

# Describing Complex Dynamics in Life-Like Rules with de Bruijn Diagrams on Complex and Chaotic Cellular Automata

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Received: January 6, 2014. Accepted: June 22, 2015.

De Bruijn diagrams are useful tools for a systematic analysis of one-dimensional cellular automata (CA), i.e. calculating particular kinds of configurations, ancestors, complex patterns, cycles, Garden of Eden configurations, and formal languages. The de Bruijn diagrams are barely employed in two-dimensions because complexity of their calculation increases exponentially. We apply de Bruijn diagrams for analysis of two evolution rules in two dimensions: the *Conway's Game of Life* and the quasi-chaotic *Diffusion Rule*.

*Keywords:* De Bruijn diagrams, cellular automata, complexity, chaos, game of life, diffusion rule.

## 1 INTRODUCTION

Complex dynamics in CA are studied for many years employing different techniques to understand their behaviour and possible classifications [9], some of them are: basins of attraction, mean field theory, differential equations, genetic algorithms, cellular complex networks, complexity computation, formal languages, graph theory, and so on.

In this way, the *de Bruijn diagrams* are a special kind of directed graphs, known originally as *shift register sequences* [6]. These diagrams arise from

a series of works focused to study shift register sequences of symbols for information encoding, where paths represent sequences of states.

De Bruijn diagrams already had been applied in CA (mainly in the one dimensional case), previously by McIntosh [10, 11], Wolfram [16], Jen [7], Voorhees [15], Sutner [14], and others.

In this paper, we will give an introduction selecting de Bruijn diagrams in two-dimensional CA. By the way, we consider two special cases of study: the famous the *Game of Life*\* (complex behaviour) [4] and the *Diffusion rule*† (chaotic behaviour) [8].

We want to get a practical representation of complex patterns following de Bruijn diagram sequences, mainly for the most small and compact mobile self-localizations (particles, gliders, fragments of waves) in both CA.

## 2 ANTECEDENTS

De Bruijn diagram is a powerful tool to calculate ancestors, Garden of Eden configurations, regular languages, set properties, topological properties, and some fragments of complexity in CA. In this way, McIntosh [11] and Voorhees [15] have developed a wide research on de Bruijn diagrams properties, mainly in one dimension.

In this direction, we will mention two previous relevant applications of de Bruijn diagrams in two-dimensional CA. First, McIntosh in 1988 wrote the first approximation to constructing de Bruijn diagrams for two-dimensional CA, in two papers: *Life's Still Lives* [12] and *A Zoo of Life Forms* [13]. By the way, Eppstein has applied de Bruijn diagrams as algorithms to find new complex patterns in a set of Life-like rules [2, 3].

In this paper, we will concentrate our attention on small and compact complex patterns for the Game of Life [4] and Diffusion rule [8] with de Bruijn diagrams.

## 3 DE BRUIJN DIAGRAMS

De Bruijn graph is a directed graph with  $s^n$  nodes, which represent length sequences  $n$  of  $s$  symbols, where at least one overlapping symbol is given.

Thus, applied to the CA representation:

- Symbols represent states, each state value will be represented by  $v$ .
- Nodes of such graphs are partial neighbourhoods formed typically by the half of a neighbourhood.
- Evaluated cell at  $t + 1$  is conventionally the *center cell*.

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\* <http://www.conwaylife.com/>

† [http://uncomp.uwe.ac.uk/genaro/Diffusion\\_Rule/diffusionLife.html](http://uncomp.uwe.ac.uk/genaro/Diffusion_Rule/diffusionLife.html)

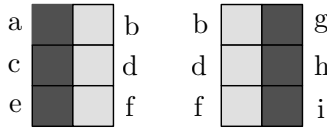


FIGURE 1  
 A representation of Moore partial neighbourhoods. Overlap with central cells  $b$ ,  $d$ , and  $f$  yield the full Moore neighbourhood.

For de Bruijn diagrams in one dimension nodes are strings of symbols as a partial neighbourhood. This way, two nodes connecting represent a full neighbourhood (its edge). Following the same concept for two dimensions partial neighbourhoods are defined by the next characteristics:

- *Form*: It is the original neighbourhood selected, for example Moore neighbourhood.
- *Cell number*: Cells in partial neighbourhoods are coded given its value in decimal representation.
- *Overlap condition*: Overlap condition follows the same principle than was used in one dimension. We have two partial neighbourhoods and they can be connected if the central number of cells are the same in both partial neighbourhoods to form a full neighbourhood.
- *Central cell value at  $t + 1$* : The central cell value  $v_{ce}$  is determined by the selection of the local rule for each neighbourhood.

Following this nomenclature we will illustrate quickly how works. Figure 1 shows a Moore neighbourhood partitioned in two partial neighbourhoods, the overlapping area are cells labeled as  $b$ ,  $d$ , and  $f$ . So, the central cell is the cell  $d$ ; in this case we have than  $s = 2$  and  $n = 6$  and therefore we can calculate a plot with  $2^6$  nodes.

Figure 2a displays partial neighbourhoods evaluating nine cells, these are the center cell with its eight neighbours. So, the partial neighbourhood has 15 cells, and overlap with 10 cells, the nodes number are  $2^{15}$ . Figure 2b shows the partial neighbourhoods evaluating 25 cells, overlapping cells are 21 and here we have  $2^{25}$  nodes.

#### 4 DE BRUIJN DIAGRAMS IN TWO DIMENSIONS

In this section, we describe a practical method based on paths of length  $l$ , in addition to show the possible results obtained.

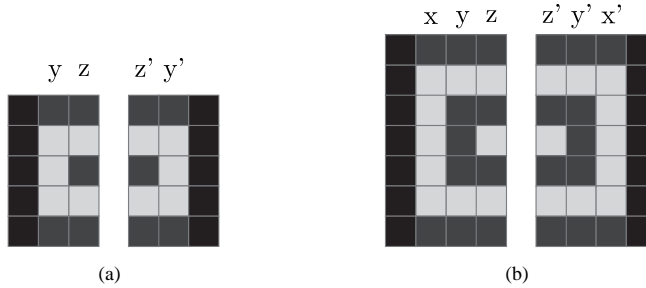


FIGURE 2

Samples of other partial neighbourhoods increasing the number of neighbours. (a) Displays a partial neighbourhood defined by 10 cells, and (b) a partial neighbourhood defined by 21 cells.

Typically, we have two basic kinds of neighbourhoods in two-dimensional CA literature: *von Neumann* and *Moore* neighbourhoods. Since each one has specific features and properties its treatment will be different and reflected in all nodes. A practical algorithm shows the number of steps for building de Bruijn diagrams in two dimensions. We shall describe an example with Moore neighbourhood only.

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**Algorithm 1** Building de Bruijn diagrams for two-dimensional CA

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1. Compute all the elements or nodes of the diagram.
  2. Look for all relations between elements according to the *overlapping condition*.
  3. Evaluate all resulting configurations with the CA rule that will be analysed, i.e., the central cells.
  4. Filter the results in accordance to the CA behaviour.
  5. Look for paths of length  $l$  into the de Bruijn diagram.
  6. In order to build the de Bruijn diagram in its second order, take the last calculated paths that will be replaced as new nodes and repeat steps from stage two.
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#### 4.1 Computing nodes

As saw in Sect. 3, the number of elements to construct de Bruijn diagrams depends given the number of states and the number of cells in its partial neighbourhoods.

This paper shows the analysis on Life-like CA rules for two states and Moore neighbourhood. Giving values to the variables  $s = 2$ ,  $n = 6$ , we have  $2^6 = 64$  nodes. The overlap condition is showed in the Figure 1, light cells highlights the overlapped cells.

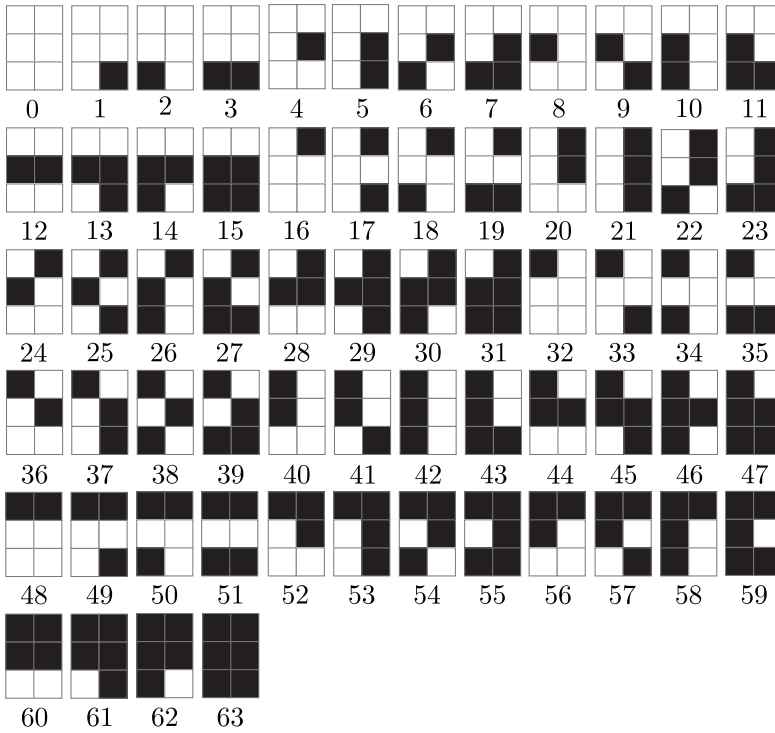


FIGURE 3  
The whole set of partial neighbourhoods of size  $2 \times 3$ , deriving  $2^6$  configurations.

Each node represents a possible combination of state values for each partial neighbourhood. In order to label each partial neighbourhood, its binary representation is used. The sequence will be read from right to left and bottom-up, (see Figure 1), as follows:

- 1 will be when the cell  $f$  is in black,
- 32 when cell  $a$  is black,
- 0 if all cells are white,
- 63 when all cells are black.

This way, Figure 3 displays the whole set of partial neighbourhoods of size  $2 \times 3$ , deriving  $2^6$  configurations.

#### 4.2 Working relations

A full neighbourhood is created through overlapping two partial neighbourhoods (see Figures 1 and 2). By the way, Figure 4 shows one example of the

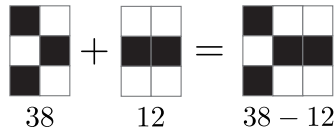


FIGURE 4

Illustrating partial neighbourhoods overlapping to form a full neighbourhood represented in its numerical equivalence.

overlapping between two partial neighbourhoods also in numerical representation.

### 4.3 Evaluating configurations

Once there are all the relationships known for this partial neighbourhoods, it is necessary to know the state value of each for the next generation; following the evolution rule. The resulting string will be the size and shape of the region to the original evaluated neighbourhood.

### 4.4 Filtering results

Typically analysis on CA is through on its evolution. In this process generally we can observe two kinds of common patterns: *stable* and *shifting*. Due to these features, is possible to find a diversity of complex patterns, such as: *still life*, *oscillators*, and *gliders*.

- Bottom to top: taking the first node, is when the evaluated cell has the same value which the cell  $f$ .
- Left to right: taking the first node, is when the evaluated cell has the same value which the cell  $c$ .
- Diagonal: taking the first node, is when the evaluated cell has the same value which the cell  $e$ .

### 4.5 Paths in de Bruijn diagrams

In order to build an evolution space whose state at time  $t + 1$  will be known, we have to look for all possible relationships between nodes. This query can be carried out by methods of searching paths graphs, such as Euler and Hamiltonian paths, where cycles have a given size, with the purpose to have an order among all possible configurations [11]. This classification of paths will lead us to know all periodic patterns in the rule with a specific size.

Figure 5 shows the result of performing the steps described above, where a permanence filter with CA Diffusion rule was done. Following the previous configuration we can design an *agar*<sup>‡</sup> configuration for the Diffusion rule

<sup>‡</sup> <http://conwaylife.com/wiki/Agar>

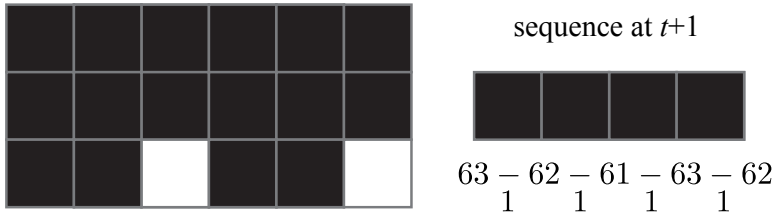


FIGURE 5  
Concatenating two partial neighbourhoods that yield a still life configuration in one generation. This configuration takes partial neighbours from the de Bruijn diagram calculated in Figure 11, this cycle is determined by nodes 63-62-61.

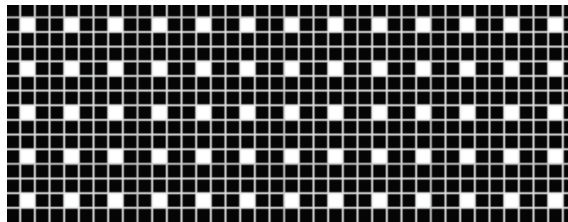


FIGURE 6  
Agar configuration in CA Diffusion rule. Basic mosaic of live cells for construct this agar is derived from Figure 5.

(see Figure 6). An agar configuration preserve its form inside a static universe, thus boundaries properties should be applied to contain the colony of live cells forever.

### 5 LIFE-LIKE PATTERNS VIA DE BRUIJN DIAGRAMS

In order to show the results given by de Bruijn diagrams, this section shows some specific examples with the Game of Life [4] and Diffusion rule [8].

#### 5.1 The Game of Life

Complex behaviour in the famous Conway’s CA, the *Game of Life*<sup>1</sup> (represented as  $B3/S23$ ,  $R(2, 3, 3, 3)$ , or simply *Life*) has been studied since 70’s. Recently, in 2010 year Game of Life was celebrating its 40 anniversary collecting a number of historical and recent publications on Life-like rules in a special book [1]. In order to make universal computation with Life, a extensive list of complex patterns have been found and designed for several years. Several of these patterns emerge as results of specific strings.

<sup>1</sup> The Game of Life Sites [http://uncomp.uwe.ac.uk/genaro/Cellular\\_Automata\\_Repository/Life.html](http://uncomp.uwe.ac.uk/genaro/Cellular_Automata_Repository/Life.html)

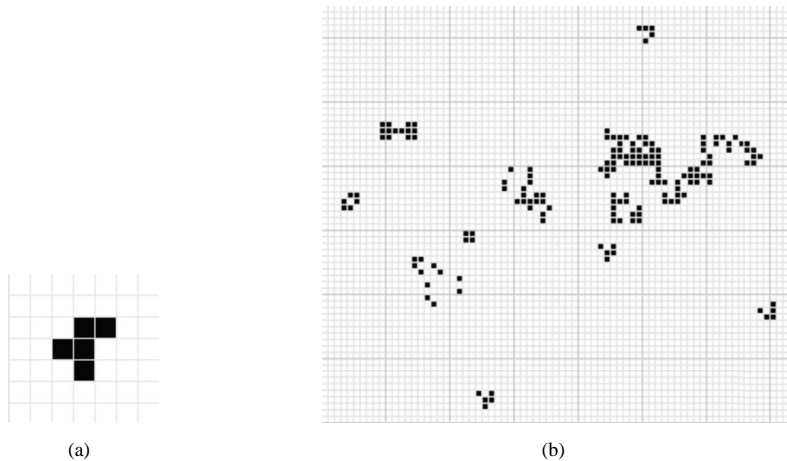


FIGURE 7  
Evolution starting from a (a) *R*-pentomino configuration. (b) Some complex patterns emerging late 173 generations, such as: gliders, oscillators, and still life.

Remembering the game rules, we have that:

- One dead cell will live at the next time if it has three alive neighbours.
- A live cell will remain alive at the next time if it has two or three alive neighbours.
- A live cell will die at the next time if has less than two or more than three alive neighbours.

Figure 7 illustrates a typical evolution starting with a *R*-pentomino<sup>§</sup> configuration. However, this configuration reaches a stability after 1,103 generations. Its history evolution display a diversity of complex patterns, such as: oscillators, still life, chaotic regions, and gliders.

A way to find systematically interesting patterns in the CA behaviour is using de Bruijn diagrams. Figures 8 and 9 show a part of the full diagram for small configurations; it shows the relation between nodes and the state value after one evaluation.

Figure 8 uses the *permanence filter* criteria where the central cells will remain in its original state value, and Figure 9 uses the *shifting filter* in diagonal orientation. Thus, the string given for the sequence of partial neighbourhoods 18-33-7-10-1-18 yield the string 10110.

<sup>§</sup> <http://conwaylife.com/wiki/R-pentomino>



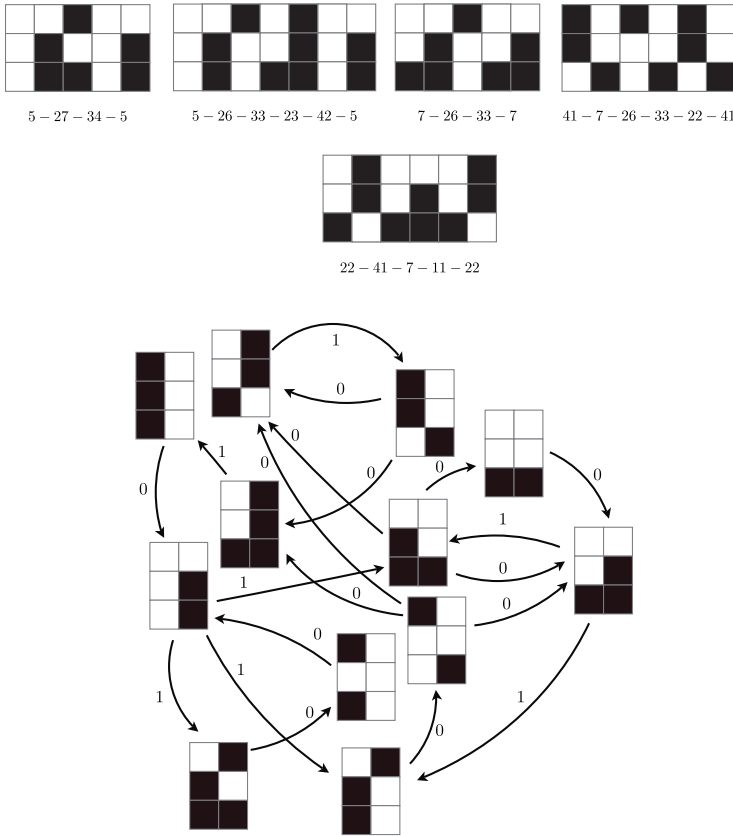


FIGURE 8  
De Bruijn diagram for the Game of Life with *permanence filter* criteria where the central cells will remain in its original state value.

### 5.2 The Diffusion Rule

Another interesting rule is known as the *Diffusion rule* (represented as rule *B2/S7* or *R(2, 2, 7, 7)*) [8]. Particularly, this CA presents commonly chaotic evolutions (see Figure 10). However, complex behaviour emerge starting from very low initial densities where you can see some different complex patterns, mainly gliders, puffers trains but exploiting in chaos quickly [8].

The *Diffusion rule* is defined just for two conditions, as follows:

- One dead cell will born for next generation, if it has exactly two alive neighbours. Otherwise, the cell remains dead.
- One live cell will remain alive if it has exactly seven alive neighbours. Otherwise, the cell will dead.

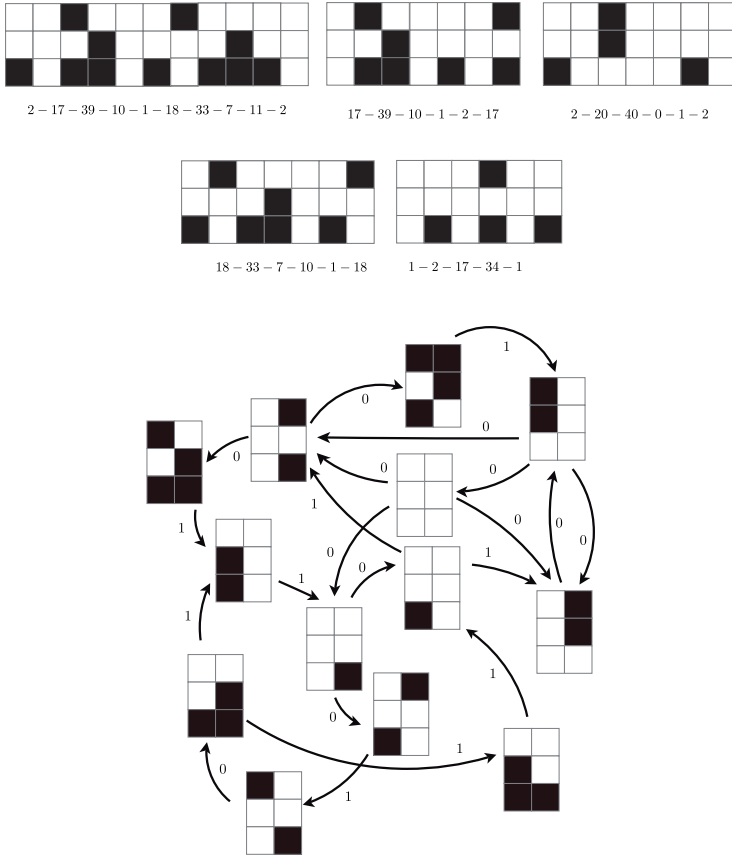


FIGURE 9  
De Bruijn diagram in Life with shifting filter in diagonal orientation.

How was worked in the Game of Life, for the Diffusion rule in Figure 11 we have used *permanence filter* showing strings with length  $l$ . By the way, Figure 14 use *shifting filter* in diagonal orientation and shows the strings that we can derive. Concatenations of these patterns (as configuration of Figure 12) are useful to explore the behaviour of periodic structures. Indeed, from some of these strings we could find some new complex patterns.

Figure 12 displays a particular configuration that will evolve to states 1's in the central cells in one generation (obtained from diagram Figure 14). In Figure 13 we can see a number of complex patterns emerging such a puffer trains and some gliders, reported in the Diffusion rule. Evolution expand quickly with two puffer trains joined (north side) while the south side shows two symmetric puffer trains after 523 generations with 103,918 alive cells.

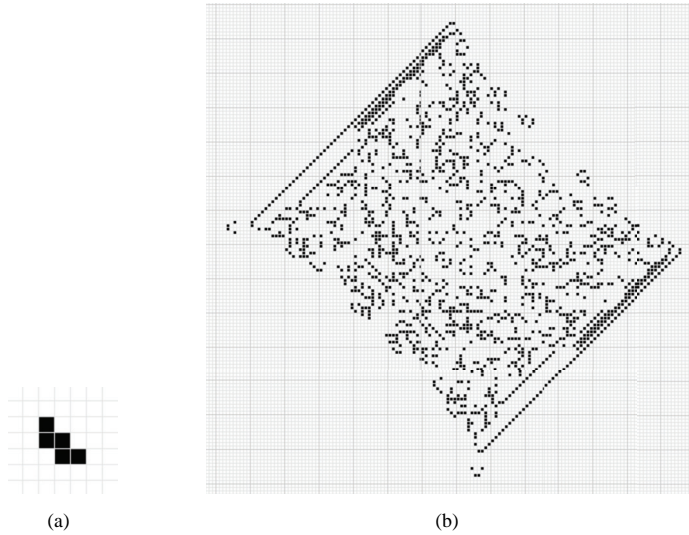


FIGURE 10  
 Evolution starting on a (a) *W*-pentomino configuration. (b) Some complex patterns emerge, such as: gliders and puffer trains, frequently they have very short histories and traveling very fast. But the main feature is that these patterns interact quickly and produce in few steps, as we can see in this simulations after 1,643 generations.

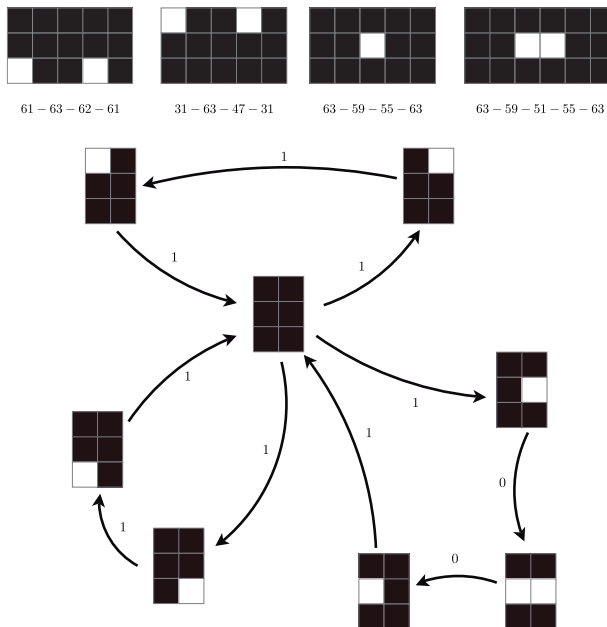


FIGURE 11  
 De Bruijn diagram in Diffusion Rule with permanence filter.

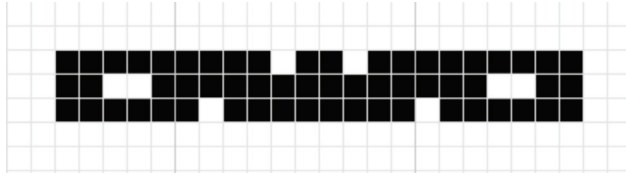


FIGURE 12  
Initial configuration derived following a cyclic way from diagram calculated in Figure 11, starting from node 63.

Figure 14 displays a part of the full diagram, calculating configurations with displacement in one generation. This way, following the cycle with sequence 0-16-49-34-0, we have an initial condition that evolve in two *new* puffer trains in the Diffusion rule. Figure 16 displays the evolution of pattern in Figure 15, showing two new puffer trains reported in the Diffusion rule. Both puffer trains are travelling at north and east, label with two red circles.

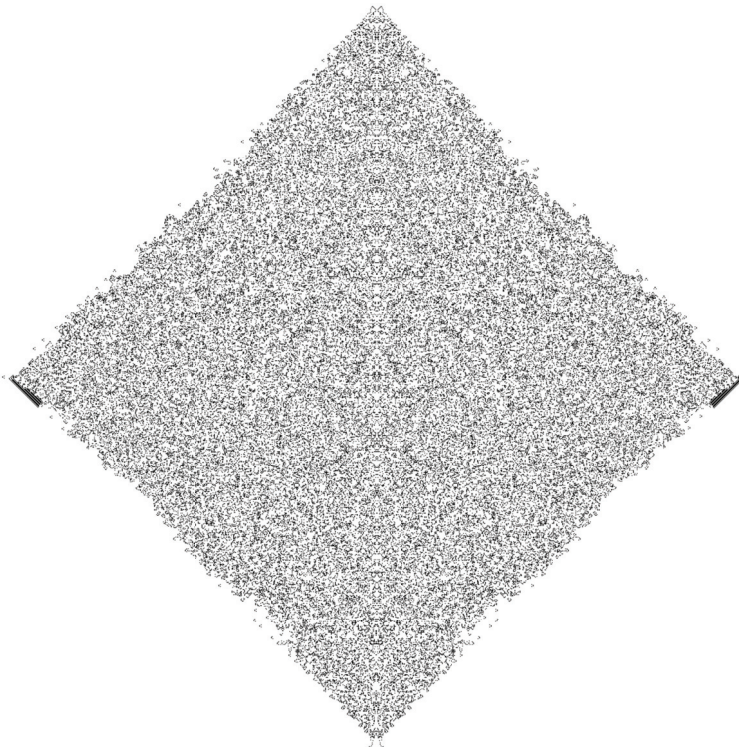


FIGURE 13  
Evolution of initial configuration of Figure 12 for 523 generations and 103,918 alive cells.

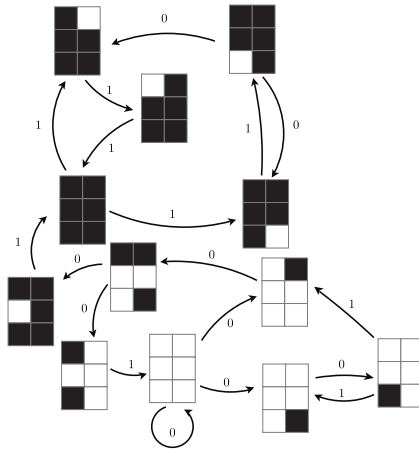
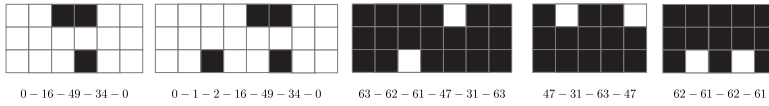


FIGURE 14  
De Bruijn diagram in the Diffusion rule with shifting filter in diagonal orientation.

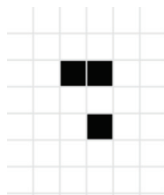


FIGURE 15  
Initial configuration derived from diagram calculated in Figure 14, nodes 0-16-49-34-0.

## 6 FINAL NOTES

This paper gives a brief introduction about the de Bruijn diagrams in Life-like rules domain. Cycles in the de Bruijn diagrams represent precisely a kind of formal language. Such a string helps us in this paper to find small complex patterns emerging in the Game of Life and the Diffusion rule CAs. Of course, the Game of Life historically has the most large research in this direction with several tools [1–3,5]. But, selecting de Bruijn diagrams we have obtained new results for the Diffusion rule, mainly for small complex patterns. Our goal is classify systematically these patterns and construct most large and complex

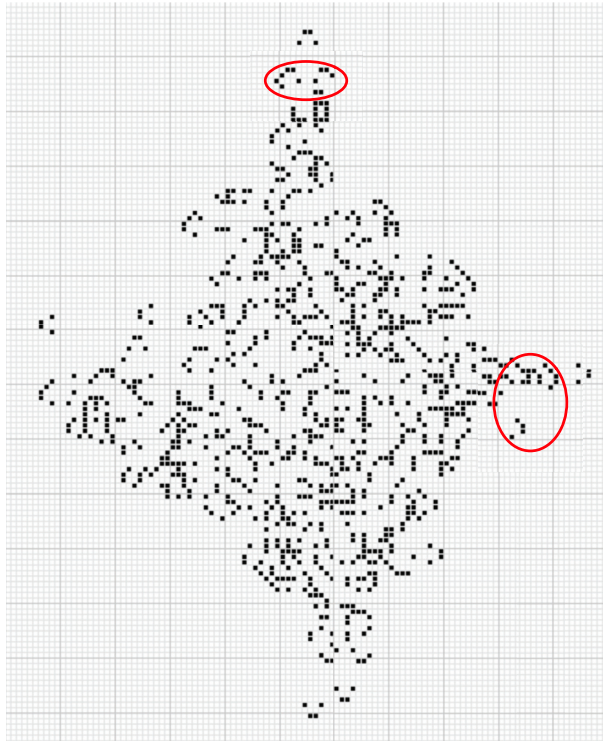


FIGURE 16  
Evolution of initial configuration given in Figure 15 later of 68 generations and 971 alive cells. In this case, a pair of new puffer trains are reported (red circles) for the Diffusion rule.

configurations. Of course, to generate these patterns we need increase the number of shifts and generations that is the future work.

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## 7 APPENDIX

In this appendix we explain with details the de Bruijn matrices for partial neighbourhoods  $4 \times 3$ .

So, in the next pages we calculate every de Bruijn matrix for partial neighbourhoods in a size of  $4 \times 3$  cells for the Game of Life.

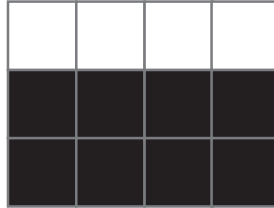


FIGURE 17  
Partial neighbourhood in a size of  $4 \times 3$  cells.

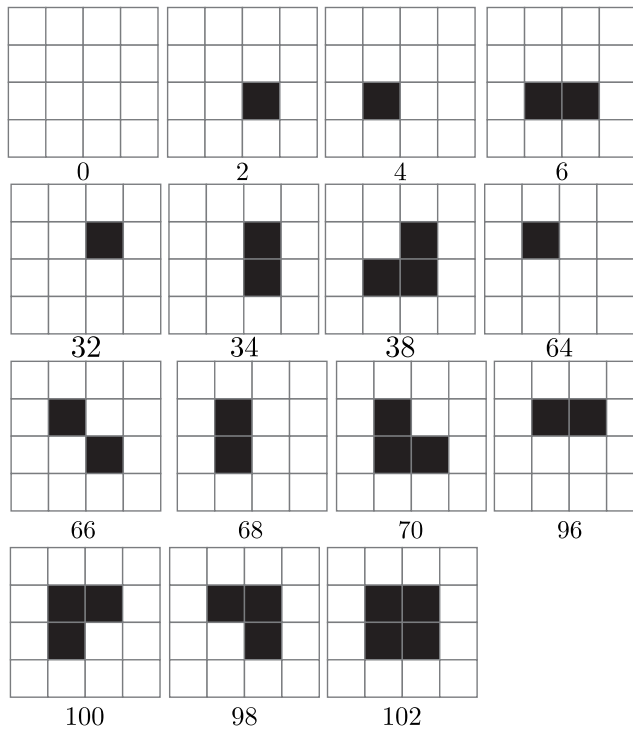


FIGURE 18  
Possible configurations derived from partial neighbourhoods in a size of  $4 \times 3$  cells.



0	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
1	-	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
256	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
512	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
513	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
768	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
769	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	32	32	32	34	32	34	34	34	32	32	32	32	34	32	34	38	36
1024	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
1280	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
1281	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	32	32	32	34	32	34	34	34	32	32	32	32	34	32	34	38	36
1536	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
1537	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	32	32	32	34	32	34	34	34	32	32	32	32	34	32	34	38	36
1792	32	32	32	32	32	32	32	34	32	32	32	32	32	32	36	38	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
1793	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
2048	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
2304	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
2305	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
2560	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	6	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
2561	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	2	0	2	2	0	0	0	0	2	0	2	6	4	
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2817	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	32	32	32	34	32	34	34	34	32	32	32	32	34	32	34	38	36
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516	0	0	0	2	0	2	6	4	0	0	4	6	4	6	6	4																	









