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Intelligent Systems

16th International Conference on Intelligent Systems, INTELS 2024
Moscow, Russia, December 2–4, 2024
Proceedings, Part I

Part 1

 Springer

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Preface

The 16th International Conference on Intelligent Systems (INTELS 2024) took place at the Lomonosov Moscow State University, Faculty of Computational Mathematics and Cybernetics, on 2–4 December 2024. The conference has been held for 32 years and is conducted biennially. It was established by a well-known control theory specialist, Konstantin Pupkov, who led several chairs dedicated to control theory at the Bauman Moscow State Technical University, MIREA – Russian Technical University, and Peoples’ Friendship University of Russia. The name of the conference – “Intelligent Systems” – has not changed ever since. The first chairman chose a prospective subject for the conference, as he had a clear understanding that this topic would be dominant for many years.

INTELS 2024 was organized by several institutions: the Federal Research Center “Computer Science and Control” of the Russian Academy of Sciences, the Lomonosov Moscow State University, the Ivannikov Institute for System Programming, the St. Petersburg State Electrotechnical Institute (LETI), and the Bauman Moscow State Technical University.

The majority of conference participants were control specialists who research complex systems of various natures. The goal of the conference was to enable people to share their experience in the investigation and development of intelligent systems, as this term is understood nowadays.

The conference included four plenary presentations. Genaro Martinez presented research on microrobots and their ability to solve complex tasks when combined into a structure, very similarly to how cellular automata behave. Nikolay Kuznetsov demonstrated a phenomenon of hidden oscillations, occurring in systems of higher dimension and sometimes being extremely difficult to spot or model numerically. Sergey Bezrodnikh elaborated on the use of hypergeometric functions and their application to optimization problems. Askhat Diveev proposed a number of crucial problems that require finding a function in the form of an explicit mathematical expression and proposed a method of symbolic regression that may be applicable to these problems.

A significant part of the materials presented at the conference was dedicated to the use of artificial neural networks in various spheres: object control, identification and parametric optimization, text and image analysis, object recognition, etc. Among these works, a new type of network should be emphasized: the development of a binary perceptron-based neural network. Traditionally, works have been presented concerning the development of intelligent systems based on symbolic regression.

Among the spheres of application, significant attention was paid by the participants to medical topics in the context of artificial intelligence and big data analysis, which is an essential part of intelligent systems.

A new but promising direction of research is the problem of trust in decisions made by or with the help of artificial intelligence. It has been noted that, along with the rise

of the impact of AI systems on everyday life, the problems of their security cannot be neglected.

The educational mission of the INTELS Conference must also be mentioned. Throughout its more than 30-year history, it has attracted students, postgraduates, and young scientists whose scientific and professional future is tied to their knowledge in the sphere of control theory, optimization, and artificial intelligence. In 2024, the organizers of the conference conducted a workshop on software and applied solutions for artificial intelligence, where young scientists had a chance to collaborate with their more experienced colleagues.

Since 2016, the proceedings of the INTELS Conference have been published by leading international publishers and are indexed in global scientific databases – Scopus and Web of Science. In 2024, the conference gathered over 250 participants from Belarus, China, Czech Republic, India, Japan, Kazakhstan, Mexico, Russia and Vietnam.

December 2024

Askhat Diveev

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On Cellular Automata and Unconventional Computation

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Abstract. Cellular automata are discrete, rule-based systems that exhibit complex behavior emerging from simple local interactions. This paper explores the foundational principles of cellular automata and their applications in unconventional computing paradigms, including the modeling of natural phenomena, emergent computation, and robotics. We highlight how cellular automata systems provide a versatile framework for solving computational problems beyond traditional architectures, leveraging their inherent parallelism, adaptability, and scalability. Furthermore, we examine their potential in robotics for decentralized control and swarm behavior, emphasizing their role in advancing unconventional computation.

1 Antecedents and Notation

From their inception by Ulam and von Neumann, cellular automata have captured attention as tools for simulating natural phenomena in physics, chemistry, biology, social science, computer science, and mathematics. What has proven particularly powerful is the concept of a cellular automaton functioning as the algorithmic solution to several of these problems [1].

Cellular automata are discrete dynamical systems developed by von Neumann around the 1950s. He was primarily interested in nonlinear phenomena, such as the activity of the human nervous system, self-reproduction, organization in organisms, and complex devices like cellular *constructors* [2]. Over more than half a century, the cellular automata scientific community has developed a vast and extensive body of contributions, some of which can be found in the following books [3–11].

Generally, cellular automata can evolve in any dimension on a regular lattice. Each position in this lattice represents an indivisible *cell*, which must take a value from a finite alphabet. Their dynamics are determined by a *local function* that evaluates each central cell with respect to a number of associated neighbors, collectively forming a *neighbourhood*. The local function, in turn, induces a *global transition*, which represents a *configuration* of the system. Consequently, the evolution of a cellular automaton is a sequence of configurations of the lattice over time, where every local transformation is performed in parallel to produce the next global configuration.

Recurrent interest is often focused on cellular automata with chaotic or complex dynamics, such as Conway’s Game of Life, Langton’s ant and loops, Critters rule, WireWorld, HPP, spiral and beehive rules, R rule, stepper rule, rule 184, rule 110, and others.¹

Cellular automata are a 4-tuple $A = \langle \Sigma, \mu, \varphi, c_0 \rangle$ evolving on a regular d -dimensional lattice, where $d \in \mathbb{Z}^+$ and,

- Σ is the finite alphabet
- μ is the local connection, such that, $\mu = \{x_{0,1,\dots,n-1:d} | x \in \Sigma\}$, and μ is the neighbourhood
- φ is the local function, such that, $\varphi : \Sigma^\mu \rightarrow \Sigma$
- c_0 is the initial condition, such that, $c_0 \in \Sigma^{\mathbb{Z}}$

The local function induces a global transition between configurations such as

$$\Phi_\varphi : \Sigma^{\mathbb{Z}} \rightarrow \Sigma^{\mathbb{Z}}.$$

Global functions contain inherently problems such as self-organization, non-trivial global behaviour, and emergence. We will illustrate some of them in the following sections.

2 Cellular Patterns Construction

Popular aspect of cellular automata is their ability to generate a vast array of patterns rapidly. Some of these patterns have the capacity to solve intriguing problems, including simulations of populations, growth, artificial life, fractals, wave propagation, self-organization, and pattern formation, among others. One of the most fascinating and powerful aspects of cellular automata is their potential for computability.

The design of specific rules can take several approaches: a relation where every argument is specified explicitly (Fig. 1), semi-totalistic functions, totalistic functions, Cartesian products, concatenation, automated methods (e.g., genetic algorithms or convolution algorithms), or random generation. Many functions evolve under a basic condition—a stable state—which is often crucial for the emergence of non-trivial patterns.

¹ Complex Cellular Automata Repository. https://www.comunidad.escom.ipn.mx/genaro/Complex_CA_repository.html.

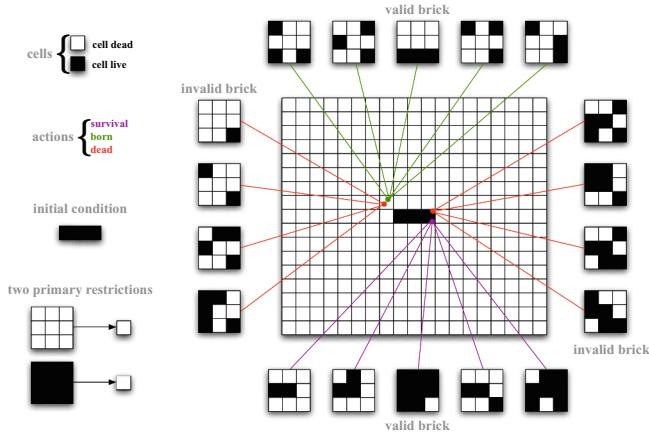


Fig. 1. Scheme where you can design evolution rules in two dimensions with a binary alphabet in an isotropic neighbourhood.

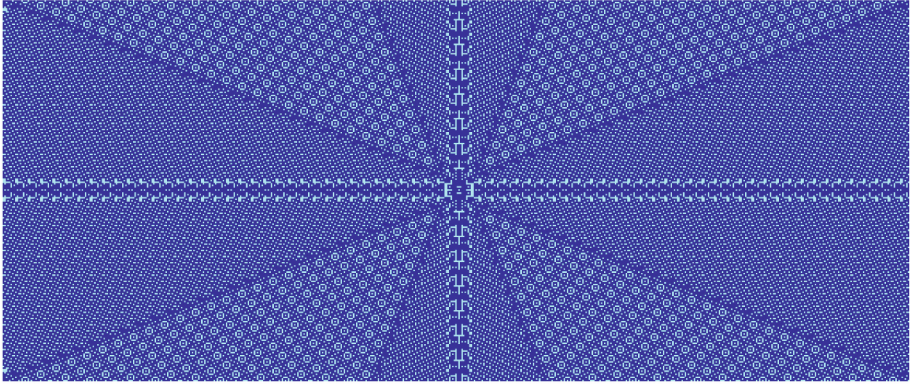
Figure 2 illustrates two examples of semi-totalistic functions in the context of Conway’s Game of Life [12, 13]. Figure 2a shows a high density of live cells, resulting in three periodic static patterns growing together like a Turing pattern, derived from the symmetric evolution rule $B2 - 7/S2 - 7$. Figure 2b simulates population growth, where regions of live cells interact to produce new organisms. The evolution rule $B3/S125 - 8$ specifies three conditions for birth, which occurs only when a cell’s neighbors include two, three, or four live cells. In addition, the survival condition doubles the number of living cells, ensuring a stable population of living cells throughout its evolution.

Several rules exhibit continuous growth, and it is often challenging to halt their expansion once it begins. However, certain functions can be adjusted to control specific processes.

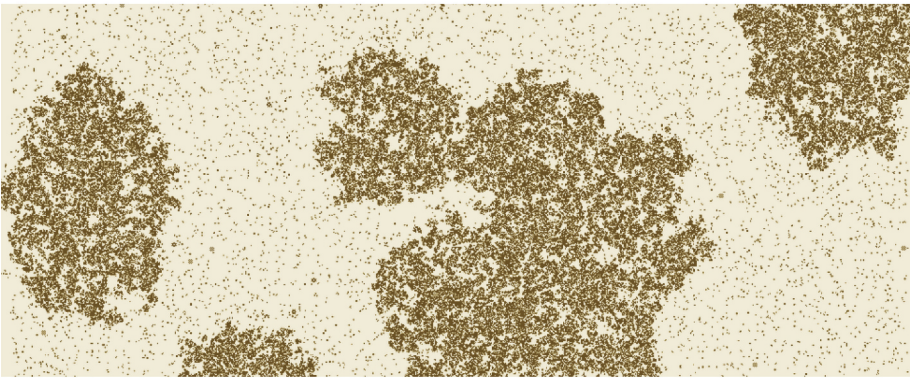
3 Unconventional Computation

A growing interest in the physical implementation of majority gates is being explored in several directions. Three examples illustrate this trend. The first is a spintronic device—the spin-wave majority gate—which offers low space complexity and ultra-low power consumption. Fischer et al. [14] demonstrate a microwave device that can be constructed from majority gates using a trident topology. This device leverages the interference of spin waves, which are synchronized patterns of electron spin.

The second example is the plasmonic majority gate, which operates at the interface between a metal and a dielectric material. Dutta et al. [15] implement plasmonic majority gates in nanoscale cascable photonic media. Here, information is encoded in the amplitude and phase of the electric wave intensity.



(a)



(b)

Fig. 2. Cellular automata pattern formation (a) evolution rule $B2 - 7/S2 - 7$ constructing periodic patterns in 471 times with a population of 345,348 live cells. (b) Evolution rule $B3/S125 - 8$ construct complex pattern in 1,000 times with a population of 3,804,839 live cells, initial density to 4% with 28,816 live cells.

Finally, quantum dot cellular automata circuits utilize majority gates by stimulating a field of energy that manipulates four electrons within a quantum dot to control their distribution, representing binary values [16].

Cellular automata performing computations have been implemented through the interaction of atomic signals (cell by cell). This approach dates back to von Neumann's era and has been applied to numerous other rules. For example, Fig. 3a illustrates a reversible Turing machine updating its values using single signals [17].

Another approach involves reactions between particles—such as gliders or mobile localizations—where complex patterns are utilized. A well-known example is Conway's Game of Life, where the presence or absence of these patterns

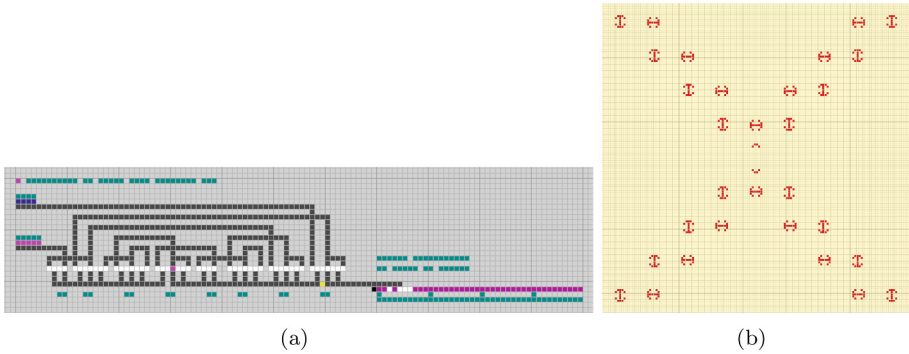


Fig. 3. Computing with (a) single signals (primitive) and (b) compound signals (gliders) in cellular automata spaces.

represents specific values. For instance, Fig. 3b shows the implementation of a FANOUT gate through the collision of gliders [18].

An alternative paradigm in cellular automata spaces involves competing patterns, as proposed in [19]. The simplest way to control patterns propagating in a non-linear medium circuit is by constraining them geometrically. Geometrically constraining the medium is a common technique in designing computational schemes within spatially extended non-linear media. For example, ‘strips’ or ‘channels’ are constructed within the medium (e.g., excitable medium) and connected together.

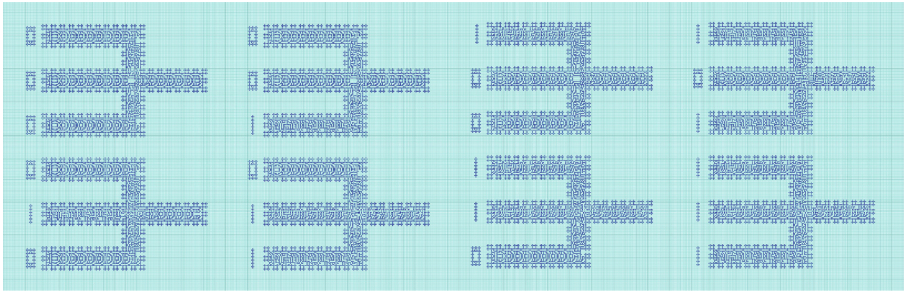


Fig. 4. Three-input majority gates implementation by competing patterns.

Fronts of propagating phases (excitation) or diffusive waves represent signals or values of logical variables. When these fronts interact at junctions, some fronts annihilate while new fronts may emerge. Consequently, the propagation in the output channels represents the results of the computation. A 3-input majority gate is implemented in Fig. 4, every input data is codified across a particle reaction that start the propagation with dozen of alive cells competing

into the channels [20]. This paradigm can be applied in chemical computing, biological computing, optical computing and wave computing [21].



Fig. 5. Robotic binary adder with optical computation, inspired in competing patterns.

Figure 5 shows the implementation of a robotic binary adder using Cubelets robots, where light propagation is inspired by the binary adder based on competing patterns. The input calculated in this snapshot is $(a = 0, b = 0, c = 1)$, yielding a $sum = 0$ and a $carry\ out = 0$.² The presence and absence of light represent true and false values, respectively (binary values), in this construction [22].

At this stage, we can construct a robot capable of solving a variety of problems based on its description. This addresses a problem of computability where the objective is to design a programmable system. This is achieved by building a robot that can simulate any algorithm. In 2020, a robotic Post machine was constructed (using modular Cubelets robots [23]). A Post machine is a tag system, which functions as a substitution system.

A tag system is defined by a finite alphabet Σ and a set of production rules P , where a constant v determines the number of digits to be deleted from the string. The production rule specifies the number of symbols to be added at the end of the string.

Figure 6 illustrates the execution of an algorithm in several steps. The string is represented in a three-line format, where the first line stores 1s, the second line stores 0s, and the third line stores blank symbols B . Three distance sensors

² A video showing all operations is available at: <https://youtu.be/v6O4-liGDk0>.

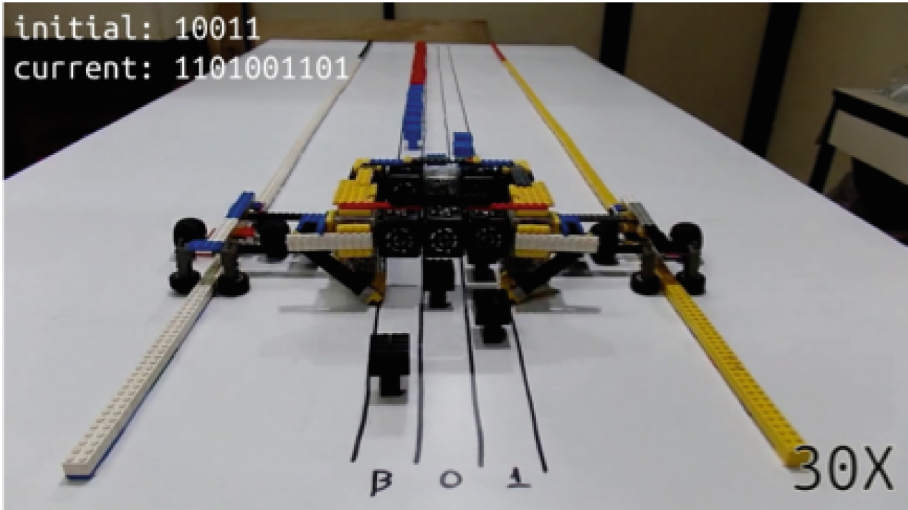


Fig. 6. Robotic Post tag machine. (Artificial Life Robotics Laboratory, ESCOM, IPN, 2020)

read the presence or absence of a cube in each line, and the production rule determines whether a symbol will be added.³

4 Final Remarks

Cellular automata (CA) have proven to be a versatile and powerful computational model with wide-ranging applications in various domains such as physics, biology, social sciences, and computer science. The exploration of unconventional computing paradigms, such as the use of competing patterns or the physical implementations of majority gates, demonstrates the vast potential of CA in simulating complex systems and solving real-world problems.

One notable advancement is the ability of cellular automata to perform computations via the interaction of atomic signals, as demonstrated in the design of reversible Turing machines and other computational constructs. The development of systems such as robotic binary adders, where light propagation inspired by CA patterns enables the computation of binary operations, further highlights the practical applications of this approach. Additionally, the use of modular robots, such as Cubelets, in simulating algorithms and solving problems, showcases the adaptability of CA in robotic systems and programmable machinery.

The ability to control competing patterns geometrically in non-linear media offers a promising avenue for developing computational systems that can solve diverse problems. By constraining media and utilizing the interactions between

³ https://www.comunidad.escom.ipn.mx/ALIROB/RoboticPostMachine/Robotic_Tag_System.html.

propagating fronts, it is possible to simulate logical operations and computational processes. These advancements open up new possibilities for designing more efficient, flexible, and scalable computational systems, both in theory and practice.

In conclusion, the continued exploration of cellular automata in unconventional computing and robotics holds great promise for advancing our understanding of complex systems and developing innovative solutions to pressing challenges. As new methods for controlling and manipulating these systems emerge, we can expect to see even greater advancements in the field, further blurring the lines between computational models and physical implementations.

References

1. Zenil, H., Martínez, G.J.: Cellular automata. *Scholarpedia* **19**(4), 53227 (2024)
2. von Neumann, J.: *Theory of Self-Reproducing Automata* (Edited and completed by A. W. Burks). University of Illinois (1966)
3. Toffoli, T., Margolus, N.: *Cellular Automata Machines: A New Environment for Modeling*. The MIT Press (1987)
4. Langton, C.G. (ed.): *Artificial Life: An Overview*. The MIT Press (1995)
5. Sipper, M.: *Evolution of Parallel Cellular Machines: The Cellular Programming Approach*. Springer (1997)
6. Chopard, B., Droz, M.: *Cellular Automata Modeling of Physical Systems*. Cambridge University Press (1998)
7. Adamatzky, A.: *Computing in Nonlinear Media and Automata Collectives*. CRC Press (2001)
8. Wolfram, S.: *A New Kind of Science*. Wolfram media Champaign, IL (2002)
9. Boccarda, N.: *Modeling Complex Systems*. Springer (2010)
10. Mainzer, K., Chua, L.: *The Universe as Automaton: From Simplicity and Symmetry to Complexity*. Springer Briefs in Complexity (2011)
11. Das, S., Martínez, G.J. (eds.) *Proceedings of Second Asian Symposium on Cellular Automata Technology: ASCAT 2023*. Springer (2023)
12. Adamatzky, A.: *Game of Life Cellular Automata*. Springer (2010)
13. Johnston, N., Greene, D.: *Conway's Game of Life: Mathematics and Construction* (2022)
14. Fischer, T., et al.: Experimental prototype of a spin-wave majority gate. *Appl. Phys. Lett.* **110**(15) (2017)
15. Dutta, S., et al.: Proposal for nanoscale cascaded plasmonic majority gates for non-boolean computation. *Sci. Rep.* **7**(1), 17866 (2017)
16. Snider, G.L., et al.: Quantum-dot cellular automata: line and majority logic gate. *Jpn. J. Appl. Phys.* **38**(12S), 7227 (1999)
17. Morita, K.: *Reversible World of Cellular Automata: Fantastic Phenomena and Computing in Artificial Reversible Universe*. World Scientific (2024)
18. Martínez, G.J., Adamatzky, A., McIntosh, H.: Localization dynamics in a binary two-dimensional cellular automaton: the diffusion rule. *J. Cell. Autom.* **5**(4–5), 289–313 (2010)
19. Martínez, G.J., Adamatzky, A., Morita, K., Margenstern, M.: Computation with competing patterns in life-like automaton. In: *Game of Life Cellular Automata*, pp. 547–572. Springer (2010)

20. Martínez, G.J., Adamatzky, A., Ninagawa, S., Morita, K.: On wave-based majority gates with cellular automata. In: *Handbook of Unconventional Computing: Volume 2: Implementations*, pp. 271–288. World Scientific (2022)
21. Adamatzky, A.: *Advances in Unconventional Computing: Volume 1: Theory*, vol. 22. Springer (2016)
22. Martínez, G.J., et al.: Computing with modular robots. *Int. J. Unconventional Comput.* **17**(1–2), 31–60 (2022)
23. Schweikardt, E.: *Designing modular robots*. Ph.D. thesis, Carnegie Mellon University (2009)