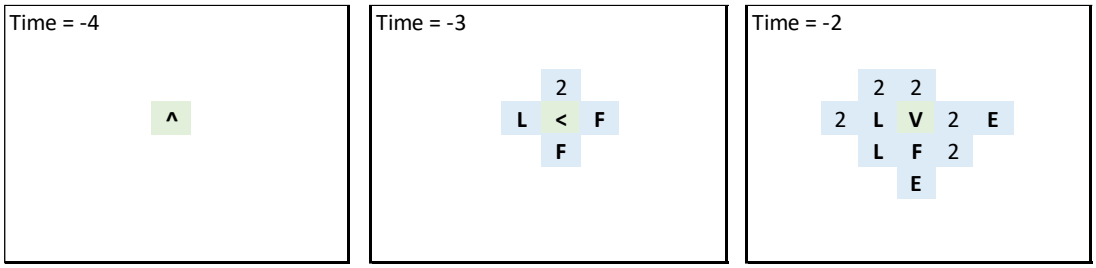


Figure 1. A sterile loop. The state-2 cell labelled with gold highlight at Time = 0 is in state 5 within a viable replicator [1],[7]. The absence of state 5 prevents subsequent replication, and the 2x2 cell instruction loop (green background) rotates counter-clockwise and unproductively from (3, 1; 3, 4) at Time = 0 → (1, 4; 3, 3) → (4, 3; 1, 1) → (3, 3; 4, 1), and back to (3, 1; 3, 4) again at Time = 4 to complete a cycle which continues indefinitely as the state-transition function is applied iteratively.

Results

Figure 2 below shows one way the J. Byl replicator can emerge from a single non-quiescent cell (the oriented state **^**). In addition to introducing this state, the three new non-oriented states L, E and F are also introduced to the state-set.



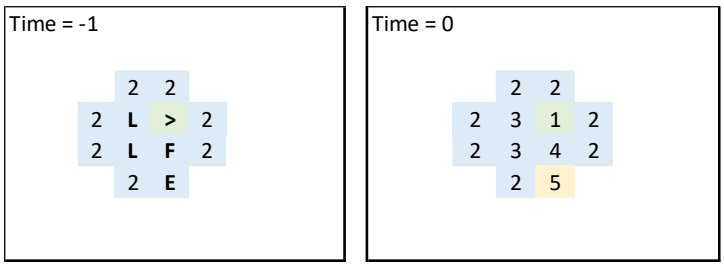


Figure 2. A constructed sequence showing emergence of the J. Byl replicator [1] at Time = 0 from a single non-quiescent cell (oriented state **^** at Time = -4). The green highlighting indicates the counter-clockwise rotation of the initial non-quiescent oriented state **^** until it transitions to state 1 within the completed replicator. The state 5 cell (gold highlight, Time = 0) is essential for subsequent replication of the structure. The state-transition function is shown as the list of rules in Table 1.

In the sequence of development of a replicator from a cell in state **^** within a quiescent (state 0, white space in the Figures) background, this oriented state **^** rotates counter-clockwise (**^** → **<** → **V** → **>**) as more non-quiescent states accumulate around it. At Time = -1, the structure incorporates states 2 (sheath state), **>**, L, F and E. States **>**, L, F and E serve as placeholders which are replaced respectively by states 1, 3, 4 and 5 in the transition from Time = -1 to Time = 0. The configuration incorporating states 1, 2, 3, 4 and 5 at Time = 0 is the Byl replicator [1],[7]. Table 1 below shows the state-transition rules required for development of a replicator from the **^** state. These rules contain no contradictions with the rules established for subsequent replication [1], so they can be added to the established J. Byl replicator state-transition function to give a more comprehensive transition function supporting both replication and emergence of the replicator from a simple origin.

Table 1. The list of 43 von Neumann state-transition rules supporting development of the J. Byl replicator from a single cell of oriented state **^** shown in Figure 2. No rotational-symmetry equivalents are included. The format of each rule is **C**NESW → **C'**, where **C** is the state of the centre cell of the von Neumann neighbourhood at time t. State **C** is replaced with state **C'** at time t+1. The quiescent state is shown as 0 in the rule statements, and as white space in the Figures.

00000 --> **0**	**0**000F --> **E**	**2**002> --> **2**	**F**<000 --> **F**
00002 --> **0**	**0**00F2 --> **0**	**2**00V2 --> **2**	**F**>2EL --> **4**
00022 --> **0**	**0**02L0 --> **2**	**2**02L0 --> **2**	**F**000< --> **2**
^0000 --> **<**	**0**0L00 --> **2**	**2**0E2V --> **2**	**F**V2EL --> **F**
<2FFL --> **V**	**0**200E --> **0**	**2**0L00 --> **2**	**L**0<00 --> **L**
>22FL --> **1**	**0**E002 --> **0**	**2**0L20 --> **2**	**L**2>L2 --> **3**
0^000 --> **F**	**0**F00F --> **2**	**2**200F --> **2**	**L**2VL2 --> **L**
00^00 --> **L**	**0**LE00 --> **2**	**2**LE00 --> **2**	**L**LF00 --> **L**
000^0 --> **2**	**0**LF00 --> **L**	**E**0002 --> **0**	**L**LF22 --> **3**
0000^ --> **F**	**2**00<0 --> **2**	**E**F000 --> **E**	**V**22FL --> **>**

0000E --> **0** **2**00>2 --> **2** **E**F002 --> **5**

(end of Table 1)

To illustrate the weak rotational symmetry of rules containing oriented states, the rule **<**2FFL → V yellow-highlighted in Table 1 is shown below with its three unlisted equivalent rotations:

<2FFL → **V** **V**FFL2 → **>** **>**FL2F → **^** **^**L2FF → **<**

Just as left- and right-handed replication of the J. Byl replicator cannot coexist under one state-transition function [8], some of the Table 1 state-transition rules are contradicted by mirror-rules:

Rule **^**0000 → **<** is contradicted by its mirror-rule **^**0000 → **>**

The mirror-rule of **0**0^00 → **L** is **0**000^ → **L** which contradicts **0**000^ → **F**

The mirror-rule of **0**000^ → **F** is **0**0^00 → **F** which contradicts **0**0^00 → **L**

The origin pathway producing a right-handed loop cannot coexist with its mirror origin pathway to a corresponding left-handed loop. More comprehensively, origin of right-handed loops and subsequent replication cannot coexist with origin of left-handed loops and their replication.

Discussion

In the **Introduction** above, the general question of quantification of complexity was noted, and in the context of this work, a degree-of-complexity comparison between Byl replication [1] and Chou and Reggia replication [2] is of specific interest.

In conducting my past work on CA replicators, I derived lists of all explicit state-transition and state-preserving rules to facilitate work specifically about the chirality of replication of CA structures, *e.g.*, [8]. If we accept a count of explicit state-transition and state-preserving rules necessary for one cycle of exact replication as a relevant complexity quantifier, the values are 140 von Neumann rules supporting replication of the Byl replicator and 192 Moore rules supporting generation of a 2x2-cell child from a 2x2-cell Chou and Reggia replicator.

In the interest of condensing their results, the authors of the original research [1], [2] provided short-form state-transition functions which exclude many state-preserving rules as implied default rules, and condense multiple rules into one rule statement with “wild-card” characters where possible.

We can ask which abstraction of replication is the less complex: Byl, or Chou and Reggia? The first point to note in making this comparison is that the Chou and Reggia system is a comprehensive CA ecology incorporating an origin mechanism by which replicators emerge, *extended replication* which over time generates a dynamic and diverse size spectrum of replicators, and rules necessary for handling the inevitable interaction of replicators within the dynamic environment. The state transition function which comprehensively supports the system is presented in their **Appendix** as three pages of code incorporating about 70 code-statements. By contrast, the state transition function supporting Byl replication is a table of cell state-transition rules condensed to 57 rule

statements, but before [2], most CA replicator research was motivated exclusively by the question of quantifying the minimum complexity supporting non-trivial self-replication, which limits the number of rules required.

There are further comparisons to consider. A set of five active cell states is required for Byl replication, but exact replication of an isolated 2x2-cell Chou and Reggia replicator requires eight active states, with a control-bit set (→ *) in some cells at various times to facilitate the replication cycle. State transitions within Chou and Reggia replication require eight neighbour cell inputs (Moore rules apply), compared with only four neighbour cell inputs (von Neumann rules) required for Byl replication. We can conclude that although the 2x2-cell Chou and Reggia replicator structure is smaller than the Byl replicator with its outer sheath of state-2 cells, the state transition function required for basic replication of the 2x2-cell Chou and Reggia structure is larger and more complex.

We have observed that rotation of a single oriented state can facilitate emergence of a Byl replicator structure (Figure 2), and that the 2x2 cell information loop within the structure rotates as a replication cycle proceeds. Continuing to iterate, we can see another emergent level of rotation with further replication cycles. Figure 3 below shows a second replication cycle underway at Time = 29.

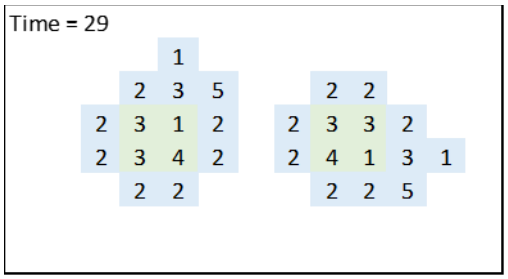


Figure 3. After one replication cycle, the parent structure (the left of the two shown) has produced a child structure to the right, which is replicating its own child to its right. The parent structure is blocked by its child, so at Time = 29 a second replication is occurring up ("North"). The orientation of the parent structure and the direction of its next replication has rotated counter-clockwise.

After the second child is formed and blocks replication north, a third replication occurs to the left ("West"), and after that the continuing counter-clockwise rotation of the replication direction allows a fourth and final replication down ("South"). All directions of replication of the parent structure are by this point blocked so no further replications of the parent are possible.

We have now seen three successive manifestations of counter-clockwise rotation. The domain of counter-clockwise rotation has expanded from rotation of the oriented-state **^** of a single cell, to rotation of the 2x2 cell instruction loop during replication, to rotation of the entire replicating structure as sequential production of children occurs. Rotation of the 2x2 cell information loop, and rotation of replication direction as sequential blocking of replication by child structures occurs are both observable in the animation of the Byl replicator [1] by C. Rocchini [7].

There is no doubt that many origin pathways to a specific CA replicator can be constructed. In biology, the structures and functions observed in anatomy and physiology are often not parsimonious, indicating an expectation that the sequence of OOL steps was not simple and direct.

Allowing for the likelihood of an indirect *ad hoc* OOL pathway opens up a vast number of prospective OOL histories, with perhaps no means of determining any correct one [6].

There is nothing in the J. Byl replicator (from Figure 2, Time = 0) and its subsequent replication process which retains any evidence of the pre-replicator states **^**, L, E and F. These states permanently disappear from the system on establishment of the initial replicator. In the history of real biology, it is as good as certain that much evidence of the chemistry and physics crucial to the emergence of biological replication has been lost permanently. We can only hope that some universalities relevant to the OOL problem exist and are tractable [6].

There are many questions still waiting for answers, including:

In the search for OOL universalities, are there any meaningful isometries of logic between any cellular automata replicators and material chemistry and biophysics?

Of specific interest to CA enthusiasts, can other J. Byl replicator origin pathways be derived requiring no active states more than the set {1, 2, 3, 4, 5} that is sufficient for subsequent replication?

The specific Byl replicator origin presented in this work models OOL as a process which is exclusively chiral from pre-biotic conditions to subsequent chiral replication. In comparison, the Chou and Reggia system [2] models OOL as a sharp transition from achiral conditions to chiral replication. In contrast with both of these, a current viewpoint is that biochirality developed from a preceding racemic condition, *i.e.*, of two initially-coexisting chiralities, one was gradually excluded by its now-ubiquitous complement.

References

[1] J Byl, Self-reproduction in small cellular automata, *Physica D* **34** (1989) 295-299.

[2] H-H Chou and JA Reggia, Emergence of self-replicating structures in a cellular automata space, *Physica D* **110** (1997) 252-276.

[3] L da F Costa and GS Domingues, Cost-Based Approach to Complexity: A Common Denominator?, *arXiv:1905.11925v2[cs.OH]* (2020) 1905.11925v2.pdf (arxiv.org) 12 pages.

[4] CG Langton, Self -reproduction in cellular automata, *Physica D* **10** (1984) 135-144.

[5] W Poundstone, *The recursive universe. Cosmic complexity and the limits of scientific knowledge*, Oxford University Press, Oxford (1987).

[6] A Pross and R Pascal, The origin of life: what we know, what we can know and what we will never know, *Open Biology* **3**:120190.120190 (2013) http://doi.org/10.1098/rsob.120190

[7] C Rocchini, https://commons.wikimedia.org/wiki/File:Byl_loop_animation.gif , (2017, edited 7 May 2020). Accessed November, 2021.

[8] PW Swanborough, An Analysis of the State-Transition Function of a Self-Reproducing Structure in Cellular Automata Space. *viXra:2001.0340* (2020).