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Cellular Automata and Astronomy: Usage and Viability

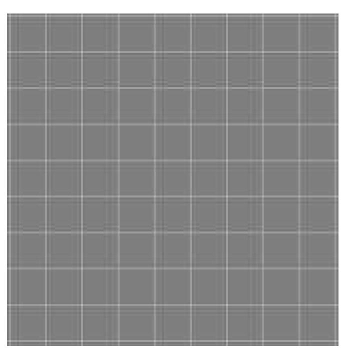
Cellular Automata

Since their invention in the 1940s by mathematician John von Neumann, cellular automata have lended themselves to a variety of uses (“Cellular Automata”, 2021). Whether it be biology, ecology, seismology, neurology, or astronomy, the applications of these delightful structures have likely surpassed their creator’s initial intent.

Generally, cellular automata can be defined as: “model[s] of a spatially distributed process that consists of an array (usually two-dimensional) of cells that “evolve” step-by-step according to the state of neighbouring cells and certain rules that depend on the simulation” (“cellular automata”, 2021). They are thought of as being:

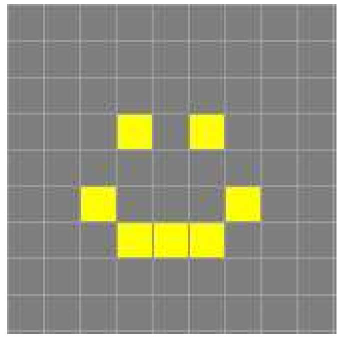
> composed of a finite or denumerable set of homogenous, simple units, the *atoms* or *cells*. At each time unit, the cells instantiate one of a finite set of states. They evolve in parallel at discrete time steps, following state update functions or dynamical transition rules: the update of a cell state obtains by taking into account the states of cells in its local neighborhood (Berto and Tagliabue, 2017).

To explain this all a bit more plainly, cellular automata are composed of simple, discrete squares composing a grid, each of these squares being known as the *cells*. Each one of these cells possesses a predetermined state; this could be just about anything, but for simplicity’s sake, we will use a simple binary of states: *on* or *off*, *alive* or *dead*. The conductor of this simulation would likely have all cells automatically set to a default state, *off* or *dead* in this example.



9x9 grid in the default off *state*

Before beginning the simulation, they would then set each of their desired cells to the opposing *on* or *alive*.



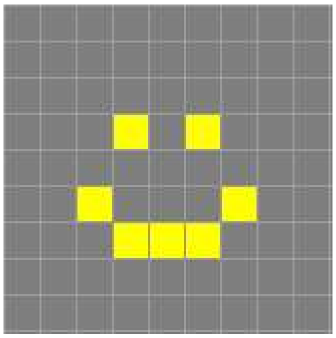
9x9 grid with 7 cells set to the on *state*

As time progresses through the simulation of this grid, each of these cells may interact with each other according to a predetermined system of rules. The key here is that the cells may only interact with *local* cells -- that is, the cells which directly border one another via edge or corner. A cell in the far left corner of the grid cannot have a direct interaction with a cell in the bottom right corner of the grid, unless of course it is only a 2x2 grid.

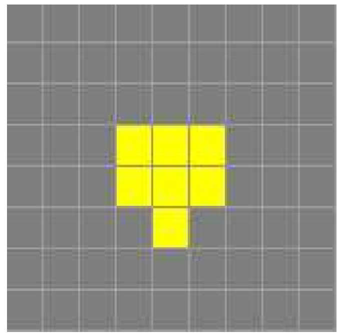
We will use the famous mathematician John Conway's legendary "Game of Life" to demonstrate the actual cellular interaction. Conway's "Game of Life" is a specific cellular automaton is a system of fairly simple rules through which the starting configuration must "fad[e] away completely (from overcrowding or becoming too sparse), settl[e] into a stable configuration that remains unchanged thereafter, or enter an oscillating phase in which they repeat an endless cycle of two or more periods," with two strong caveats: 1. "There should be no initial pattern for which there is a simple proof that the population can grow," and 2. "There should be initial patterns that apparently do grow without limit" (Gardner, 1970). The rules for the automaton proceed as follows:

1. Survivals. Every [*on* cell] with two or three neighboring [*on* cells] survives for the next generation.
2. Deaths. Each [*on* cell] with four or more neighbors dies (is removed) from overpopulation. Every [*on* cell] with one neighbor or none dies from isolation.
3. Births. Each empty cell adjacent to exactly three neighbors--no more, no fewer--is a birth cell. An [*on* cell] is placed [here] at the next move. (Gardner, 1970)

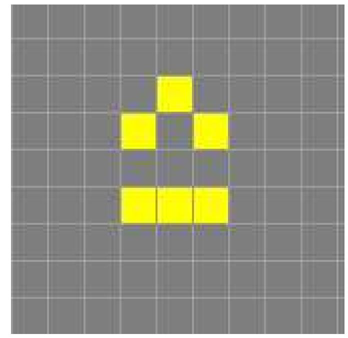
By applying these rules to our smiling 9x9 grid, we would obtain a progression such as this (each image representing a discrete and sequential time stage):



Stage 0



Stage 1



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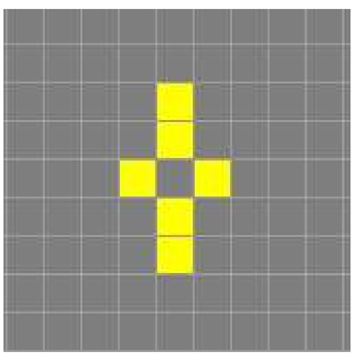

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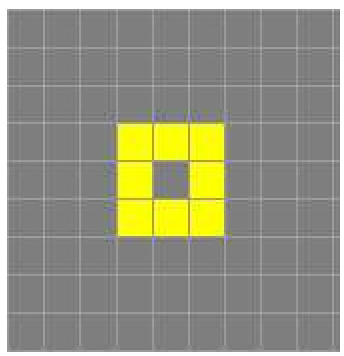

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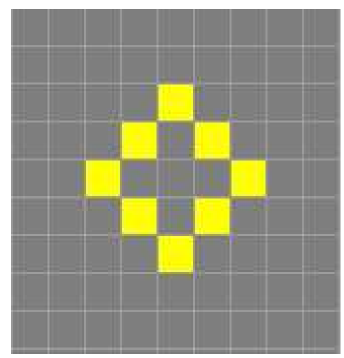
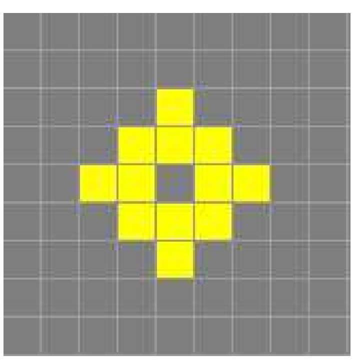
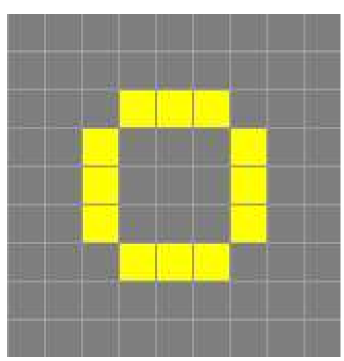


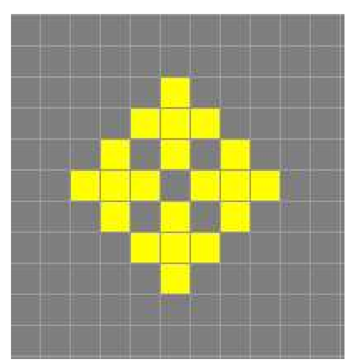
Stage 5



Stage 6



Stage 7



Stage 8

Beyond Stage 8, the pattern falls into a stable repeating sequence of two patterns, one of the required end conditions for the automaton. As should now be clear, cellular automata take often-seemingly simple initial configurations of cells in a grid, apply a set of rules to these cells over a period of time, and, lo and behold, complex patterns and behavior should start to emerge from the interactions of these cells.

Applications in Astronomy

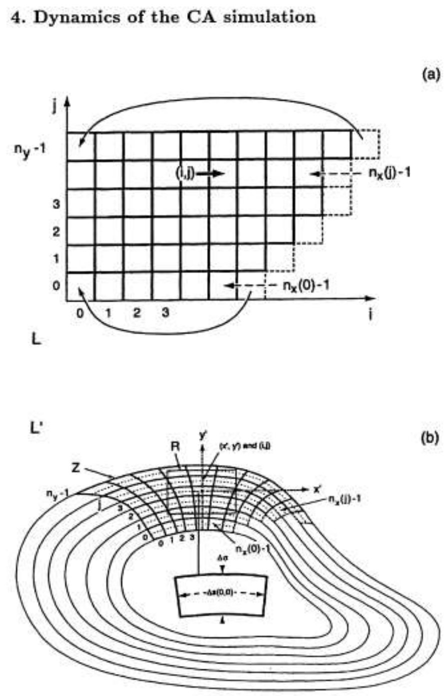
As previously mentioned, the list of fields with potential applicability of cellular automata is expansive, and astronomy is certainly no exception. Whether it be modeling the formation of galactic structures, star formation, the propagation of said star formation through space, or analyzing potential astrobiological diversity, the simple complexities of cellular automata are bound more-so by the limits of imagination in their employers than by the design of their functions alone.

To further our understanding of how one might use a cellular automaton in the dazzlingly complex field of astronomy, we will look to the greater end of the cosmic scale and examine how cellular automata might be used to model galactic formation. In an attempt to employ a more complicated model, one would likely be forced to note the challenges of modeling the creation of a structure as complex as a spiral galaxy, as this involves "the gravitational interactions of billions of stars with the addition of gas dynamics, magnetic fields and much more" (Block, 2020). The usage of cellular automata, however, makes the creation of such a model a deceptively simple process. Below are the steps for doing just that:

1. Simulate a "galaxy" through a massive, potentially infinitely large, grid of cells.
    a. Each cell represents a stellar nursery, dense nebulae within which stellar formation occurs (O'Dell, 2005).
    b. Grid size is ultimately up to the user, but of course larger is preferred when working on such a scale.
2. Arrange the cells in series of concentric circles in order to simulate an initial galactic disk
    a. A galactic disk can be understood as the "thin, basically circular distributions of stars, gas, and dust" where "material moves on nearly circular orbits about a common center" (Barnes, 2002).
    b. It is through the rotation of this galactic disk that spiral galaxies ultimately form.

3. Apply the necessary rules to the simulation.
    a. Apply a rule such that "each ring of gas [cells] will rotate at some angular velocity with differential rotation between them" (Block, 2020).
        i. Differential rotation is described as such: "In a rotating solid body, regions that are adjacent at one point in time will remain adjacent as the body rotates. This means that points further from the rotation centre will travel at greater speeds than those closer in. If the rotating body is not solid, however, regions that are adjacent at one point in time do not necessarily maintain that configuration" ("Differential Rotation").
    b. Apply rules allowing cells to "supernova" as stars might in reality; each supernova should carry with it the chance to initiate star formation in neighboring cells of gas.
        i. Supernovae, put simply, are the incredibly powerful explosions which stars might achieve at the end of their lifetime ("Supernova").
    c. Apply a rule such that the star formation in one cell has a chance to trigger the formation of stars within another cell.
        i. This would mean that, upon a supernova, one might encounter a dramatic chain reaction of star formation in the surrounding regions of space, provided the present conditions allow for such an event.
    d. Apply a final rule which dictates that some cells/gas clouds may age to the point of becoming inactive, signalling a loss of the energy required to produce further stars.
        i. These cells should also be subject to the previous rule allowing the activation of dormant gas cells, meaning that even if a cell ages to inactivity, a nearby donation of energy might kickstart the stellar nursery once more.

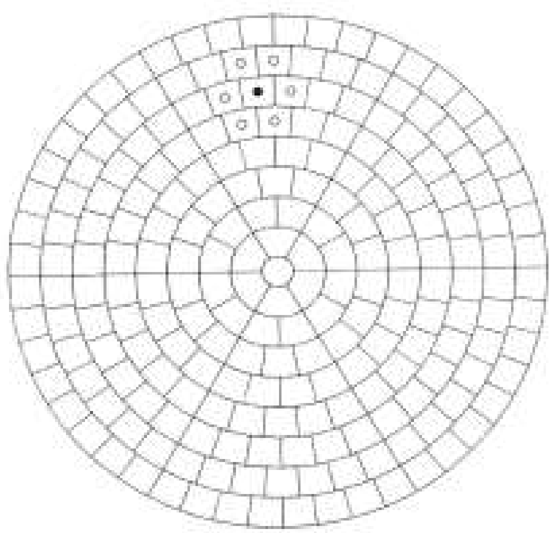
In order to provide a clearer example of some of these rules, your attention is once again pointed towards some hopefully illuminating illustrations on the next page:



(Perdang and Lejeune, 1998)

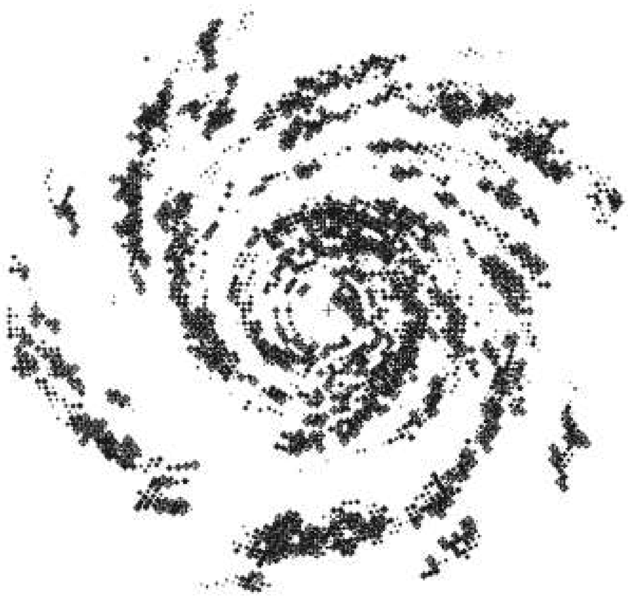
This image, while certainly suggesting a greater complexity of knowledge than the above rules might, is an excellent demonstration of how an inherently rectangular structure could be moulded into a more suitable circular shape. While it is of course not possible to *actually* bend and shape the cellular grid in such a manner (especially since the grid is not technically tangible and could be said to not exist), through mathematical relationships between specific cells, one is able to evoke the behavior of a more concentric arrangement. This would allow for the general rotation of the simulated galaxy, and by extension the desired spiral shape.

The image below provides another example of concentric arrangement of the cellular grid. While a much more regular circle than shown in the previous image, here we see a small demonstration of what an *active* cell might look like compared to its surrounding *inactive* cells. Following the rules described previously, a supernova originating from that singular black-dotted cell might initiate stellar formation in any one of the six surrounding cells, thus changing their white dots to black, representing their change of status. Simulations such as this one could conceivably be scaled to the third dimension, overlapping many of these



(Schiff, 2007)

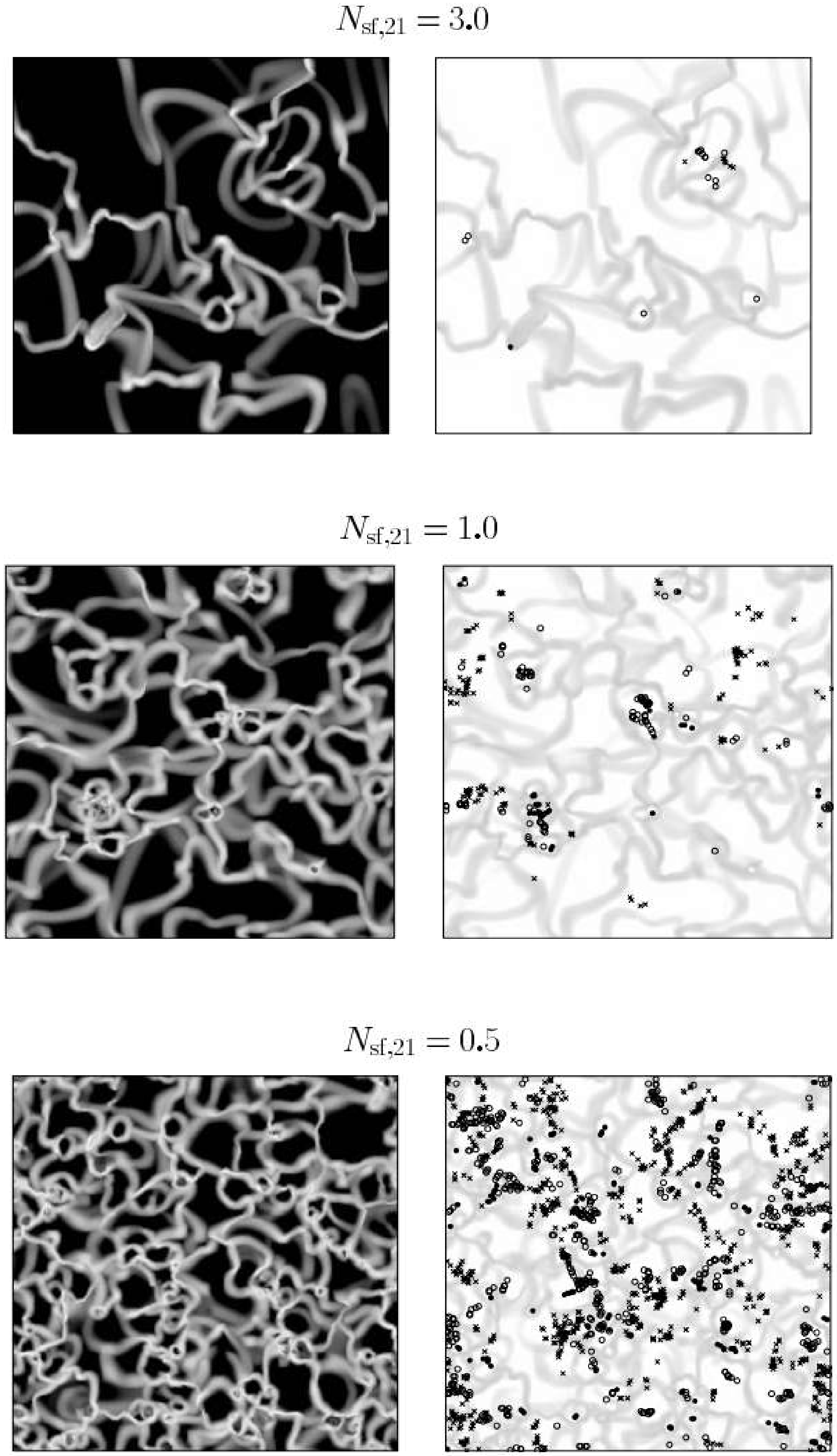
two-dimensional cellular grids upon one another and allowing interactions between cells above and below each other, rather than simply allowing interactions diagonally or orthogonally.



(Schiff, 2007)

This image would be the result of running such a simulation. While certainly not as infinitely complex as a true spiral galaxy, the resemblance is undeniable. Through the systematic manipulation of data through mathematical means, structures which form and exist on scales of time and space beyond human comprehension are able to be condensed and visualized in a much more readily comprehensible format.

An astute reader will likely have noticed that this simulation of galactic structural formation involved not only the simulation of the galaxy itself, but simultaneously the process of the interstellar propagation of stellar births. For the purpose of providing some clarifying information, the propagation of star formation can be more easily understood through the *stochastic self-propagating star formation model* (SSPSF). The SSPSF model suggests that "star formation is continued through the energy dumped back into the interstellar medium by evolving massive stars through HII region [(regions of interstellar ionized hydrogen)]expansions, stellar winds, and supernovae" (Gallagher, 1984). While the modeling of this SSPSF has just been demonstrated to be possible as an element of a larger system, is it possible to model the SSPSF itself, and with more detail? Certainly, though the mathematics behind such an endeavour are perhaps too complicated to explain here. Nonetheless, a picture is worth a thousand words, and through the analysis of previously published results we can hope to achieve a clearer understanding of the role of cellular automata in this process.



(Chapell and Scalo, 2012)

In the example of this cellular automaton, we see a much more focused representation of stellar formation. Rather than focusing on stars through a galactic lens, this automaton takes a closer look at star formation and its propagation. Through the instatement of similar rules as listed above, though arguably more thorough in both a quantitative and qualitative sense (insofar as the complexity of math is concerned), the producers of this cellular automaton were able to produce a believably accurate representation of stellar formation and the interstellar interactions resulting from these energetically violent events. On the left-hand side of these images, in the regions with black backgrounds, we are shown the density of gas filaments in simulated regions of space. The more numerous and brightly colored the filaments, the more densely packed these areas must be with cosmic gasses, those near-ubiquitous atoms which, in massive enough quantities, are capable of forming the very seeds of stars. In the right-hand illustrations, we see those stellar gardens underlaid in a lighter grayscale beneath multitudes of circular points, each representing a site of star formation (Chapell and Scalo, 2012). As energy and gasses coalesce into points along these interstellar filaments, gloriously powerful sparks of fusion and combustion are born, igniting those grand cosmic foundries. These newly born stars thus churn and turn, feeding their excess energies back into the universal nursery of their brethren. As the densities of pre-star material increase, so too does the density of the stars themselves, further sequestering and encapsulating the total energy of the system but almost paradoxically kickstarting the birth of these stars' pre-stellar neighbors through the beginnings and endings of their own brilliant blazes.

The astronomical applications of cellular automata are not merely limited to the tangible (and gargantuan). In particular, cellular automata have also been employed in the search for extraterrestrial intelligence (SETI). While not used for something as immediately exciting as *contacting aliens* or even *finding them*, one group of researchers took it upon themselves to utilize a cellular automaton in the determination of various "Galactic Habitable Zones," which are the regions of the galaxy which are deemed most habitable to life as we presently know it (Vukotić and Ćirković, 2012). The researchers gave their cellular automaton a variety of parameters, notably deciding to focus their attention on problems such as:

- The discrete nature of the distribution of matter
    - This was primarily to control for the possibility of panspermia; the researchers explicitly sought to avoid this possibility

- Contingency in biology
  - The researchers provide the following explanation:

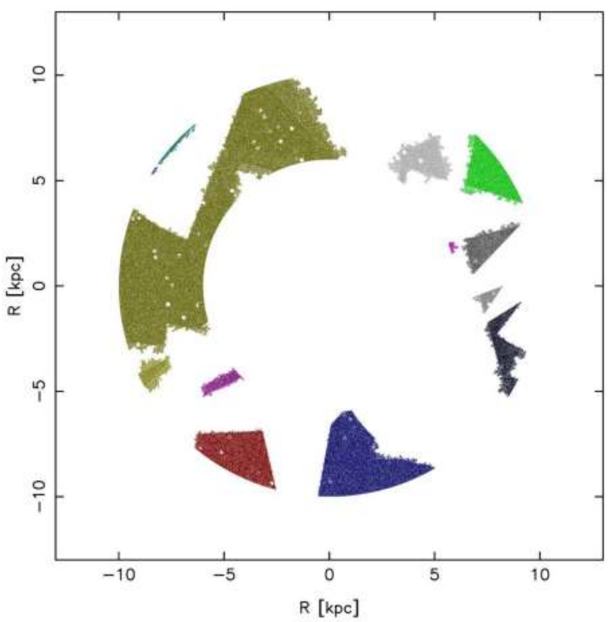
    > The contingent nature of biological evolution guarantees that the outcome is essentially random and unrepeatable. When this essential randomness is coupled with the stochastic nature of external physical changes, especially dramatic episodes of mass extinctions, we end up with a picture where the relative frequency of whatever biological trait (including intelligence, tool-making and other prerequisites for advanced technological civilization) is, in a sufficiently large ensemble, proportional only to the relative size of the relevant region of morphological space (Vukotić and Ćirković, 2012).

- Complex evolutionary processes
  - The researchers acknowledge that our understanding of the genesis of life and intelligence itself is extremely limited and that, to be responsible, a model of this kind should have the capacity to adapt to future changes or discoveries in their field.

    > "Carter (1983, 2008), Hanson (1998), Knoll and Bambach (2000) and other authors emphasize a number of crucial steps necessary for noogenesis [(the formation of reflective thought)]. Some of the examples include the appearance of the "Last Common Ancestor", prokaryote diversification, multicellularity, up to and including noogenesis … our present understanding of the conditions and physico-chemical processes leading to their completion is so poor that we might wish to start the large-scale modeling with only broadly constrained Monte Carlo simulations. Subsequent improvement in our knowledge will be easily accommodated in such a framework" (Vukotić and Ćirković, 2012).

  - Nonetheless, the researchers go on to affirm that the sort of phase transitions are changes intrinsic to these evolutionary processes "are generic features of a large class of PCA [(probabilistic cellular automata)]."

As should be clear by now, this is a complex problem of many discrete parts undergoing a variety of sequences of local interactions: a compounded, yet apt problem for a cellular automaton.



The image on the left depicts the result of the researcher's simulation. As one can see, the illustration is presented in a shape reminiscent of a disc -- the galactic disc of the Milky Way. The uncountable colored dots form clusters which represent the computed "habitable regions" of our galaxy, each a region where life might more easily develop and each colored uniquely so as not to be confused as a part of a separate but nearby region. All in all, this result of the cellular automaton suggests that our life-giving region of space is certainly not unique among the billions to trillions of stars within the Milky Way.

Discussion

By now it has hopefully been demonstrated that cellular automata find a wealth of utilization in the ever-expanding field of astronomy. By merely constructing a cellular grid and imposing a rigid framework of operations and local interactions upon this grid, one is capable of capturing the magnificence of the cosmos and tempering it into a more easily digestible representation of our grand reality. Through the mere application of arithmetic upon abstracted, rectangular, cellular structures, a machine is capable of computing that vastness which eludes the human senses and comprehension. Cellular automata are able to recreate once-unobservable patterns and present them to their operator in a manner which would be utterly awe-inspiring if one was not aware of the astonishingly simple principles at work. Even still, it is almost humbling to see such complex patterns emerge from such deceptively simple configurations.

The implementation of such rules and structures is, of course, much easier said than done and would absolutely require a breadth of programming experience which is not readily available to a curious beginner. The fact remains, however, that the enumeration and presentation of these logic-bound rules demonstrates the feasibility of their implementation in a computerized system. Each step described in the sections above is merely the application of mathematics to discrete units in order to produce localized results which, when combined with one another, have the capability to produce complex patterns. Such is the nature of cellular automata, and ultimately much of reality.

Thus I propose that cellular automata could in fact be utilized to model most, if not all, of the structures of our natural universe. If this is truly a reality of mathematical structure and interaction, then surely each of the elements is a reflection of the whole. With this and the potential dimensionally-additive capabilities of cellular automata in mind, it does not seem a stretch to conclude that, with infinite time and a sufficiently powerful computer, one would be able to simulate reality itself (inasmuch as the laws of math and physics are understood, and humankind admittedly has some work to accomplish in this regard).

Works Cited

Barnes, J. E. “Galaxies, Disk, and Evolution.” *Level 5*, Knowledgebase for Extragalactic Astronomy and Cosmology, by Dr. Barry Madore, 2002. Online: (ned.ipac.caltech).

Berto, F., Tagliabue, J. “Cellular Automata.” *The Stanford Encyclopedia of Philosophy*, edited by Edward N. Zalta, Metaphysics Research Lab, Stanford University, Mar 2021. Online: (plato.stanford.edu).

Block, Adam. “Galactic Cellular Automaton.” Adam Block - Fine Astrophotography, 20 Jun. 2020. Online: (adamblockphotos.com).

“cellular automata.” Encyclopedia Britannica, 10 Sep. 2021. Online: (brittanica.com).

Chappell, D., Scalo, J. “Wind-driven gas networks and star formation in galaxies: reaction-advection hydrodynamic simulations.” Monthly Notices of the Royal Astronomical Society, Volume 325, Issue 1, Jul. 2001, pp. 1–33, Online: (doi.org).

“Differential Rotation.” *COSMOS*, Swinburne Astronomy Online, Swinburne University of Technology. Online: (astronomy.swin.edu.au).

“Galactic Cellular Automaton.” Youtube, uploaded by Adam Block, 21 Jun. 2020. Online: (youtube.com).

Gallagher, J. S. “SSPSF: A Possible Model.” Annual Review of Astronomy and Astrophysics, Volume 22, 1984, pp. 37-74. Online: (ned.ipac.caltech.edu).

Gardiner, L. T., Turfus, C., Wang, M. “A Hybrid N-Body/Cellular Automaton Scheme for Modelling Propagating Star Formation in Galaxies.” Publications of the Astronomical Society of Japan, Volume 50, Issue 4, 1 Aug. 1998, pp. 375–387. Online: (doi.org).

Gardner, Martin. “Mathematical Games: The fantastic combinations of John Conway's new solitaire game "life."” *Scientific American*, Oct. 1970, pp. 120-123. Online: (web.stanford.edu).

O'Dell, C. R. "Nebula." *World Book at NASA*, World Book, Inc, 29 Apr. 2005. Online: (web.archive.org).

Perdang, J., Lejeune, A. “Cellular Automaton experiments on local galactic structure. I. Model assumptions.” Astronomy and Astrophysics Supplement Series, Volume 119, pp. 231-248, 2 Oct. 1996. Online: (doi.org).

Schiff, Joel L. “One Dimensional Cellular Automata.” *Cellular Automata: A Discrete View of the World*, John Wiley & Sons Inc., Hoboken, NJ, 2008, pp. 39–53. Online: (texnology.com).

“Supernova.” *COSMOS*, Swinburne Astronomy Online, Swinburne University of Technology. Online: (astronomy.swin.edu.au).

Vukotić, B., Ćirković, M. “Astrobiological Complexity with Probabilistic Cellular Automata.” Origins of Life and Evolution of Biosphere, Volume 42, pp. 347-371, 29 Aug. 2012. Online: (doi.org)