Abhandlung

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In Between the Natural and the Artificial: The Mode of Existence of Self-Reproducing Cellular Automata

Abstract

In the context of the invention and construction of the computer in the 1940's and 1950's, John von Neumann and Stanislaw Ulam designed and built artificial automata, i.e. so-called cellular automata. One key feature of cellular automata was self-reproduction. For this reason, the development of models was greatly inspired by crystallography, electrical engineering and molecular biology of that time. In this article, we reconstruct von Neumann's and Ulam's inventive train of thought of cellular automata and how other individuals such as Arthur Burks or John Holland contributed to the further development of the history of cellular automata. As cellular automata emerge, adapt to other cells, reproduce, mutate and evolve, it is possible to speak of a mode of existence of cellular automata, in the sense of Gilbert Simondon's philosophy of technology. That is to say, technical objects can be described with the help of biological concepts and it is important to follow the inventive thought of the constructor.

Im Rahmen der Erfindung und Konstruktion der ersten Computer in den 1940er und 1950er Jahren haben John von Neumann und Stanislaw Ulam artifizielle Automaten – sogenannte zelluläre Automaten – entworfen. Eine zentrale Eigenschaft von zellulären Automaten ist ihre Fähigkeit sich selbst zu reproduzieren. Um Selbstreproduktion aber gewährleisten zu können, sind zelluläre Automaten von Modellen aus der Kristallographie, Elektrotechnik und der Molekularbiologie beeinflusst gewesen. Demnach werden in diesem Artikel die Erfindung und Konstruktion von zellulären Automaten von John von Neumann, Stanislaw Ulam und weiteren Personen wie Arthur Burks oder John Holland rekonstruiert. Gerade weil zelluläre Automaten entstehen, sich an andere Zellen anpassen, reproduzieren, mutieren und evolvieren, ist es in einem weiteren Schritt möglich von einer Existenzweise von zellulären Automaten im Sinne von Gilbert Simondons Technikphilosophie zu sprechen. Konkret bedeutet das, dass technische Objekte mit Hilfe von biologischen Begriffen und Konzepten beschrieben werden können, wobei es wichtig ist den erfinderischen Gedankengängen der Konstrukteure zu folgen.

1. Introduction

During World War II at Los Alamos, physicists were confronted with a severe theoretical problem with building the atomic bomb. As Peter Galison highlights: "[...] the central problem was to understand the process by which neutrons fission, scatter, and join uranium nuclei deep in the fissile core of a nuclear weapon."[1] Experiments

1 Peter Galison: "Computer Simulations and the Trading Zone," *The Disunity of Science: Boundaries, Contexts, and Power*, ed. P. Galison and D. J. Stump, Stanford: Stanford UP 1996, p. 120.

were not helpful and theory led to unsolvable equations. Here, John von Neumann, Stanislaw Ulam and others came up with a new problem solver called Monte Carlo, which immediately led to a new form of scientific inquiry: computer simulation. By the means of stochastics, Monte Carlo simulation allowed to model "[...] a sequence of random scatterings on a computer."[2] As the quote already reveals, Monte Carlo simulations highly relied on the computational power of the computer, creating – in Galison's eyes – a so-called artificial reality, which existed "[...] in the vacuum-tube computers—the JONIAC, the ENIAC, and, [...] the MANIAC."[3]

The intention of this article however, is not to discuss Monte Carlo simulations but rather another invention which John von Neumann and Stanislaw Ulam were working on more or less at the same time: *cellular automata*. Similar to Monte Carlo, cellular automata emerged in the context of the computer as a technical object and method of computer simulation. Our interpretation thereof is slightly different from Galison's though. By highlighting the newly created epistemology of Monte Carlo in science, its novel ontology of discrete entities and the relationship of theory and experimentation, Galison concentrates on Monte Carlo as a *scientific* enterprise.[4] In this article however, we would like to engage in a reading of cellular automata within the philosophy of technology. More specifically, we rely on the concept of the *mode of existence* of technical objects introduced by Gilbert Simondon.[5] Such a reading of cellular automata is still missing in the literature.[6]

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2 Galison: "Computer Simulations," p. 120.

3 Ibid.

4 For an overview of computer simulation in science from a philosophy of science perspective, see Eric Winsberg: "Computer Simulations in Science," *The Stanford Encyclopedia of Philosophy*, ed. E. N. Zalta, 2019, URL: https://plato.stanford.edu/archives/win2019/entries/simulations-science/ (retrieved 13.01.2020); For a history of computer simulation from a history of science perspective, see Franck Varenne: *From Models to Simulations*, London/New York: Routledge 2019.

5 For a usage of Simondon's concept of mode of existence with regards to digital objects, see Yuk Hui: *On the Existence of Digital Objects*, Minneapolis/London: Minnesota UP 2016.

6 Philosophy of technology interpretations of von Neumann's automata have to be searched for in the context of cybernetics, due to von Neumann's participation at the famous Cybernetics Macy Conferences, see Claus Pias, ed., *Cybernetics. The Macy Conferences 1946–1953. The Complete Transactions*, *Volume 1*, Berlin/Zurich: Diaphanes 2016. Jan Müggenburg highlights how models from different scientific disciplines were used by von Neumann in analogy to design the first computer. However, he is not discussing cellular automata, cf. Jan Müggenburg: *Lebhafte Artefakte. Heinz von Foerster und die Maschinen des Biological Computer Laboratory*, Konstanz: Konstanz UP 2018, p. 120–139. Erich Hörl shows how cybernetics became a so-called new technological condition influencing metaphysical thinking. In this context, Hörl refers to Simondon. The concept of mode of existence and cellular automata are not mentioned, see Erich Hörl: "Die offene Maschine, Heidegger, Günther und Simondon über die technologische Bedingung," *MLN* 123/3 (2008), pp. 632–655. Since computer simulations produce and create data, Juan Manuel Duran speaks of a new technological paradigm in *science*. Duran however does not speak of the mode of existence of these models, see Juan Manuel Duran: *Computer Simulations in Science and Engineering. Concepts, Practices, Perspectives*, Cham: Springer 2018, pp. 147–170. For a classical reading of cybernetics as a scientific enterprise, see Michael Hagner: "Vom Aufstieg und Fall der Kybernetik als Universalwissenschaft," *Die Transformation des Huma-*

In 1958, Simondon published *On the Mode of Existence of Technical Objects*. As the title indicates, he was interested in showing how technical objects have a mode of existence of their own, yet to be determined.[7] In order to establish such a mode of existence, Simondon started by meticulously analyzing objects such as vacuum tubes and power plant turbines. Thereby, he did not only describe these objects by relying on knowledge from mechanical and electrical engineering, he furthermore borrowed concepts and models from biology. The mode of existence of the Guimbal turbine for example is described as being a machine, which operates in and adapts to a natural and technical environment, e.g. the turbine stands in seawater and is connected to a powerplant via pipes and tubes. Furthermore, by looking at several turbines or vacuum tubes as well as their constituent parts and elements, an evolution can be grasped. The triode evolves from the diode to the tetrode by adding electrotechnical elements such as grids or electrodes. Surprisingly, Simondon was not alone with this kind of project. Before him, the anthropologist and archeologist André Leroi-Gourhan analyzed the evolution and mutations of prehistoric technical devices such as spear-throwers or hand axes.[8]

By realizing their projects, both Simondon and Leroi-Gourhan, responded to a request expressed by one of Simondon's teachers, Georges Canguilhem. In 1952, Georges Canguilhem published an article, *Machine and Organism*, in which he proposed to analyze machines by the means of the structure and function of the organism.[9] But why would Canguilhem express such a request? What was the benefit of his proposal? Why understand machines in biological terms?

The answer lies in the biological concepts and models themselves. That is to say, biological concepts such as adaptation, milieu, reproduction, mutation, evolution refer to the genesis and historicity individuals within populations undergo. Consequently, as Simondon and Leroi-Gourhan have shown, machines then become individuals which adapt to a milieu and mutate to contribute to a population of machines in evolution. Moreover, in Canguilhem's eyes, describing the genesis and construction of machines shows that technical objects are not capable of inventing themselves; but they are human creations. Furthermore, these inventions refer to a *man-*

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nen. Beiträge zur Kulturgeschichte der Kybernetik, eds. M. Hagner and E. Hörl, Frankfurt am Main: Suhrkamp 2008, p. 38–71.

7 See Gilbert Simondon: *On the Mode of Existence of Technical Objects*, transl. C. Malaspina and J. Rogove, Minneapolis/London: Minnesota UP 2017. Recently, Bruno Latour has also written on the mode of existence of the technical, see Bruno Latour: *An Inquiry into Modes of Existence: An Anthropology of the Moderns*, trans. C. Porter, Cambridge: Harvard UP 2013, pp. 207–232.

8 See André Leroi-Gourhan: *L'homme et la matière*, Paris: Albin Michel 1971; see also André Leroi-Gourhan: *Milieu et technique*, Paris: Albin Michel 1973. With regards to Simondon's and Leroi-Gourhan's methods borrowed from biology, see Henning Schmidgen: "Machine Cinematography," *INFLeXions* 5 (2012), pp. 130–147.

9 see Georges Canguilhem: "Machine and Organism," *Knowledge of Life*, eds. P. Marrati and T. Meyers, transl. S. Geroulanos and D. Ginsburg, New York: Fordham UP 2008, pp. 75–97.

machine interaction, which cannot be neglected.[10] Simondon highlights this fact by saying: "Man's presence to machines is a perpetuated invention. What resides in the machines is human reality, human gesture fixed and crystallized into working structures."[11] The question of the mode of existence of a technical object, be it a cellular automaton or a vacuum tube, thus goes hand in hand with the question of invention and construction. Speaking of a mode of existence therefore does not mean to attribute full autonomy to technical objects. Rather, it highlights a vivid man-machine interaction.

In this paper, we firstly aim to show what the mode of existence of technical objects specifically means to Simondon (section 2). Secondly, we show how von Neumann and Ulam were involved in a man-machine interaction with regards to cellular automata. More precisely, we show how both used models borrowed from crystallography, molecular biology and many more in order to obtain processes of self-reproduction for artificial automata (sections 3, 4 and 5). Due to the strong connection of cellular automata to molecular biology, we compare in section 6 the self-reproduction of cellular automata to models of self-reproduction in molecular biology in the 1940's and 1950's. Hence, it is our intention to re-create the inventive and constructive train of thought of von Neumann and Ulam. In addition to von Neumann and Ulam, we will look in section 7 at other individuals involved in the further development of cellular automata such as Arthur Burks, John Holland, John Conway, Stephen Wolfram and more. Finally, in section 8, we conclude that the mode of existence of technical objects is bound to a vivid usage of technical objects thereby fulfilling a certain purpose. Due to the connection of cellular automata to the operationality of the computer, they are primarily used as computer models for computer simulations.

2. *Simondon's Mode of Existence of Technical Objects and its Cybernetical Heritage*

Methodologically, Simondon's conception of the mode of existence of technical objects begins with a thorough analysis of technical objects allowing a close look at the mode of operation of objects such as vacuum tubes, combustion engines or turbines. Thereby, three essential points can be borrowed from Simondon's philosophy of technology with regards to the analysis of the mode of existence of cellular automata: 1) technical objects have a *structural* and *operational* aspect, which describes

10 For a cultural and historical overview on man-machine interaction, see Kevin Liggieri and Oliver Müller, eds., *Mensch-Maschine-Interaktion. Handbuch zu Geschichte – Kultur – Ethik*, Stuttgart: Metzler 2019.

11 Simondon: *On the Mode of Existence*, p. 18.

their spatial configuration and dynamic functionality; 2) technical objects can be described with the help of *biological* concepts such as adaptation, milieu and evolution; 3) it is important to follow the inventive thought of the *constructor* to better understand the structural and operational disposition of technical objects.

1) To conceptually frame his analysis, Simondon initially borrows concepts from cybernetics such as structure, operation, system and feedback mechanisms.[12] Simondon's most famous example is his description of the above-mentioned Guimbal turbine, invented by the French engineer Jean-Claude Guimbal in the 1950's. From a structural point of view, i.e. with regards to the spatial configuration, the specificity of the Guimbal turbine is that the generator is contained in the crankcase filled with pressurized oil, whereas the turbine itself is lying in seawater in the penstock.[13] From an operational point of view, i.e. with regards to the functionality of the turbine, it is important to highlight that single structures such as oil for example takes over several functions, e.g. it lubricates the generator, insulates the windings, transfers the generated heat form the winding to the crankcase and prevents the seepage of water.[14] The water in turn conveys energy by activating the generator and transfers heat from the generator.[15] Important to highlight is that structure and operation are not categorically separated from one another but always occur together.[16]
2) In addition to the structural and the operational description of a technical object, a biologically orientated description can be added. Hence, what becomes significant with regards to the Guimbal turbine is not only the adaptation of structural sub-systems one to another, but also the adaptation of the technical object as a whole to a *geographical* and *technical* environment, a so-called associated milieu.[17] That is to say, the Guimbal turbine is introduced into a wider range of technologies such as a power plant, a dam wall and a natural habitat such as seawater. The created techno-geographic milieu in turn only emerges

12 For an influence of cybernetics on Simondon's philosophy, see Xavier Guchet: *Pour un humanisme technologique, culture, technique et société dans la philosophie de Gilbert Simondon*. Paris: Presses Universitaires de France 2010. Simondon himself discusses the importance of cybernetics in several articles, see Gilbert Simondon: "Cybernétique et philosophie," *Sur la philosophie, 1950–1980*, Paris: Presses Universitaires de France 2016, pp. 35–68; Gilbert Simondon: "Épistémologie de la cybernétique," *Sur la philosophie*, *1950–1980*, Paris: Presses Universitaires de France 2016, pp. 177–199. To what extent the concept of operation has played an important role for Simondon and Leroi-Gourhan and how it was used by proponents of cybernetics, see Dieter Mersch: "Operation," *Mensch-Maschine-Interaktion*, eds. K. Liggieri and O. Müller, Stuttgart: Metzler 2019, pp. 287–290.
13 See Simondon: *On the Mode of Existence*, p. 57.
14 Ibid.
15 Ibid.
16 This convergence of several functions and operations into several structures is termed by Simondon a concretization process, see Simondon: *On the Mode of Existence*, p. 57.
17 Ibid., p. 58.

with the invention and physical construction of the turbine and the power plant themselves.

3) But before becoming a concrete object in an associated milieu, the turbine needs to be invented and constructed. It is here, where Jean-Claude Guimbal had the inventive idea of building turbines capable of lying within the penstock and having the generator integrated within their crankcase. Prior to Guimbal's invention, generators could not be placed into the turbine. It is the convergence of the water-tightness, electrical insulation and the intermediary of both oil and water that allows the construction of the Guimbal turbine. By providing the possibility to integrate generators into the turbines themselves without endangering their existence, the Guimbal turbine thus represents, from an evolutionary point of view, a further development in the engineering realm of turbine construction.

When Jean-Claude Guimbal invented the Guimbal turbine, he did not describe his invention with biological and cybernetical concepts. Simondon however, did. By doing so, Simondon followed a methodology already applied by the French tradition of cybernetics represented by Albert Ducrocq or Pierre de Latil. Ducrocq and de Latil used cybernetical concepts to describe a wider range of different types of tools and machines, thereby not only classifying them morphologically and genetically but also describing their evolutionary process.[18] Indeed, cybernetics was from its very beginning connected to methods and concepts of biology, neurology and physiology. Either one tried to explain physiological functions with the help of modes of operations of machines such as Wiener's, Bigelow's and Rosenblueth's famous paper on feedback and teleology or to build machines inspired by physiological processes such as William Grey Walter's tortoise or William Ross Ashby's homeostat.[19]

As we will show in this article, connecting the biological and the technical is no different for von Neumann, Ulam, Burks, Holland and so on. All these individuals implemented biological concepts and models directly into cellular automata. Therefore, it is obvious that when interpreting the experimental results and behavior of their constructions, descriptions follow biological terms similar to Simondon (and Leroi-Gourhan), i.e.: Cellular automata subsequently emerge, adapt to an environ-

18 See Christopher Johnson: "French Cybernetics," *French Studies*, 69/1 (2014), pp. 60–78; doi: 10.1093/fs/knu229.

19 See Julian Bigelow, Arturo Rosenblueth, Norbert Wiener: "Behavior, Purpose, Teleology," *Philosophy of Science*, 10/1 (1943), pp. 18–24. For a thorough description of Ashby's and Walter's robots, see Andrew Pickering: *The Cybernetic Brain. Sketches of Another Future*, Chicago: Chicago UP 2010. Notice, that contrarily to the literature on cybernetics we do not intend to show how cellular automata dissolve the difference between the living and the artificial, an event some cyberneticians had hoped for to happen, see Ronald R. Kline: *The Cybernetics Moment. Or Why We Call our Age the Information Age*, Baltimore: Johns Hopkins UP 2015, pp. 44–55.

ment of other cells, die, self-reproduce and while doing so mutate and furthermore evolve.

Similar to Simondon's procedure of analysis, we will therefore not only reconstruct which different models were used to invent and construct cellular automata, we will also describe how different types of cellular automata evolved, i.e. changed structurally and operationally over time and how their behavior is describable with the help of biological concepts.[20]

3. John von Neumann's Initial Kinematic Automata

When John von Neumann came up with the idea of artificial automata, which ought to be built in analogy to natural systems, i.e. inorganic and organic alike, he thought of it first in theoretical terms. These artificial automata were supposed to reproduce, adapt and evolve.[21] The result would have been a general theory of self-reproducing automata, but as von Neumann died in 1957, the project was only partially completed.[22]

The establishment of a general theory of automata crystallized itself already in the monograph on the EDVAC in 1945 (Electronic Discrete Variable Automatic Computer), which also includes von Neumann's description of the meanwhile famous von-Neumann-architecture, still used in today's computers.[23] It is here, where von Neumann begins to use computing models in order to obtain an abstract description of a

20 Notice, that it is not the intention of this paper to show how the philosophy of technology of Simondon can be compared to the works of von Neumann, Ulam, Burks etc. The intention is to show that Simondon's concept of the mode of existence of the technical can be applied to an analysis of cellular automata, an analysis, Simondon did not apply on cellular automata himself. The common denominator for the latter lies in the tradition of cybernetics, i.e. von Neumann, Ulam, Burks etc. not only participated in but also contributed with research to this tradition. Simondon in turn relies vividly on cybernetical concepts in order to form his philosophy of technology.

21 See George Dyson: *Turing's Cathedral. The Origins of the Digital Universe*, London: Penguin 2013, pp. 286–293.

22 See John von Neumann: *Theory of Self-Reproducing Automata*, ed. A. Burks, Urbana/London: Illinois UP 1966.

23 See John von Neumann: *First Draft of a Report on the EDVAC*, Philadelphia: Moore School of Electrical Engineering 1945. Von Neumann's work on the computer was not solely due to scientific purposes but also related to governmental and military work. The literature has shown this extensively, which, due to lack of space, cannot be subject of inquiry in this paper, see Jérôme Segal: *Le zero et le un. Histoire de la notion scientifique d'information au 20e siècle*, Paris: Éditions Syllepse 2003, pp. 67–128; Steve J. Heims: *John von Neumann and Norbert Wiener. From Mathematics to the Technologies of Life and Death*, Cambridge/London: MIT Press 1980, pp. 179–200 and 230–290; Wolfgang Hagen: "Die Camouflage der Kybernetik," *Kybernetik. The Macy Conferences 1946–1953. Essays und Dokumente*, *Vol. 2*, ed. C. Pias, Zürich/Berlin: Diaphanes 2004, pp. 191–207.

computer.[24] What is meant by computing models are for example Warren McCulloch's and Walter Pitts' model of neural networks published in their renowned paper, *A Logical Calculus of the Ideas Immanent in Nervous Activity*.[25] Three years later in 1948, von Neumann refers to McCulloch's and Pitts' paper again and discusses it in a lecture entitled *The General and Logical Theory of Automata*, presenting for the first time his ideas on automata theory.[26] On an abstract level, von Neumann relates concrete objects such as vacuum tubes, which are necessary hardware components for signal transmission and information storage within computers, and neurons, as they were described by McCulloch and Pitts. But what made von Neumann compare biological neurons in a brain with technological devices such as vacuum tubes?

According to McCulloch and Pitts, logic lends itself as a descriptive device because of the all-or-nothing character of the neuron, meaning that the neuron's activity is either firing or not firing: it is binary.[27] Furthermore, each neuron "[...] has some threshold, which excitation must exceed to initiate an impulse."[28] However, even though at first sight it seems that von Neumann relied on a neurophysiological model, i.e. a neuron's activity within a brain, it has to be highlighted that McCulloch's and Pitts' model was itself influenced by electrical engineering. In this context, McCulloch writes: "It is because communication engineering deals with signals, true or else false, that neurophysiology, is part of engineering, not merely of physics."[29] In his monumental thesis written in 1937 at MIT, Claude Shannon used binary Boolean logic to represent the arrangement of digital circuits in electrical engineering.[30] So, by bringing the binary mode of operation of neurons into his abstract theory of automata, models from electrical engineering were covered in the same breath, because it is the binary functioning of electronic digital circuits that influ-

24 See Arthur W. Burks: "Editor's Introduction," *Theory of Self-Reproducing Automata*, ed. A. Burks, Urbana/London: Illinois UP 1966, pp. 9–10. Arthur Burks is not only one of the designer engineers of the EDVAC's precursor the ENIAC (Electronic Numerical Integrator and Computer), he is also an important figure when it comes to the history of cellular automata as he edited and published von Neumann's unfinished manuscript on cellular automata. Moreover, Burks completed and continued von Neumann's works on cellular automata with his research team, see Arthur W. Burks, ed., *Essays on Cellular Automata*, Chicago: Illinois UP 1970.

25 See Warren S. McCulloch and Walter Pitts: "A Logical Calculus of the Ideas Immanent in Nervous Activity," *Embodiments of Mind*, Cambridge/London: MIT Press 1988, pp. 19–39.

26 See John von Neumann: "The General and Logical Theory of Automata," *Cerebral Mechanisms in Behavior, The Hixon Symposium*, ed. L. A. Jeffress, New York/London: Hafner 1951, pp. 1–41.

27 See Gualtiero Piccinini: "The First Computational Theory of Mind and Brain: A Close Look at McCulloch and Pitts's 'Logical Calculus of Ideas Immanent in Nervous Activity'," *Synthese* 141/2 (2004), pp. 175–215.

28 McCulloch and Pitts: *A Logical Calculus*, p. 19.

29 Warren S. McCulloch: "The Brain as a Computing Machine," *Electrical Engineering IEEE* 6/6 (1949), p. 493.

30 See Claude Shannon: "A Symbolic Analysis of Relay and Switching Circuits," *Transactions of the American Institute of Electrical Engineers IEEE* 57/12 (1938), pp. 713–723.

enced McCulloch and Pitts in the first place. In this sense von Neumann writes: “The neuron, as well as the vacuum tube, [...] are then two instances of the same generic entity, which it is customary to call a *switching organ* or *relay organ*.”[31]

To conclude this section: the theoretical basis of von Neumann’s theory of automata unites models from neurophysiology and electrical engineering. But von Neumann did not only that, he also introduced how self-reproducing automata could be built, since artificial automata are supposed to function similar to natural systems.[32]

4. John von Neumann’s Cellular Automata

In *The General and Logical Theory of Automata*, von Neumann came up with a model of self-reproduction, which is called a *kinematic automaton*.[33] Firstly, an automaton with different primitive elements is given and described *structurally* and *operationally* as follows: 1) an artificial hand for moving elements around; 2) a cutting element, which can disconnect two elements; 3) a fusing element for welding and soldering disconnected elements together; 4) a rigid element such as a girder or a bar giving structural support to several elements; lastly, 5) a sensing element, recognizing different elements and communicating to a computing element. The latter being composed by switches such as *and*, *or*, *not* and *delays*; so again the logical structure of McCulloch’s and Pitts’ neurons are present.[34] The computing element also controls the artificial hand, the cutting element and the fusing element. Secondly, to self-reproduce, the automaton is put in an *environment* (or milieu as von Neumann and also Simondon would say) which contains all the enumerated primitive elements out of which the automaton is composed. These elements float in an infinite number on the surface of an infinite body of liquid, “[...] moving back and forth in random motion, after the manner of the molecules of a gas.”[35] Notice that here a model from thermodynamics, i.e. kinetic theory of gases, is used. Thirdly, for self-reproduction to happen, a constructing machine stores on a tape (similar to a Turing machine) a list of all its elements and floats around in the above-mentioned environment. The constructing machine then interprets

31 von Neumann: *The General and Logical Theory*, p. 12.

32 Notice, that von Neumann also refers to an important model in mathematics: the Turing machine, see Burks: *Editor’s Introduction*, p. 14–15. Furthermore, with regards to the reliability of the hardware, it was also necessary that von Neumann relies on models from thermodynamics for his description of artificial automata, e.g. dissipation of energy by computing elements, as much as Claude Shannon’s information theory with regards to the probability of information transmission, see Burks: *Editor’s Introduction*, p. 22–28. Due to lack of space and because we concentrate on biological models, these models cannot be discussed in this article.

33 See von Neumann: *The General and Logical Theory*, p. 29–31.

34 See Arthur W. Burks: “Von Neumann’s Self-Reproducing Automata,” *Essays on Cellular Automata*, ed. A. W. Burks, Chicago: Illinois UP 1970, pp. 4–5.

35 Burks: *Von Neumann’s Self-Reproducing Automata*, p. 5.

its own description and creates a copy.[36] Hence, in order to describe a self-reproductive automaton, von Neumann relied on models borrowed from neurophysiology (McCulloch and Pitts) and thermodynamics.

As Arthur Burks highlights, for these theoretical outlines to be effective the powers of each element and also the rules of operation of the elements need to be specified.[37] However, finding these precise set of rules is very difficult. Therefore, von Neumann came up with another operating structure called *cellular automaton*. Cellular automata are discrete and have the advantage of being two-dimensional. Moreover, they avoid physical aspects such as the fusing operation of physical parts in the kinematic automaton.[38] On a spatial, i.e. structural dimension, a cellular automaton is a grid of cells with a neighborhood relation defined between adjacent cells (figure 1).[39] Furthermore, every cell has the possibility of having a specific state chosen from a finite set of states. On an operational dimension, a set of rules or of transition functions then defines what state a cell will have in a next time step $t+1$. The transition function thereby considers the state of the cell and its neighbors at time t. While operating or computing, the cellular automaton continuously grows by defining more and more states of the next generation of cells. Von Neumann came up with 29 potential states (figure 2). Notice, that all these states can be translated into a binary sequence using a so-called pulser and a decoder (figure 3). So again, the binary structure of neurons is acknowledged. At last, structural and operational dimensions are – similar to Simondon's conception – not separable from one another but complementary.

While the processing of the 29 states allows different paths of signal transmission from one cell to another, this also allows to *reproduce* automata. Thus, it is here, where biological terms come into play. Similar to the example of the kinematic automaton, a constructing automaton is introduced which builds a second automaton according to a certain plan: "If the constructing automaton contains its own plan, the area [...]"[40] of the newly built automaton is in the same state as the area of the constructing automaton after the construction is completed. The link and signal transmission between the constructing automaton and the replicated automaton is made by a constructing arm, which also operates on a grid of cells (figure 4). The constructing arm is thus nothing else than a communication channel and changes the state of a cellular area via signals.[41] In contrast to the kinematic automaton, the cel-

36 Ibid., p. 6.
37 Ibid.
38 See William Aspray: *John von Neumann and the Origins of Modern Computing*, Cambridge/London: MIT Press 1992, p. 203.
39 See Burks: *Von Neumann's Self-Reproducing Automata*, p. 7.
40 Ibid., p. 42.
41 Ibid., p. 50.

lular automaton does not need to move around to reproduce, but rather operates via signal transmission due to the underlying spatial cellular grid.[42]

While in the context of reproduction, it seems obvious to relate the concept of *cell* within the word cellular automata to the biological model of a cell. Von Neumann however, being trained amongst others as a chemical engineer, had the concept of a *unit cell* in mind, used in crystallography.[43] In this sense, von Neumann also talked about *crystalline regularity*, *crystalline medium*, *granular structure* and *cellular structure*.[44] In crystallography, the description of a crystalline structure or regularity is the ordered arrangement of atoms or molecules.[45] The structures are ordered according to the intrinsic properties of the particles themselves and form symmetric patterns that repeat in space. The unit cell represents the smallest grouping of particles repeating a certain pattern. Since the crystal repeats this unit cell periodically, the single unit cell represents the symmetry and structure of the entire crystal. Lastly, one could say that once a crystal is growing, it is also reproducing its single unit cell periodically over time.

However, despite von Neumann's clear allusions to crystallography, an anecdote of Julian Bigelow concerning another type of model coming from electrical engineering is of great importance. Bigelow was a trained electrical engineer and was involved in the construction of the infamous IAS machine at the Institute for Advanced Study in Princeton. In a paper from 1980 entitled *Computer Development at the Institute for Advanced Study*, Bigelow wrote about his recollection of working on the IAS computer.[46] He started by describing how the machine was constructed from the perspective of electrical engineering, i.e. the electrotechnical components such as vacuum tubes and the design of the digital circuits. With regards to fast arithmetical and gating circuitry Bigelow mentions bistable circuits. A "[...] bistable circuit is a device that has two stable states, changeable at will, to which may be assigned representation of the digit 0 or 1."[47] In electrical engineering, these bistable circuits are also called flip-flops, which when presenting the ability to store information, are also called *binary cells* or more generally a *memory cell*; Bigelow calls flip-flops toggles and hence, also speaks of toggle cells. The computer needed hundreds of such cells and the experimentation with them played a major role in the construction of the IAS machine.[48] Furthermore, the model of *sending cells* and *receiving cells*

42 See John G. Kemeny: "Man Viewed as a Machine," *Scientific American* 196 (1955), pp. 58–67.
43 See Arthur W. Burks: "Introduction," *Essays on Cellular Automata*, ed. A. W. Burks, Chicago: Illinois UP, 1970, p. xxv.
44 See von Neumann: *Theory of Self-Reproducing Automata*, p. 94.
45 See Walter Borchardt-Ott: *Crystallography*, Berlin/Heidelberg: Springer 2012.
46 See Julian Bigelow: "Computer Development at the Institute for Advanced Study," *A History of Computing in the Twentieth Century. A Collection of Essays*, eds. N. Metropolis, J. Howlett, G-C. Rota, London/New York: Academic Press 1980, pp. 291–310.
47 Bigelow: *Computer Development*, p. 295.
48 See Bigelow: *Computer Development*, pp. 295–296.

was introduced in order to securely transmit binary signals. It is at this point where Bigelow gave his account of von Neumann's cellular automata: "We enjoyed some interesting speculative discussions with von Neumann at this time about information propagation and switching among hypothetical arrays of cells, [...] and I believe that some germs of his later cellular automata studies may have originated here."[49]

Hence, from Bigelow's perspective von Neumann's cellular automata have originated through his own experience in the field of electrical engineering and the design and construction of the IAS computer. The model of the cell is thus borrowed from the concept of memory cell in electrical engineering. In the literature on cybernetics, it has been shown how the mode of operation of technical objects such as antiaircraft fire control or servomechanisms had an influence on the theoretical conceptualization of feedback mechanism.[50] This might also hold for von Neumann's experiences with the first computers and the consequent conceptualization of cellular automata.

5. *Stanislaw Ulam's Cellular Automata*

Whereas von Neumann worked rather theoretically with cellular automata, Stanislaw Ulam, von Neumann's colleague and good friend, concentrated more on experiments with the computer.[51] In his essay *On Some Mathematical Problems Connected with Patterns of Growth of Figures*, Ulam analyzed how cellular automata grow from initial conditions via successive generations.[52]

The calculations of the machine showed that during their growth cellular automata produced complex patterns of periodicity and aperiodicity. Ulam also referred to the growth of crystals, highlighting that cellular automata show in some cases a stronger complexity than crystals. For this reason, he positioned them between the inorganic and organic.[53] Compatible with talking of growth, Ulam also used vocabulary from botany such as stems, which represent the four perpendicular axes of figu-

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49 Bigelow: *Computer Development*, p. 297; see Dyson, *Turing's Cathedral*, p. 137.

50 See David A. Mindell: *Between Human and Machine. Feedback, Control and Computing before Cybernetics*, Baltimore/London: Johns Hopkins UP 2002; see Stuart Bennett: *A History of Control Engineering 1800–1930*, New York/Stevenage: Peregrinus 1979.

51 See M. Mitchell Waldrop: *Complexity. The Emerging Science at the Edge of Order and Chaos*, New York: Simon&Schuster 1992, p. 219. It has to be highlighted that it was Ulam, who suggested to von Neumann a crystal-like arrangement for cellular automata, see Stanislaw M. Ulam: *Adventures of a Mathematician* (1976), Berkeley/Los Angeles: California UP 1991, p. 241.

52 See Stanislaw M. Ulam: "On Some Mathematical Problems Connected with Patterns of Growth of Figures," *Essays on Cellular Automata*, ed. A. W. Burks, Chicago: Illinois UP 1970, pp. 219–231; Stanislaw M. Ulam: "On Recursively Defined Geometrical Objects and Patterns of Growth," *Essays on Cellular Automata*, ed. A. W. Burks, Chicago: Illinois UP 1970, pp. 232–243; Burks, *Introduction*, p. xxi.

53 See Ulam: *On Some Mathematical Problems*, p. 219–220.

re 5 and from which then so-called “[...] side branches of variable lengths will grow.”[54] Ulam experimented with cellular automata in the sense that he let the automaton compute and then interpreted the results. In order to give such interpretation, he combined the botanic vocabulary with that from genealogical research of lineages, as it has been done in biological systematics and taxonomy, i.e.: cells in a consequent generation except at $t = 0$ are named *child*, cells from the same generation are called *siblings* and cells from older generations *parent* or *grandparent*, not to mention the concept of *generation* itself.[55] As the transition function contains the rules of behavior and in most cases the last morphology of the last generation influences the growth of the next generation, the last influencing generation of cells is called *alive*. At the same time, Ulam simplified von Neumann’s cellular automata. The number of states was reduced and also the transition functions were simplified.[56] The transition function for figure 5 for example is the following: “[...] given a number of squares in the *n*th generation, the squares of the (*n*+1)th generation will be all those which are adjacent to the *n*th generation square but with the following proviso: the squares which are adjacent to more than one square of the *n*th generation will *not* be taken.”[57]

Similar to von Neumann’s cellular automata, Ulam’s constructions are bound to an interplay of structural and operational dimensions. The set of rules or transition functions generate new generations of cells, but concomitantly, depend on the structural composition of the preceding generation. Furthermore, the milieu of the cells remains the neighborhood in which the cells ‘live’. However, with the works of Ulam, it furthermore becomes obvious that the physical milieu of the whole cellular automaton – the totality of the single cells – grounds on the hardware of the computer. Consequently, two types of milieus can be distinguished: on the one hand, the milieu and neighborhood *between* single cells of the cellular automaton and on the other hand, the computer as the physical milieu of the *entire* cellular automaton. Similar to the Guimbal turbine, whose milieu is techno-geographical, the technical milieu of cellular automata becomes the hardware of the computer. The fact that cellular automata have a proper ›natural‹ or ›geographical‹ milieu has to be doubted, since they only operate within the limits of the hardware of the computer. Even though it is possible to draw cellular automata with a pencil or to build them three-dimensionally with toy blocks, the computer becomes indispensable if a certain lifelike effect and autonomy of behavior of cellular automata is desired. Then, the computer as

54 Ulam: *On Some Mathematical Problems*, p. 221.
55 See Georg Toepfer: *Das Historische Wörterbuch der Biologie, Geschichte und Theorie der biologischen Grundbegriffe,* Bd. 3, Stuttgart/Weimar: Metzler 2011, pp. 443–493.
56 For an overview of von Neumann’s mathematically rather complicated transition functions, see Burks: *Von Neumann’s Self-Reproducing Automata*.
57 Ulam: *On Some Mathematical Problems*, p. 220 (emphasis in original).

milieu becomes analogous to the milieu of natural organisms.[58] Hence, the computer becomes the necessary device by which experiments with different sets of rules can be executed and the created patterns interpreted. The computer is the technical medium that allows for cellular automata to gain a certain autonomy, as computations independently evolve and constantly create new patterns of behavior. We will come back to this topic in section 7.

Lastly, in his essay *On Recursively Defined Geometrical Objects and Patterns of Growth*, written together with Robert G. Schrandt, Ulam described self-reproducing automata.[59] While the cells were growing due to a specific transition function Ulam and Schrandt used an elimination rule or *death rule*, i.e. each cell which is older than a defined number *dies* and disappears. As figure 6 shows, this leads to a periodic emergence of the same pattern, which Ulam and Schrandt call self-replicating and self-reproducing. Identical to von Neumann's self-reproduction process, a pattern is repeated, contrarily to von Neumann however, the constructing arm is missing.

Up until now, self-reproduction was solely described within the behavior of cellular automata themselves. But which process of self-reproduction is precisely adopted by von Neumann and Ulam when it comes to the comparison with self-reproduction in biology? If this question is to be answered, we need to take a look at biological models and theories as they were present in the 1940's and 1950's.

6. Self-Reproducing Automata and Molecular Biology

When it comes to von Neumann, it is known that with the engagement in the construction of the IAS computer, he also looked for interdisciplinary collaborations with the biomedical community. Since 1946, von Neumann was in contact with several scientists such as the biochemist Sol Spiegelman, the chemist and engineer Irving Langmuir and many more.[60] It was with Langmuir that von Neumann discussed the chemical and crystallographic study of proteins. Von Neumann was also in contact with Max Delbrück, a leading figure in biochemical research at the time. Through Delbrück von Neumann got interested in the replication of bacteriophages, a virus having a very simple reproduction process.[61] Bacteriophages seemed to have the same biochemical properties of protein molecules and this meant that processes

58 See Georg Toepfer: *Das Historische Wörterbuch der Biologie. Geschichte und Theorie der biologischen Grundbegriffe,* Vol. 2, Stuttgart/Weimar: Metzler 2011, p. 403.
59 See Ulam: *On Recursively Defined Geometrical Objects*, pp. 237–243.
60 See Aspray: *John von Neumann*, pp. 182–183.
61 See Lily E. Kay: *Who wrote the Book of Life. A History of the Genetic Code*, Stanford: Stanford UP 2000, pp. 107–108.

of autocatalysis were active.[62] In other words: For Delbrück viruses were living molecules.[63] In 1944, Erwin Schrödinger published his infamous book *What is Life?* in which he sums up all the biomolecular knowledge and research of his time including Delbrück's findings.[64] Schrödinger's two most famous concepts directly refer to modes of operation von Neumann integrated into cellular automata: genes contain a code-script, which is transmitted during reproduction and therefore life grows just like an aperiodic crystal.[65]

However, as Kay emphasizes, Schrödinger himself was mainly interested in bringing together thermodynamics and the emergence of order as much in organic as in inorganic systems.[66] The interpretation of Schrödinger's code-script as information transmission would only later become paramount with the upcoming of cybernetics and the theories of Wiener, Shannon and last but not least von Neumann. So, by using the crystal lattice and periodicity as a basic model for their self-reproducing cellular automata von Neumann and Ulam position cellular automata not only between organic and inorganic systems, they also helped to shape the biomolecular discourse of the 1950's.[67]

And indeed, the reproduction of the kinematic and the cellular automaton is quite simple, i.e. the automaton simply replicates itself based on an inscribed code. Hence, during self-reproduction the important aspect is that the automaton contains all the necessary information in order to reproduce itself. Therefore, in this context, von Neumann contributes to the description of reproduction in molecular biology as it will be described in the next couple of years, starting with the discovery of the double helix structure of DNA by Watson and Crick. All the cellular machinery such as mRNA, tRNA, ribosomes, polymerases, and so on, involved in the replication of DNA, are encoded in that very DNA.[68]

In 1953, von Neumann stopped working on the manuscript of a *Theory of Self-Reproducing Automata* probably due to his extensive governmental work, leaving the theory of automata unfinished.[69] Especially on the biological level, further con-

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62 See Lily E. Kay: "Conceptual Models and Analytical Tools: The Biology of Physicist Max Delbrück," *Journal of the History of Biology* 18/2 (1985), p. 226.

63 See Kay: *Conceptual Models*, p. 239.

64 See Erwin Schrödinger: *What is Life? The Physical Aspect of the Living Cell*, New York: Cambridge UP 2007; see also Kay, *Who wrote*, pp. 59–66.

65 See Kay: *Who wrote*, p. 61. Already in the 1930's comparisons between organismic growth and crystallization processes were discussed, reaching even back to the 19th century, see Kay: *Who wrote*, p. 48. Since the 1950's several theories tried to describe the emergence of life from crystallization processes, see for example Stuart A. Kauffman: *The Origins of Order*. *Self-Organization and Selection in Evolution*. New York/Oxford: Oxford UP 1993.

66 See Kay: *Who wrote*, p. 64.

67 See Kay: *Who wrote*, pp. 102–115.

68 See Melanie Mitchell: *Complexity. A guided Tour*, New York: Oxford UP 2009, p. 93; see also Kay: *Who wrote*, pp. 113–115.

69 See Heims: *John von Neumann*, p. 212.

cepts such as adaptation, mutation and evolution would have to be elaborated. Von Neumann was aware of this but only hinted at these concepts and their further elaboration.[70]

7. *The Further Development of Cellular Automata*

After von Neumann and Ulam finished working on cellular automata the history and further development of the latter did not come to an end. Burks as well as his students such as John H. Holland subsequently took over. The pluralism of models however, was not widened but rather narrowed down to the usage of biological concepts and models.

Holland, for example, concentrated especially on the concept of *adaptation* and *mutation*, describing his own method as *genetic algorithms*.[71] In addition to von Neumann's cellular automata, which start from the self-reproduction of one single automaton, the method of genetic algorithms starts with a population of single individuals or strings of bits, numbers or symbols, which obtain a fitness value.[72] The fitness value measures how well a program is able to fulfill a given task. If one selects a number of individual programs with the highest fitness, one obtains parents in the next generation. These in turn are recombined and produce a next generation and so forth. Mutations arise randomly by probabilistic calculations and finally result in a continuously evolving computer program, just like populations of living beings. To Holland, reproduction thus no longer occurs for a single cellular automaton but for an entire population of individual cellular automata. This in turn is better understandable if one considers that Holland's genetic algorithms are conceptually based on the works of the geneticist Ronald A. Fisher and his landmark book *The Genetical Theory of Natural Selection*.[73] Fisher is known to be part of the modern synthesis of the 1930's and 1940's, a theory of evolution that tried to combine Mendelian discrete genetics with Darwin's continuous theory of natural selection.[74] Evolution is a gradual process, based on natural selection and small variations in individuals, whereas variation between individuals arises from random genetic mutations and recombinations.[75] Macroscale phenomena can be explained by microscopic processes of gene variation and natural selection.[76] Holland implemented these biologi-

70 See von Neumann: *Theory of Self-Reproducing Automata*, pp. 126–131.
71 See John Holland: *Adaptation in Natural and Artificial Systems. An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*, Cambridge/London: MIT Press 1975.
72 See Mitchell: *Complexity*, pp. 127–142.
73 See Holland: *Adaptation*, p. 89.
74 See Mitchell: *Complexity*, pp. 81–87.
75 Ibid., p. 83.
76 Ibid., p. 83.

cal conceptions directly into computer programs relying not only on cellular automata but also on revisions of Fisher's core concepts such as selection acting solely on one gene and believing that the goal of evolution is equilibrium; for Holland multiple genes are interacting and the goal of evolution is rather the open-ended adaptation to new challenging situations.[77]

In the 1970's and 1980's, John Conway's game of life and Christopher Langton's artificial life further developed cellular automata.[78] However, neither of them introduced a new model. Rather fruitful experimentations on the structural and operational levels were conducted with transition functions and the spatial dimensionality of the cells. In Conway's game of life, for example, the transition function is kept simple, similar to Ulam's transition function, and reveals nevertheless complex behavior after several computations (figure 7). It also happens that the complete automaton dies out. Reproduction happens here, similar to Ulam's cellular automata, on the level of the emerging patterns, when cells are *alive* or *dead*.[79] Another important figure in the further development of cellular automata is Stephen Wolfram, who also experimented with cellular automata since the 1980's and introduced four classes of behavior, i.e. created patterns: stable, chaotic, complex, periodic (figure 8).[80] In his main work, Stephen Wolfram computed and gathered a grand variety of differently formed patterns widening therewith the behavioral analysis of how cellular automata evolve under the circumstance of different set of rules – thus again, the structural and operational dimensions of different behavior of cellular automata is explored and discovered.

8. Conclusion

Technical objects are not passive entities waiting to be discovered. They actively operate and work within an environment. Therefore, one ought to say that technical

77 See Waldrop: *Complexity*, pp. 163–167.

78 Conway's game of life was popularized by Martin Gardner, see Martin Gardner: "The Fantastic Combinations of John Conway's New Solitaire Game 'Life'," *Scientific American* 223 (1970), pp. 120–123. For a historical overview and the further development of the game of life, see Andrew Adamatzky, ed., *Game of Life Cellular Automata*, London: Springer 2010. With regards to artificial life, see Christopher G. Langton, ed., *Artificial Life. An Overview*. Cambridge/London: MIT Press 1995. For a social and cultural embedment of cellular automata into the history of computer games, see Claus Pias: *Computer Spiel Welten*, München: Sequenzia 2002, pp. 253–260.

79 See Toepfer: *Das Historische Wörterbuch der Biologie*, p. 402.

80 See Stephen Wolfram: *A New Kind of Science*, Champaign: Wolfram Media 2002, pp. 231–250. Wolfram is essentially developing cellular automata further on a mathematical level, see also Tommaso Toffoli and Norman Margolus: *Cellular Automata Machines. A New Environment for Modeling*, Cambridge/London: MIT Press 1991; see Andrew Ilachinski: *Cellular Automata. A Discrete Universe*, Singapore: World Scientific 2001.

objects are invented in order to fulfill a certain purpose. The Guimbal turbine, for example, is constructed to produce electricity. With the milieu of cellular automata being primarily the computer, they become computer models, which in turn, are used to solve computational problems. In other words: based on the above-mentioned experimentations, a wide range of applications of cellular automata was developed, which participated in a new form of scientific inquiry: computer simulations. The application of cellular automata to solve partial differential equations for vibrating membranes, heat flow of diffusion processes or the simulation of heart tissue has already been highlighted by Burks.[81] Today, applications range from simulations of bacterial growth, seashell patterns and snow crystals to steady-state heat flow.[82] Genetic algorithms in turn have been used in a wide range for automating parts of aircraft design, analyzing satellite images, computer chip design, discovering new pharmaceutical drugs, computer animations in movies such as *Lord of the Rings*, detecting fraudulent trades in finance and so on.[83]

Aside from these applications, the history and development of the mode of existence of cellular automata however, also highlights something else. When Ulam, Conway or Wolfram were experimenting with cellular automata and investigating the patterns thus produced and how cells behave under certain rules and so on, they were not necessarily thinking about the potential *usage* of cellular automata. Rather, they broadened the description of the mode of existence of cellular automata. And this is precisely one of Simondon's main ideas: technical objects cannot be reduced to their mere usage, they also need to be described in their mode of existence, if one wants to grasp the reality of the technical.[84] The mode of existence of a technical object is represented by a middle course between an evolutionary development bound to invention and construction and the usage of that same object working in an environment.

In line with Simondon's concept of mode of existence, our article describes both the invention and construction of cellular automata by means of specific models, and their biological behavior once operating within a certain environment in order to fulfill a certain purpose. The description of the further development in the history of cellular automata not only underlines a vivid man-machine interaction, but also shows how cellular automata themselves evolved from von Neumann's theoretical and Ulam's experimental approach to Holland's genetic algorithms, Conway's game of life, Langton's artificial life and Wolfram's four classes. All these individuals, and

81 See Burks: *Von Neumann's Self-Reproducing Automata*, p. 53.
82 See Joel L. Schiff: *Cellular Automata. A Discrete View of the World*, Hoboken: Wiley & Sons 2008, pp. 123–224.
83 See Mitchell: *Complexity*, p. 130. For applications of genetic algorithms in science, see Melanie Mitchell: *An Introduction to Genetic Algorithms*, Cambridge/London: MIT Press 1996, pp. 85–115.
84 See Simondon: *On the Mode of Existence*, pp. 25–29.

there would certainly be more to mention, contributed to the mode of existence of cellular automata.

Figures

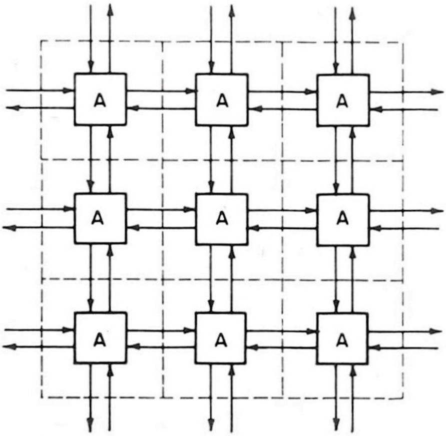

Figure 1

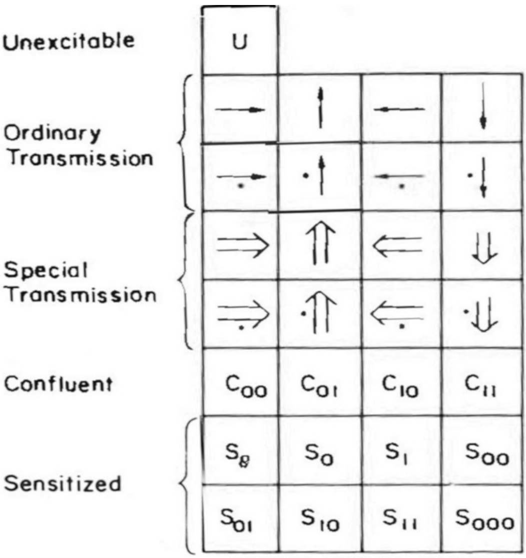

Figure 2

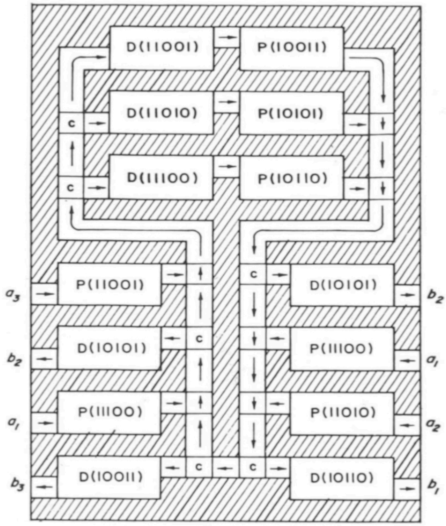

Figure 3

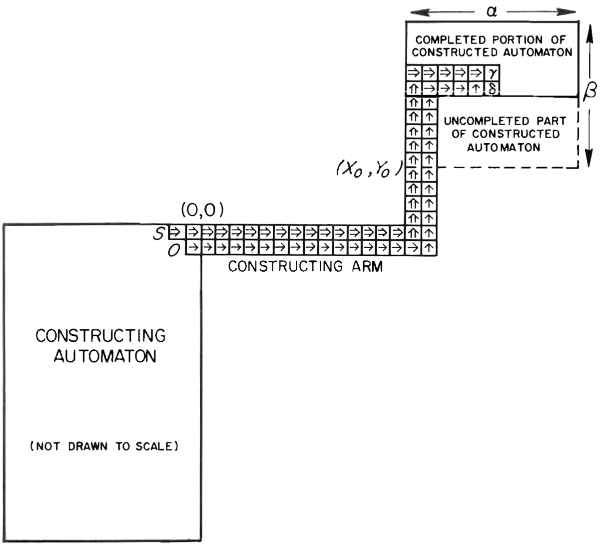

Figure 4

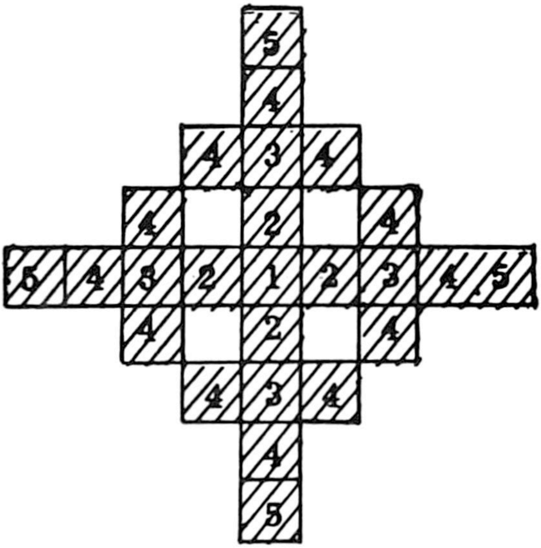

Figure 5

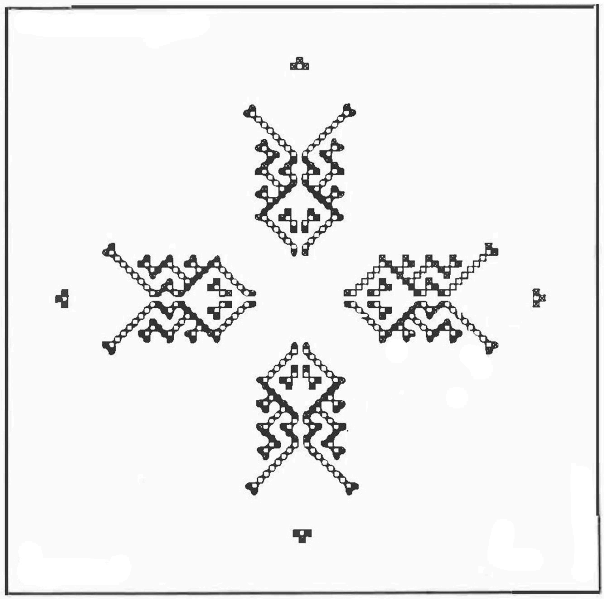

Figure 6

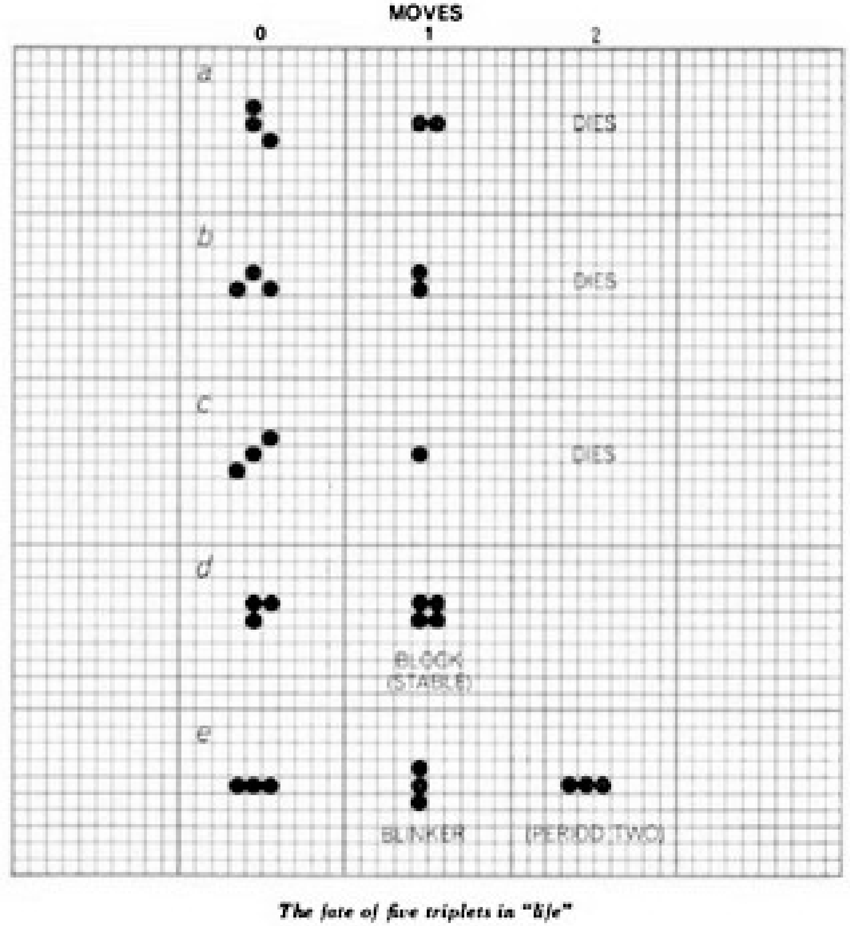

Figure 7

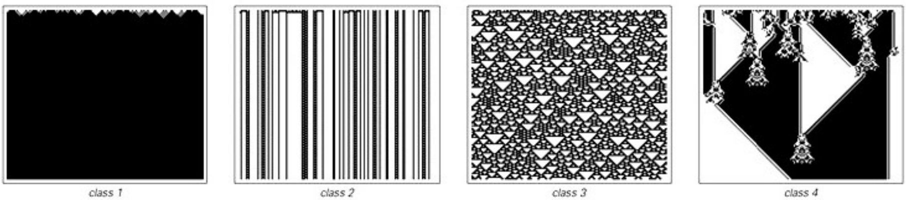

Figure 8