ISSN 2707-1898 (print)
Український журнал інформаційних технологій
Ukrainian Journal of Information Technology
https://science.lpnu.ua/uk/ujit
https://doi.org/10.23939/ujit2021.03.085
Article received 14.04.2021 р.
Article accepted 01.06.2021 р.
UDK 004.932

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EVOLUTION OF TWO-DIMENSIONAL CELLULAR AUTOMATA. NEW FORMS OF PRESENTATION

The paper considers cellular automata and forms of reflection of their evolution. Forms of evolution of elementary cellular automata are known and widely used, which allowed specialists to model different dynamic processes and behavior of systems in different directions. In the context of the easy construction of the form of evolution of elementary cellular automata, difficulties arise in representing the form of evolution of two-dimensional cellular automata, both synchronous and asynchronous. The evolution of two-dimensional cellular automata is represented by a set of states of two-dimensional forms of cellular automata, which complicates the perception and determination of the dynamics of state change. The aim of this work is to solve the problem of a fixed mapping of the evolution of a two-dimensional cellular automaton in the form of a three-dimensional representation, which is displayed in different colors on a two-dimensional image The paper proposes the evolution of two-dimensional cellular automata in the form of arrays of binary codes for each cell of the field. Each time step of the state change is determined by the state of the logical "1" or "0". Moreover, each subsequent state is determined by increasing the binary digit by one. The resulting binary code identifies the color code that is assigned to the corresponding cell at each step of the evolution iteration. As a result of such coding, a two-dimensional color matrix (color image) is formed, which in its color structure indicates the evolution of a two-dimensional cellular automaton. To represent evolution, Wolfram coding was used, which increases the number of rules for a two-dimensional cellular automaton. The rules were used for the von Neumann neighborhood without taking into account the own state of the analyzed cell. In accordance with the obtained two-dimensional array of codes, a discrete color image is formed. The color of each pixel of such an image is encoded by the obtained evolution code of the corresponding cell of the two-dimensional cellular automaton with the same coordinates. The bitness of the code depends on the number of time steps of evolution. The proposed approach allows us to trace the behavior of the cellular automaton in time depending on its initial states. Experimental analysis of various rules for the von Neumann neighborhood made it possible to determine various rules that allow the shift of an image in different directions, as well as various affine transformations over images. Using this approach, it is possible to describe various dynamic processes and natural phenomena.

Keywords: Cellular automata; image; cell neighborhood; evolution.

Introduction

We dont really know how we think. Sometimes solutions to long-standing tasks come to us unexpectedly. We often forget about them, but the brain works and works on its own. Cellular automata will help us to understand these processes.

Today, the development of scientific research in the field of information technology, as well as scientific experiments using modeling, is increasingly being implemented on the basis of cellular automata (CA), which are built on new paradigms and models of their representation [2], [3], [7], [9], [15], [17]. CAs are a physical space of discrete elements that change their states in time, and, therefore, the state of the entire CA (the entire discrete physical space) changes in time. Such changes in CA states in time enable researchers to simulate various dynamic processes, as well as achieve and predict system states based on various initial settings [2], [9], [16], [24]. One of these works, considering the primitive behavior of cell colonies, is the Game of Life, which was proposed by Conway [16]. This work examines the evolution of various colonies formed from different initial forms of "living" cells. The formation of new forms of colonies, the movement of colonies and their death are considered. However, at the final time of the evolution of the colony, only the final form of such evolution is recorded, and intermediate forms are lost. In this case, it is impossible to recreate a clear picture of the change process. You need to repeat all over again. The Game of Life is still being researched in many publications [2], [16].

Research objectives. Due to the fact that the representation of the evolution of two-dimensional CAs in the form of a set of two-dimensional arrays with different states often leads to the construction of false models of dynamic processes, the paper solves the problem of representing the evolution of two-dimensional cellular automata in the form of a single two-dimensional picture. This representation of evolution allows you to efficiently simulate dynamic processes and effectively solve image processing problems.

The object of study – the process of presenting the evolution of two-dimensional cellular automata.

Subject of research – methods for constructing the evolution of two-dimensional cellular automata based on Wolfram coding and presenting them as a two-dimensional color image to display the process of changing the states of cellular automata over time.

The purpose of research – the aim of this work is to solve the problem of a fixed display of the two-dimensional cellular automata evolution in the form of a three-dimensional representation, which is displayed in different colors on a two-dimensional image, which makes it possible to efficiently process and recognize images.

The scientific novelty of the obtained research results – to study new forms of representation of the evolution of two-dimensional cellular automata using Wolfram coding, which allowed image processing using typical logical functions from several arguments.

The practical significance of the research results – that the obtained results allow to build a structure for the description and processing of images in the grayscale and color images. Research makes it possible to define functions based on cellular automata to perform various affine image transformations.

Analysis of literary sources. One-dimensional CA, which are also called elementary CA (ECA), play a huge role in the formation of the picture of the display of evolution. They are detailed by Stephen Wolframs in work [24]. In this work, S. Wolfram considered all possible functions of cell transitions at each time step. Functions of two arguments are considered, which are signals of the states of two nearest neighboring cells. On the basis of ECA, a two-dimensional picture of evolution is well formed. ECA are used to solve many problems in various areas of human life [1], [17].

At the same time, a large volume of problems in science and technology is solved using two-dimensional CA (TDCA). In this case, the evolution of a TDCA can only be represented by forming a set of two-dimensional images of the CA at fixed times. This approach complicates the analysis of the general picture, in which the dynamics of changes in the states of the CA is recorded (memorized) during a given set of time steps.

In modern literature, the evolution of two-dimensional cellular automata is represented by a sequence of two-dimensional arrays, which complicates the analysis of the dynamics of changes in the CA states over time [1], [2], [9], [7], [17]. Behavioral schemes in modeling the dynamics of changes in the states of various systems and the interaction of elements of such systems are mainly considered. On the basis of field two-dimensional pictures in CA modeling of dynamics of behavior of objects is carried out. This approach often gives a misconception about the behavior of the system [1], [13], [19], [22], [25]. Therefore, new effective forms of representing the evolution of two-dimensional cellular automata are now being sought [7], [9].

There are also various approaches to the representation of evolution that use genetic algorithms and instructions [11], [18], [21], based on conditionally appropriate rules [4] based on routine evolution for complex CAs [5], evolution based on neural networks [12], [14]. There are also works devoted to the comparison of different types of evolution [6]. However, all considered evolutions show two-dimensional paintings as a sequence of two-dimensional arrays, which complicates the process of analyzing evolution for modeling various two-dimensional dynamic processes. Especially well-known approaches do not give qualitative results in the implementation of image processing methods.

Research results and their discussion

Display of ECA evolution. ECA is one-dimensional and represents a line of cells, each of which can be in one of two states: logical "1" or logical "0". For each cell, a rule is defined, according to which the state of the cell is determined at the next time step [23], [24]. The states of the considered cell and the states of its neighbors at the current time step are taken into account.

Since only three cells are used, $2^3 = 8$ possible combinations of the state of a cell and its two neighbors can be used to implement all the rules. For the two nearest neighboring cells (right and left), Stephen Wolfram established the order of using 256 rules for the transition of the cell state at the next time step [24]. Each rule sequence number defines a rule number as well as a binary transition code. This means that the cell can go to one of eight states, determined by the binary code of the rule. For example, the rule $184_{10}=10111000_2$. Each digit from right to left is indicated by a three-bit binary code, as shown in Table 1 for rule 184.

Table 1. Transition rule 184 for ECA

Cells			The state of the cell $a_i(t+1)$ at the next time step
$a_{i+1}(t)$	$a_i(t)$	$a_{i-1}(t)$	
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	1

What are the rules set up for?

These rules allow you to analyze the evolution of ECA behavior and determine the possible application of each rule. So rule 110 leads to a complete automaton (according to Turing), and rule 90 can be used to construct a pseudo-random number generator.

The analysis of Wolfram rules for ECA is carried out by constructing the evolution of ECA behavior in time. In this case, the initial states of ECA cells are taken into account. The evolution of ECA behavior is presented in the form of a two-dimensional picture, which is represented by a matrix of size K×T (where K – ECA cell count, T – number of time steps of evolution). An example of evolution for rule 184 by one cell, which has a state of logical "1", is shown in Fig. 1.

0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	1	0

Figure 1. Evolution of ECA behavior for rule 184. There is only one cell in the initial state, which has a state of logical "1"

As can be seen from Figure 1, rule 184 for ECA with one ones cell implements the shift of the unit state to the right. If we use a different initial state of ECA, which contains more single cells, then the evolution of ECA will have a different picture. An example of such evolution on Fig. 2 is shown.

Figure 2 shows two evolutions for different initial conditions. The analysis of evolution showed that rule 184 leads to the complete establishment of all cells in the state of logical "0". Analysis of the dynamics of state change allows us to determine the possibility of choosing rule 184 to solve the specified problem.

Now such rules are used to solve problems in various fields. Research continues at the present time. The results of these studies are published in many publications. Various forms of neighborhoods are used, and hybrid ECAs with inhomogeneous cells are being investigated. The ability to clearly and visually represent evolution makes such ECAs very popular in scientific research.

0	1	0	0	0	1	1	0	1	1	1	0	0	0
0	0	1	0	0	1	0	1	1	1	0	1	0	0
0	0	0	1	0	0	1	1	1	0	1	0	1	0
0	0	0	0	1	0	1	1	0	1	0	1	0	1
0	0	0	0	0	1	1	0	1	0	1	0	1	0
0	0	0	0	0	1	0	1	0	1	0	1	0	1
0	0	0	0	0	0	1	0	1	0	1	0	1	0
0	0	0	0	0	0	0	1	0	1	0	1	0	1

Figure 2. Evolution of ECA behavior for rule 184. There are several cells in the initial ones state

TDCA evolution. TDCA are used to solve a large number of tasks [1], [17]. Specialists pay a lot of attention to solving problems of a behavioral nature [9]. An effective application of TDCAs was found in the problems of information security [7] and image recognition [8]. In TDCA studies, evolution is represented as a set of two-dimensional pictures, which complicates the analysis of the evolution of transitions and the description of two-dimensional changes in states [7], [8], [9].

Neighborhood cells can be any neighboring cells of each cell. In two-dimensional space, adjacent cells form different shapes. In this case, the geometric shapes of the neighborhoods are taken into account. The most commonly used TDCAs based on orthogonal, hexagonal, and triangular coatings. Hexagonal and triangular coverage is difficult to implement in modern computing systems. Therefore, they are rarely used. The most popular today is the orthogonal coverage.

In a TDCA with orthogonal coverage, the most popular are the von Neumann neighborhood (4 nearest neighborhood cells) and Moore (8 nearest neighborhood cells). In a von Neumann neighborhood, neighboring cells are cells that have common sides with the cell under consideration. In Moores neighborhood, four neighboring cells have one side in common (two vertically and two horizontally) and the remaining four cells have common vertices (diagonally).

Logical functions are most often used to implement TDCA transitions. The evolution of the TDCA for the logical function XOR and the von Neumann neighborhood in Fig. 3 is shown.

An example of the evolution of a TDCA with a hexagonal covering and an implemented XOR function (the neighborhood cells have common sides with the cell under consideration) in Fig. 4 is shown. In this example, the hexagonal covering on rectangular cells is organized. All odd lines are shifted on half a cell to the right or left. Thus, it is possible to represent the hexagonal coverage based on orthogonal shapes. Such a coating is presented in detail in the works [10], [20].

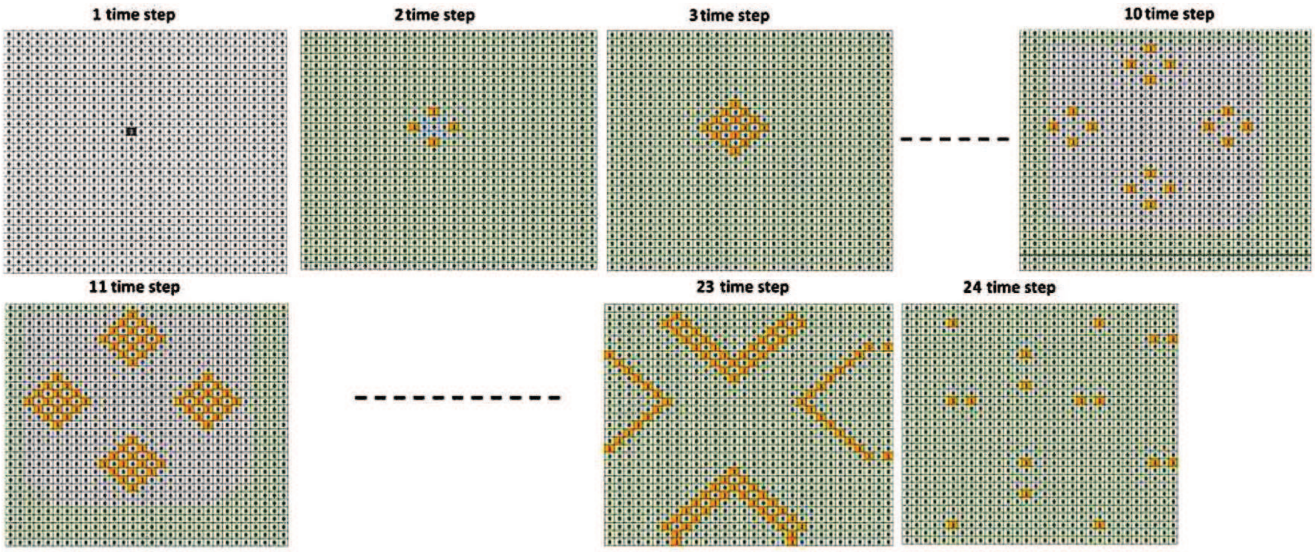

Figure 3. An example of the evolution of a TDCA with an orthogonal coverage. Implemented XOR function based on von Neumann neighborhood

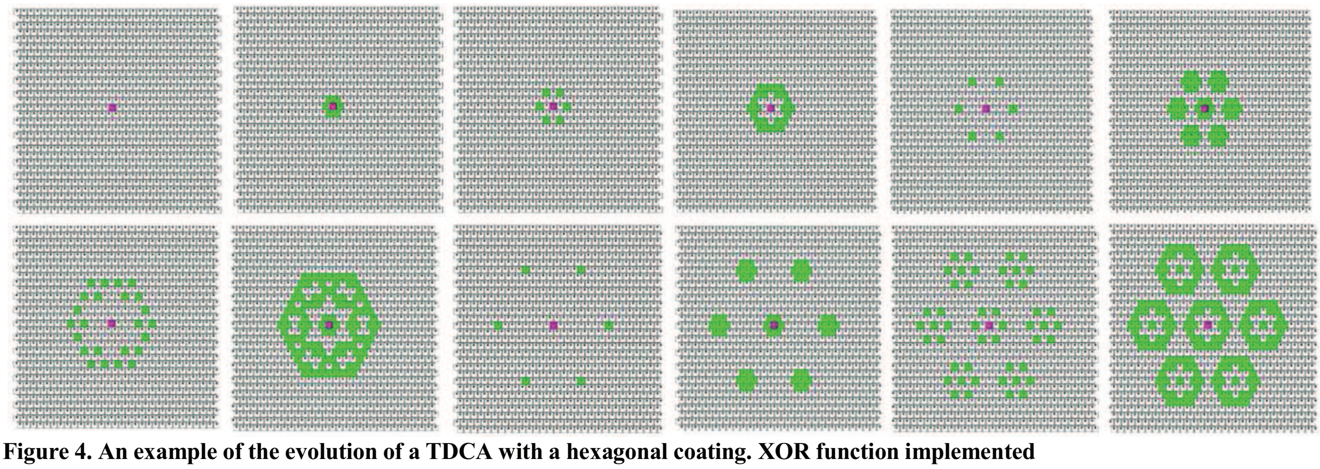

Figure 4. An example of the evolution of a TDCA with a hexagonal coating. XOR function implemented

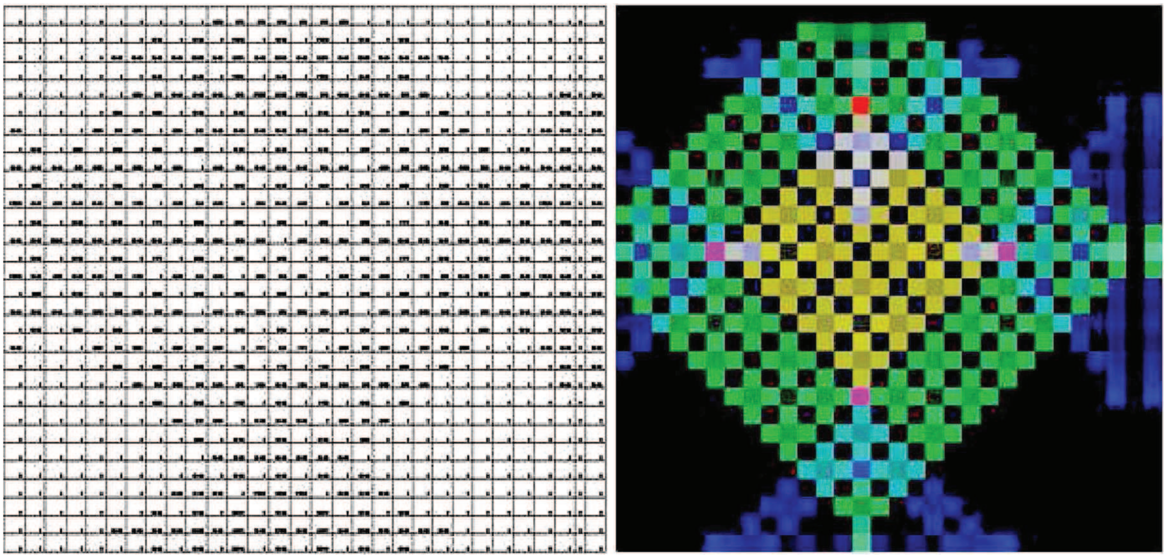

Figure 5. An example of three-dimensional evolution of a TDCA with an orthogonal coverage according to the evolution shown in Fig. 3

For a large number of time steps of evolution, it is very difficult to trace any dependence in the dynamics of the TDCA behavior. Therefore, in this work, a three-dimensional construction of the evolution of behavior is proposed, which is considered as a depth-of-depth process with color display of the results, or in the form of a two-dimensional array of numbers. An example of the evolution of a TDCA according to the proposed forms in Fig. 5 is shown. Three-dimensional evolution is described for the example shown in Fig. 3.

In the presented example (Fig. 5), at each time step, an increase in the code width for each cell of the TDCA is displayed. The size of the cell code reflects the third coordinate of three-dimensional evolution. The first TDCA represents the decimal value of the evolution of each cell, and the last TDCA represents this evolution by colors for each cell. An example of 3D evolution is presented for one logical function. For every other logical function, evolution is represented by a different set and arrangement of numbers.

As for the functions proposed by Wolfram, a set of functions with the same encoding for different forms of neighborhoods can also be implemented for TDCAs. Accordingly, the number of such functions will be greater. Several examples for several functions in Table 2 are presented. Four cells of the von Neumann neighborhood are used without taking into account the own state.

Since $2^4 = 16$ possible combinations can be realized for four cells of the von Neumann neighborhood, the number of Wolfram coding rules is $2^{16} = 65236$. Table 2 uses coding in accordance with Fig. 6.

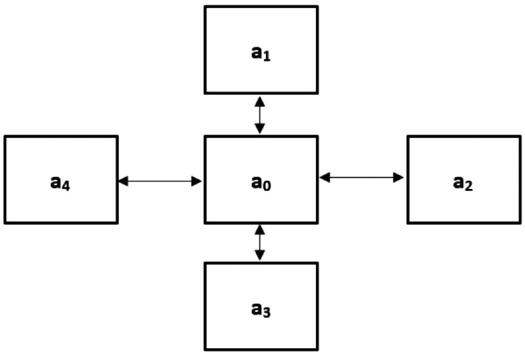

Figure 6. Coding of the cells of the von Neumann neighborhood

Table 2. 1000, 7000 and 55555 encoding rules

Cells				The state of the cell $a_0(t+1)$ at the next time step		
$a_4(t)$	$a_3(t)$	$a_2(t)$	$a_1(t)$	For rule 1000	For rule 7000	For rule 55555
0	0	0	0	0	0	1
0	0	0	1	0	0	1
0	0	1	0	0	0	0
0	0	1	1	1	1	0
0	1	0	0	0	1	0
0	1	0	1	1	0	0
0	1	1	0	1	1	0
0	1	1	1	1	0	0
1	0	0	0	1	1	1
1	0	0	1	1	1	0
1	0	1	0	0	0	0
1	0	1	1	0	1	1
1	1	0	0	0	1	1
1	1	0	1	0	0	0
1	1	1	0	0	0	1
1	1	1	1	0	0	1

The evolution of a TDCA is represented by a three-dimensional structure (Fig. 7), in which the time steps of evolution are displayed along the vertical axis. The states of the TDCA at the previous time step are the initial states for the transition of the TDCA to the next state.

The cells of all TDCAs located on the same vertical in evolution form a binary code, the least significant bit of which is the cell of the first TDCA(t_1) in evolution, and the highest bit is the corresponding cell along the selected vertical of the last TDCA(t_n).

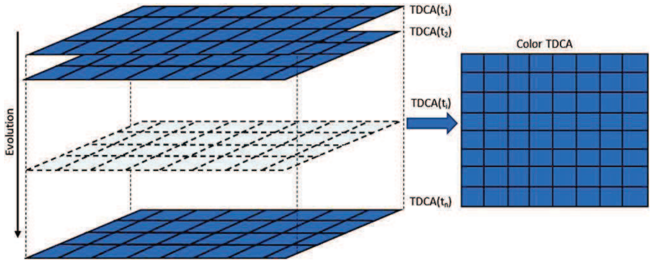

Figure 7. Formation of TDCA evolution

In accordance with the obtained two-dimensional array of codes, a discrete color image is formed. The color of each pixel of such an image is encoded by the obtained evolutionary code of the corresponding TDCA cell with the same coordinates. Examples of TDCA evolutions for the rules presented in Table 2 are shown in Fig. 8.

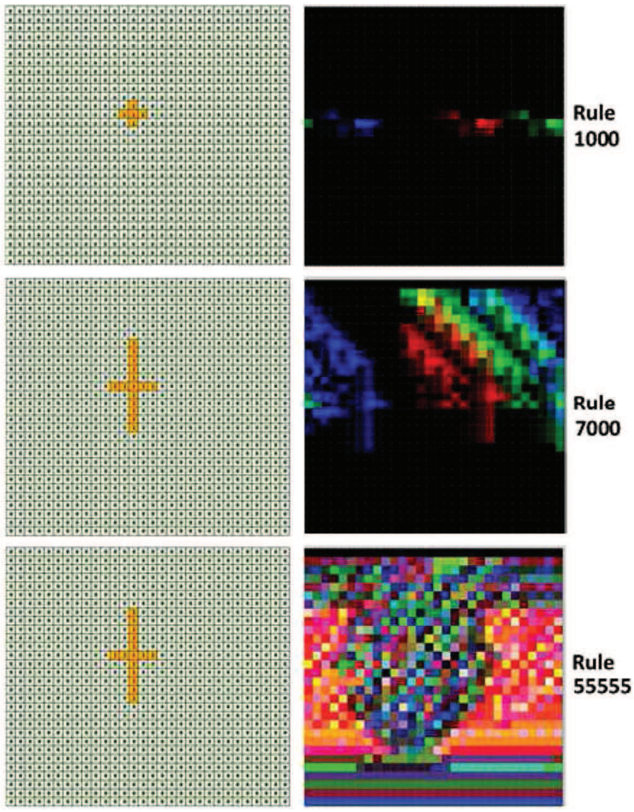

Figure 8. Examples of TDCA evolutions for rules 1000, 7000 and 55555. Only four cells of the von Neumann neighborhood are used

In the examples (Fig. 8), TDCAs with a size of 30×30 cells are used. The number of evolution steps corresponds to 24 time steps. The examples show different color images from which the initial TDCA rule can be determined. It is possible with the help of such rules to carry out various operations. For example, using rule 1 shifts the image up, and using rule 2 shifts the image to the right. Other image processing operations are also implemented. Research in this direction are continued.

Discussion of research results. The studies were carried out for different formats of color coding in pixels (CA cells). RGB coding format is used. A variant of the long-term evolution of the CA was also considered, consisting of the number of steps that exceeds the number of bits encoding the colors of each pixel. The resulting binary code of each pixel of the CA was converted into a decimal number, which was converted into color for the corresponding pixel. In this case, the number of evolutionary steps increased. In modern elementary cellular automata, it is possible to simulate dynamic processes in which each step of evolution is characterized by the states of a small number of cells at the previous step. The limited states and the linear representation of evolution do not allow modeling many complex processes. The number of possible options increases with the use of 2D cellular automata. The consistent use of various rules allows one to describe any two-dimensional process in dynamics. Modern methods for describing the dynamics of transitions in a CA do not give a complete picture of the states at various previous time steps, therefore, it is impossible to describe the dynamics of behavior or predict states at subsequent steps without displaying the complete picture of evolution, as it is displayed in the evolutions of elementary CA. Only the initial state in a two-dimensional CA and the final state are described, which leads to false predictions of various events. The use of this approach to research in CA with active cells has made it possible to obtain significant results in the study of the trajectories of moving objects.

Conclusion

The use of a three-dimensional representation of the evolution of two-dimensional cellular automata made it possible to describe images using the technology proposed by Stephen Wolfram using various rules. To date, an insignificant set of such rules that are of greatest interest have been investigated. In further research, it is planned to continue studying the transition rules in order to find useful properties for image processing.

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ЕВОЛЮЦІЯ ДВОВИМІРНИХ КЛІТИННИХ АВТОМАТІВ. НОВІ ФОРМИ ПОДАННЯ

Розглянуто клітинні автомати та форми відображення їх еволюції. Відомо і широко використовуються форми еволюції елементарних клітинних автоматів, що дало змогу фахівцям моделювати різні динамічні процеси та поведінку систем різного спрямування. В контексті легкої побудови форми еволюції елементарних клітинних автоматів труднощі виникають у представленні форми еволюції двомірних клітинних автоматів як синхронних так і асинхронних. Еволюція двомірних клітинних автоматів подається множиною станів двомірних форм клітинних автоматів, що ускладнює сприйняття та визначення динаміки зміни станів. В статті запропоновано подання еволюції двомірних клітинних автоматів у вигляді масивів двійкових кодів для кожної клітини поля. Кожний часовий такт зміни станів визначається станом логічної "1" або "0". Причому кожний наступний стан визначається збільшенням двійкового розряду на одиницю. Тобто формується двійковий код в сторону старших розрядів. Отриманий двійковий код визначає код кольору, який призначається відповідній клітині на кожному кроці ітерації еволюції. Внаслідок такого кодування формується двомірна матриця кольорів (кольорове зображення), яка за своєю кольоровою структурою (розташування кольорів на двомірному масиві) указує на еволюцію двомірного клітинного автомату. Для представлення еволюції було використано кодування Волфрама, яке збільшує кількість правил для двовимірного клітинного автомата. Правила використовувались для сусідства фон Неймана без урахування власного стану аналізованої клітини. Відповідно до отриманого двовимірного масиву кодів формується дискретне кольорове зображення. Колір кожного пікселя такого зображення кодується отриманим еволюційним кодом відповідної клітини двомірного клітинного автомату з тими ж координатами. Запропонований підхід дає змогу простежувати поведінку клітинного автомату в часі залежно від його початкових станів.

Ключові слова: клітинний автомат; зображення; околиця клітин; еволюція.

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Цитування за ДСТУ: Білан С. М. Еволюція двовимірних клітинних автоматів. Нові форми подання. Український журнал інформаційних технологій. 2021, т. 3, № 1. С. 85–90.

Citation APA: Bilan, S. M. (2021). Evolution of two-dimensional cellular automata. New forms of presentation. *Ukrainian Journal of Information Technology*, *3*(1), 85–90. https://doi.org/10.23939/ujit2021.03.085