Chiral Asymmetry of Self-Reproduction in Cellular Automata Spaces

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Abstract

Focusing on the cellular automata (CA) self-replicating structures and state-transition function of H-H Chou and JA Reggia (1997), self-replication is shown to be homochiral. More briefly, chiral asymmetry is shown also for earlier examples of CA self-replicating structures. The work concludes with brief speculation about inevitability or otherwise of homochirality observed in biology.

Keywords: chiral asymmetry, self-replication, cellular automata, artificial life, origin of life

1. Introduction

The self-reproducing structures considered in this work ([4], [1], [6], [2]) were all developed in the 1980s and 1990s. The dominating focus motivating the work was the question of the lower limit of size and complexity of structures and transition functions supporting non-trivial self-reproduction. Some conceivable questions were not explicitly considered in this work at the time, and so I considered that these works were worthy of reconsideration regarding questions of symmetry. There has been much work done and ongoing, in attempting to discover how "handedness" or chiral asymmetry of biology came to be, *e.g.* [3].

Inspired by John von Neumann's cellular universal constructor, and especially the later simplification by E. Codd, C. Langton developed a small self-reproducing structure within a cellular automata (CA) space [4]. In accordance with a state-transition function comprising 219 state-transition rules (twelve later recognized as passive [6]), the cell states of the signal path loop within Langton's 94-cell ancestral structure are copied at one locus, so that one copy of the sequence continues to cycle within the loop section of the structure, and the branching copy is interpreted at the tip of the structure's construction arm to guide its extension and direction. At 151 recursions, a separated exact copy of the parent structure exists.

Progressing the theme of the minimal size of a self-reproducing structure, J Byl derived a non-trivially self-reproducing structure comprising only twelve cells [1]. The signal path loop is reduced to 2x2 cells of three states so that the inner sheath cells of Langton's structure are absent, but an outer sheath is retained. Under the state-transition function supporting self-reproduction of this structure, a separated offspring copy is generated within 26 recursions.
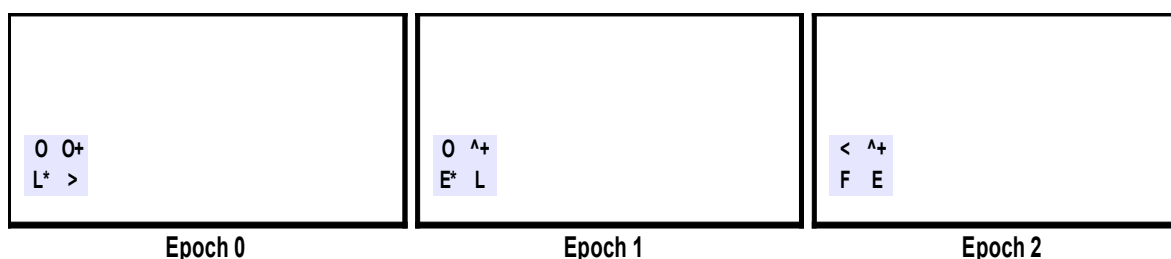
Reggia *et al.* recognized that a further size reduction was possible with the reintroduction of an oriented signal state (>) and corresponding weak rotational symmetry, allowing for the removal of the sheath altogether [6]. Under the state-transition function supporting its self-replication, their structure of only six cells (designated UL06W8V) generates a separated offspring copy in only ten recursions.

2. A comprehensive system of emergence, self-reproduction and diversification as an example for investigating the symmetry of self-reproduction

Subsequent to the work outlined in the Introduction, Chou and Reggia developed a comprehensive ecology of self-reproducing structures beginning with prebiotic emergence of minimal ancestral self-reproducing structures and subsequent development of a diverse size distribution of interacting structures forming a persistent dynamic ecology [2]. The state-transition function of John Horton 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 of on-cells within cell neighbourhoods, so it can be readily recognized that Game of Life CA physics is symmetric (the state-transition rule set is closed under mirror transformation).

Wherever and whenever the 2x2-component configuration (O O, L >) appears, the status of the four components becomes bound. Bound-component state-transition rules apply to bound components, while the unbound-component rules continue to apply for unbound components. The 2x2 configuration is capable of self-reproduction under the bound-component state-transition rules. In Figure 9 of [2], replication of a 2x2 ancestral structure in isolation is illustrated. Setting of a special bit to * within the 2x2 structure enables the branching of a construction arm in the course of forming the child loop. For the progressive development of a diverse population size structure, extended replication is supported, in which a growth bit set to + within a structure facilitates extension of the signal sequence by one component (*e.g.* L>> to L>>>) so that a larger child loop is generated. Figure 8 of [2] illustrates extended replication of a 3x3 structure to generate a 4x4 structure. Extended replication of a 2x2 structure to generate a 3x3 structure is not explicitly illustrated in [2], so for the purposes of supplementing the content of [2] and also demonstrating much of the state-transition function applying to bound-components for subsequent use in this work, Figure 1 below shows extended replication of an ancestral 2x2 structure with a growth bit set (+) to facilitate generation of a 3x3 structure. All recursions (Epochs) from 0 to 51 are shown.

After one extended replication, the L>> sequence corresponding to generation of a 3x3 structure is preserved in the re-separated initial 2x2 structure at epoch 27. This sequence can continue to be interpreted for more 2x2 to 3x3 extended replications indefinitely by allowing the rule which sets the growth bit to + in the cell occupied by component > at epoch 31 in the transition to epoch 32. Alternatively, considering this rule as optional and overriding it ensures the L>> sequence is restored to L> so that further replications of the initial 2x2 structure in isolation generate only 2x2 copies. The latter option is implemented in the Figure 1 series below, so that a 2x2 copy of the initial structure has been generated to its north by epoch 50. The 3x3 structure at epoch 51 is well advanced in its own non-extended replication.


```
O  O+              O  ^+              <  ^+
L*  >              E*  L              F   E
```

Epoch 0   Epoch 1   Epoch 2

`< L` `V F O`	`L O` `V > >`	`O   ^` `L > > B`
Epoch 3	**Epoch 4**	**Epoch 5**
`< ^` `O L > >`	`< L` `V O L > B`	`L O` `V > O L >`
Epoch 6	**Epoch 7**	**Epoch 8**
`O   ^` `L > > O L B`	`< ^` `O L > > O C`	`< L` `V O L > > C`
Epoch 9	**Epoch 10**	**Epoch 11**
`L O` `V > O L > ^`	`O   ^         B` `L > > O L   ^`	`< ^         ^` `O L > > O L`
Epoch 12	**Epoch 13**	**Epoch 14**

`B`
`< L         L`
`V O L > > O`
	`C`
	`L O         O`
	`V > O L > >`
		`C`
		`O ^         ^`
		`L > > O L >`

Epoch 15	**Epoch 16**	**Epoch 17**

`<`
`< ^         ^`
`O L > > O L`
	`B <`
	`< L         L`
	`V O L > > O`
		`< L`
		`L O         O`
		`V > O L > >`

Epoch 18	**Epoch 19**	**Epoch 20**

`B L O`
`O ^         ^`
`L > > O L >`
	`C O <`
	`< ^         ^`
	`O L > > O L`
		`C < <`
		`< L         L`
		`V O L > > O`

Epoch 21	**Epoch 22**	**Epoch 23**

Epoch 24
```
        V  <  L
L  O           O
V  >  O  L  >  >
```

Epoch 25
```
      V  L  O
O  ^     B     ^
L  >  >  O  L  >
```

Epoch 26
```
         L  O  <
<  ^     V     ^
O  L  D  O- O  L
```

Epoch 27
```
      O  <  <
<  L  L     L
V  O* O- O  O
```

Epoch 28
```
      <  <  L
L  O  O     O
V  >* O* O  O
```

Epoch 29
```
      <  L  O
O  ^  V     O
L  >* O* O  O
```

Epoch 30
```
      L  O  O
<  ^  V     O
O  L* >* O  O
```

Epoch 31
```
      O  O  O
<  L  L     O
V  E* >* >  O
```

Epoch 32
```
      O  O  O
L  E  O     O
V  F  L* >  >
```

Epoch 33
```
   O  O  O  O
O  F  O     ^
L  >  E* L  >
```

Epoch 34
```
   ^     O  O  <
O  ^  O     ^
O  L  F  E  L
```

Epoch 35
```
   B
   ^     O  <  <
<  L  O     L
O  O  O  F  E
```

Epoch 36
```
   ^
   L     <  <  L
L  O  O     O
V  O  O  O  F  O
```

Epoch 37
```
B
L
O     <  L  O
O  O  V     O
L  >  O  O  O  >
```

Epoch 38
```
C
O
O     L  O  O
O  ^  V     O
O  L  V  O  O  O  B
```

Epoch 39
```
C
O
^     O  O  O
<  L  L     O
O  O  V  >  O  O  O
```

Epoch 40
```
C
^
L     O  O  O
L  O  O     O
V  O  L  >  >  O  O
```

Epoch 41
```
<
L
O     O  O  O
O  O  O     ^
L  >  O  L  >  >  O
```

Epoch 42
```
B  L
O
O     O  O  ^
O  ^  O     ^
O  L  O  O  L  >  >
```
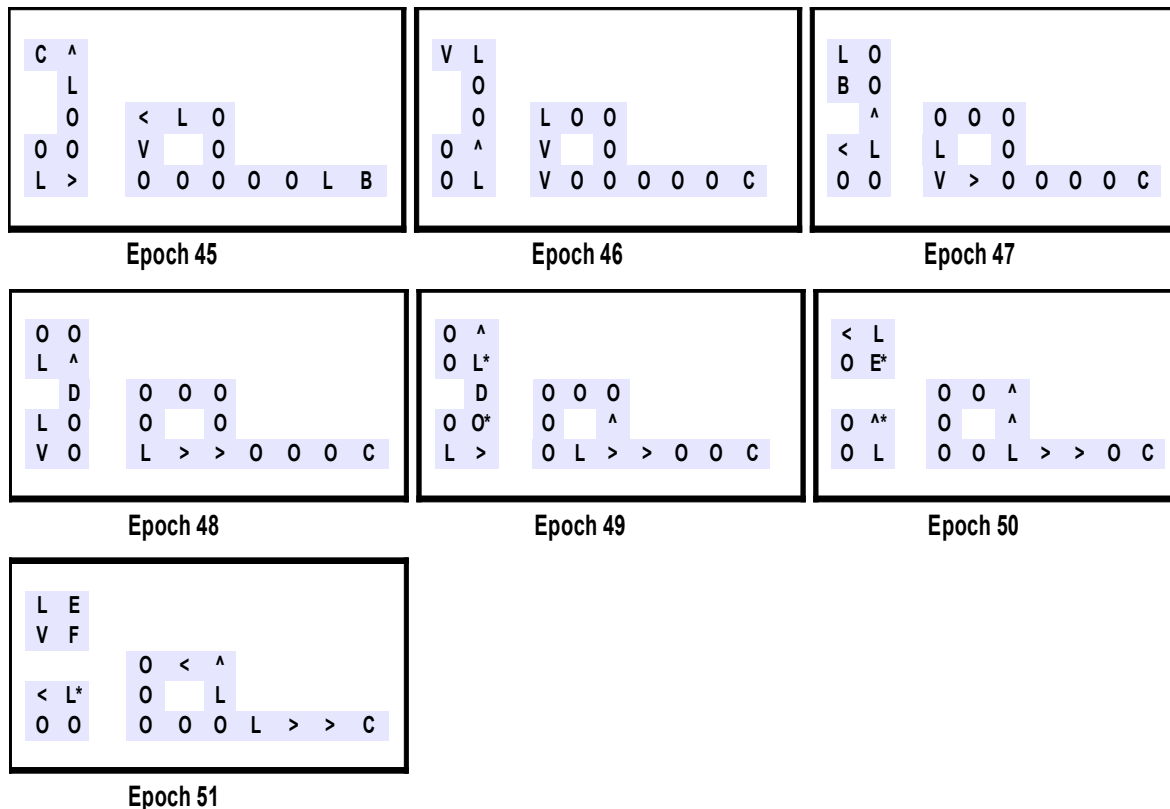
Epoch 43
```
C  O
O
^     O  <  ^
<  L  O     L
O  O  O  O  O  L  >  B
```

Epoch 44
```
C  O
^
L     <  <  L
L  O  O     O
V  O  O  O  O  O  L  >
```

```
C  ^
   L
   O        <  L  0
0  0        V     0
L  >        0  0  0  0  0  L  B
```
Epoch 45

```
V  L
   0
   0        L  0  0
0  ^        V     0
0  L        V  0  0  0  0  0  C
```
Epoch 46

```
L  0
B  0
   ^        0  0  0
<  L        L     0
0  0        V  >  0  0  0  0  C
```
Epoch 47

```
0  0
L  ^
   D        0  0  0
L  0        0     0
V  0        L  >  >  0  0  0  C
```
Epoch 48

```
0  ^
0  L*
   D        0  0  0
0  0*       0     ^
L  >        0  L  >  >  0  0  C
```
Epoch 49

```
<  L
0  E*
            0  0  ^
0  ^*       0     ^
0  L        0  0  L  >  >  0  C
```
Epoch 50

```
L  E
V  F
            0  <  ^
<  L*       0     L
0  0        0  0  0  L  >  >  C
```
Epoch 51

Figure 1. Extended replication of a 2x2 (O O, L >) structure at Epoch 0 generating a child 3x3 structure to its right by Epoch 27. By overriding a rule of the state-transition function described in [2], the initial 2x2 structure reverts to unextended replication. A second replication of the initial structure generates a 2x2 child to its north by Epoch 50.

3. The asymmetry of self-reproduction

In contrast to the symmetry of the unbound-component state-transition rules, self-replication of loop structures of [2] will be shown to be homochiral. The (O O, L >) structure shown in Figure 1, Epoch 0, is referred to from here as an "R-loop" to distinguish it from its enantiomorph (mirror form, (O O, < L), referred to as an L-loop.

Application of the enantiomorph-rules (mirror complement of the transition function supporting R-loop replication) to the 2x2 L-loop structure (O O, < L) corresponds to a mirror-image of the development illustrated in Figure 1. The question immediately suggested is:

Is a pooling of the state-transition function with its complement enantiomorph-function for the purpose of supporting self-replication of coexisting R-loop- and L-loop-structures possible? If so, heterochiral self-replication is supported, otherwise it is not.

The bound-component state-transition rules of [2] governing R-loop self-replication can be categorized into a subset of rules closed under mirror-transformation which apply to both R- and L-loop replication, and the remaining rules which apply only to R-loop replication. The complement enantiomorphs of R-loop-only rules apply only to L-loop replication. The rules common to R- and L-

loop replication include achiral rules, *i.e.* each rule is its own enantiomorph. Figure 2 shows examples.

Figure 2. The nine-cell neighbourhoods shown in a,1 and 2, and b,1 can be observed at the corresponding Epochs from Figure 1.   **a.** The two neighbourhoods are enantiomorphic, but they mutually rotate onto each other, *i.e.* they are the same neighbourhood. The transition in both Epoch instances is B → C, so they represent the same state-transition rule. The rule is achiral, therefore common to both R- and L-loop replication.   **b.** The two neighbourhoods are chiral enantiomorphs sharing the common state transition ^ → L. The rule corresponding to the "Epoch 6" neighbourhood applies only to R-loop replication, and its enantiomorph rule applies only to L-loop replication.

Figure 3 below shows the R-loop structure at Epoch 11 from Figure 1. The accompanying Mirror Epoch 11 structure shows its corresponding enantiomorph arrived at from an L-loop 2x2 initial structure (O O, < L) subject to the enantiomorphic state-transition function.
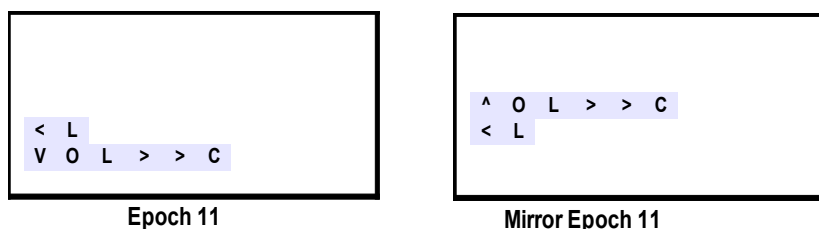

Figure 3. An R-loop developing from the initial (O O, L >) structure (Epoch 11), and its corresponding enantiomorph (Mirror Epoch 11).

In Figure 3, the C component at the end of the construction arm of the Epoch 11 structure transitions to component ^ at Epoch 12 (see Figure 1). The enantiomorph complement of this C → ^ rule applies to the C component in the Mirror (L-loop) Epoch 11 structure, so here C → V, appropriate to proper replication of the structure. Note that the neighbourhood of the C component is identical in both structures so the C component transition rules applying to R- and L-loop replication are contradictory, *i.e.* R- and L-loop replication cannot coexist: self-replication is *homochiral*.

Homochirality is not unique to the Chou and Reggia [2] self-reproduction. One rule-contradiction example each from the state-transition functions of Langton [4], Byl [1], and Reggia *et al.* [6] is sufficient to demonstrate that self-reproduction in all of these systems is homochiral:

- The enantiomorph of Langton's rule **11152 → 2** is **11125 → 2** but this contradicts rule **11125 → 1**.

- The enantiomorph of Byl's rule **31132 → 1** is **31123 → 1** but this contradicts rule **31123 → 3**.

- The enantiomorph of the Reggia *et al.* [6] rule **. . . . > → ^** is **. . . . > → V** which is a self-contradiction.

4. Discussion

Subject to the state-transition functions given in [4], [1], [6] and [2], self-reproduction of the CA structures has been shown to be homochiral.

Considering [2], heterochirality is possible for self-reproduction only by the extravagant *ad hoc* measure of including an enantiomorph-complement of the state-transition function in a way that completely separates it from the original function, perhaps by introducing a two-mode bound-status for components. Allowing for both enantiomorphs of the ancestral 2x2 structure to emerge from the unbound-component rules, the components of the R-form would become bound-components in the usual manner, subject to the original transition function, and the L-form components would become bound in the alternative binding mode, and subject to added "alternative bound rules". All contradictions otherwise of L-transition rules and R-transition rules would be reconciled by this partitioning into separated bound-status modes. More work to handle structure interactions would also be necessary.

Work in the "wet-biology" realm can also point to the physical possibility of heterochirality. Recently an RNA polymerase ribozyme showing decreased chiral discrimination was observed after a process of recursive selection [7], suggesting perhaps that homochirality in biology descends from an early historical contingency, *i.e.* is not physically prohibited.

We can speculate that when prebiotic organization reached a threshold level of complexity corresponding to appearance of self-replicating structures, homochiral self-reproduction was enabled with no subsequent pressures forcing development in a direction supporting heterochirality occurring since.

References

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