Nu-life: Spontaneous Dynamic Hierarchical Organization in a Non-uniform "Life-like" Cellular Automata

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ABSTRACT
We present a novel 2D cellular automaton with rules that are a non-uniform generalization of a Moore-neighbourhood, outer-totalistic, two-state ("life-like") cellular automaton. The system is purely deterministic and exhibits interesting multi-scale emergent behaviour, including the spontaneous formation of mobile particles and other self-organizing structures. In particular, smaller-scale structures can be shown to combine with other structures to form inhomogeneous higher-order constructions, and to do so at multiple orders of magnitude. The system has features in common with reaction-diffusion models. We propose that this system has properties that make it useful as a model of an artificial chemistry with the potential for supporting open-ended evolutionary growth. We call it Nu-life.

Categories and Subject Descriptors
F.1.1 [**Theory of Computation**]: Models of Computation – cellular automata.

Keywords
Biology and Chemistry; Cellular Automata; Adaptation/Self-adaptation; Morphogenesis.

1. INTRODUCTION
At the turn of the century, Bedau et al. [2] created a series of millennial challenges to help focus discussion about Artificial Life and give the investigation a consistent framing. One challenge was to "demonstrate an Artificial Chemistry in which the transition to life occurs in-silico." This challenge sets out to explore the nature of the pre-biotic building blocks which must be in place to facilitate the emergence of life-like behaviour. There have been a wide range of Artificial Chemistries (AC) created, utilizing a multitude of techniques and representations. Dittrich et al. [3] presented an overview of the field.

Taylor [9] suggests a set of characteristics he considers necessary for open-ended "creative" evolution, evolution in which fitness is defined entirely intrinsically through the interactions of agents within the system, and where the scope of evolvable functionality is largely unconstrained. He emphasizes the role of the environment in such an evolutionary system, underlining the idea that the agents and the environment should be materially indistinguishable, and importantly that the mechanisms of evolution and encoding of any symbolic information, such as genetic information, should also be explicit. The system's "materiality" would enforce the structural relationships that can occur, and make explicit the competition for the resources from which these structures are made. Hutton [6] asserts that Taylor's arguments lead quite naturally to the specification of an AC and that such a chemistry needs to be embedded in a world with explicit spatial dimension, localized interaction, and explicit conservation of matter. The question remains, however, what the underlying "chemical" rules should be to facilitate evolution that is open-ended. Our objective is to work toward a notationally minimal representation of an AC that is capable of higher-order structural organization and ultimately the spontaneous production of self-replicating complexes capable of evolution.

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2. RELATED WORK
Cellular automata have been studied extensively as simplified models of complex physical behaviour [e.g. 1, 2, 3, 4, 5, 7, 8, 11]. It has been asserted that the computational universality of specific cellular automata systems has some bearing on their potential to support creative evolutionary processes [eg. 11]. This relationship, is discussed by Sipper [8] although he states that computational power should not be considered to be the same thing as "capacity" for modeling life. Sipper, has studied non-uniform cellular automata. A similar system has been studied recently by Medernach et al. [7] making use of genetic programming. These systems are not per se attempting to create an AC, as much as they are exploring the co-evolution of simple interacting organisms. Sipper does, however, discuss the emergence of higher order structure in these systems. Sipper also demonstrates that non-uniform systems can be constructed with an overall computational capability higher than any of the underlying components, and in specific cases with greater computational power than is possible in any equivalent uniform system. It is this higher order structure, built from components which independently lack those structural capabilities, that interests us. The model we have come up with has features in common with a reaction-diffusion system (RDS). RDS were presented by Turing [10] as a possible model for morphogenesis in living organisms. Adamatzky [e.g. 1] has performed a detailed study of CA systems as discrete models of RDS. The CA presented here has similarities to these models, however, the underlying mechanism of the system is different and the non-uniform nature of the system leads to more complex interactions.

3. THE MODEL
Our model adds a simple extension to a standard two-state, Moore-neighbourhood, outer-totalistic cellular automaton, the so-called "life-like" class of cellular automata, which are themselves a generalization of Conway's Game of Life (GoL) [4,5,11]. In our system each cell is capable of executing any of the "life-like" rules and this rule can change at each time-step. To choose a rule, the cell runs a "pre-step". If the cell is "on", it picks a rule which is the intersection of all the rules being used by its "on" neighbours and itself. If it is "off", it picks a rule which is the

union of its "on" neighbours' rules. Once a rule has been selected, the cell evaluates it as if it were a normal outer-totalistic cell. It should be noted that the result of an intersection can sometimes be the empty set. If an empty set is evaluated the cell will be "off".

Totalistic rules can be seen as sets of activation densities. A number of different interaction types are possible, depending both on mutuality of rules and the local activation of cells. For instance, two rules with no common densities might combine to form a rule with both sets of densities, but only if the local density leads to activation. Otherwise, they will mutually inhibit one another. A rule that is a perfect subset of another can use it as a transport medium, either fully or partially replacing it, potentially leading to a "mixture" of rules. Two rules with shared densities can be converted into either their intersection or union, mixing with or replacing one or both of the original rules. The rate of "diffusion" of one rule against another can vary, dependent on local density. Additionally, the macroscopic behaviour of individual rules can be modified by their interactions with other rules, pushing them to different phases of their state-space. Rules interact in different ways based on local state, and interactions can utilize more than two rules. The system is a discrete analog of an RDS, with a large number of different "chemical" interactions, and with both diffusion rate and reaction terms controlled by local density and how different rules respond to those densities. The system defines a consistent and complete 2D chemistry.

4. HYPOTHESIS

Although it is based on simple and deterministic rules, the GoL is capable of universal computation, and an open-ended array of dynamic patterns. However, as has been stated by, for instance, Wolfram [11] and Eppstein [4], the GoL is not intrinsically "creative", requiring very specifically engineered starting states in order to produce interesting behaviour. The set of "life-like" automata is large, but tractable, with 2^{18} (262,144) rules. The variety of behaviours exhibited range from highly structured to largely chaotic. Nevertheless, open-ended evolution has not been found to spontaneously arise in any of these systems. Even if a given rule leads to the spontaneous formation of "gliders" and persistent "still life" patterns, it still appears to be lacking some inherent evolutionary power, tending to fairly uniform behaviour. Nu-life's rules facilitate competition and also create a mechanism for "locking in" evolved structure, while enabling these structures to remain dynamic. This is achieved not so much through the direct competition of rules, as in the way that reactions between rules act to inhibit growth, transform activation and modulate diffusion rate. Not all rules can mutually co-exist in close proximity, leading to erosion. Conversely, rules which are not viable on their own are sustained in combination with others. There is a self-regulating feedback system between rules active at many densities and less active rules which utilize the others as a substrate. This naturally leads to a system with both unbounded growth and complementary decay, which Eppstein has suggested are indicators of complex behaviour and structure. It also leads to a more fundamental competition between locally stable rule collections and disruptive novel interactions; rules are advected to new regions of space, leading to further interactions, drawing the system toward new equilibria.

5. RESULTS

We ran a series of simulations at a range of different resolutions, on toroidal grids, starting from random initial conditions. Similar patterns seem to form in most simulations. These are made up of rule combinations appearing with regularity across multiple runs. Once formed, these patterns tend to travel in a wave-like manner, remaining coherent for long timescales. The scale of the patterns is the same regardless of simulation resolution, so, on larger grids, larger patterns form made from the smaller ones. We have observed pattern formation at several different scales. It is unknown how many survivable rules there are and how many different patterns these rules will form spontaneously. From our test runs, a 384x384 resolution simulation ended up with only two active rules after 4000 steps. However, all the other simulations continued to have interesting dynamic pattern formation for the duration of their runs, over 192,000 steps in the case of a 768x768 resolution simulation, over 46,000 steps for 1536x1536. The number of rules active at the end of the runs is related to the resolution of the simulation: the larger the grid, the more active rules. The 1536x1536 grid had 33 rules after 11,000 steps and these same rules were active after 46,000 steps. The 3072x3072 grid had 215 active after 11,000 steps. 29 of the 33 rules were also in the set of 215. There are other properties that appear consistent over multiple executions of the system: The number of inactive cells tends toward 33.3% of the total cell count, regardless of the size of grid used. Also, the number of cells containing the rule active at all densities tends toward 45%. This rule is a member of most patterns. Additional results, images, videos and source code are available at nulifeautomata.org.

6. REFERENCES

[1] Adamatzky, A, Martínez, G, and Mora, J,2006 Phenomenology of Reaction-Diffusion Binary-State Cellular Automata in Int. J. Bifurcation Chaos 16, 2985 (2006). DOI: 10.1142/S021812740601659

[2] Bedau, M, McCaskill, J, Packard, N, Rasmussen, S, Adami, C, Green, D ,Ikegami, T, Kaneko, K, and Ray, T, 2000 Open Problems in Artificial Life in Artificial Life 2000 6:4, 363-376 DOI 10.1162/106454600300103683

[3] Dittrich, P, Ziegler J, Banzhaf, W, 2001, Artificial Chemistries – a Review in Artificial Life Summer 2001, Vol. 7, No. 3, Pages 225-275 doi:10.1162/106454601753238636

[4] Eppstein, D, 2010, Growth and Decay in Life-Like Cellular Automata in Game of Life Cellular Automata, pp 71-97, Springer London, DOI:10.1007/978-1-84996-217-9_6

[5] Garner, M, 1971, On Cellular automata, self-reproduction, and the game "life" in Scientfic American (February, 1971)

[6] Hutton, T, 2007 Evolvable Self Reproducing Cells in an Artificial Chemistry in Artificial Life Winter 2007, Vol. 13, No. 1, Pages 11-30 DOI 10.1162/artl.2007.13.1.11

[7] Medernach, D, Kowaliw, T, Ryan, C, and Doursat R. 2013. Long-term evolutionary dynamics in heterogeneous cellular automata. In *Proceedings of the 15th annual conference on Genetic and evolutionary computation* (GECCO '13), Christian Blum (Ed.). ACM, New York, NY, USA, 231-238. DOI=10.1145/2463372.2463395

[8] Sipper, M, 1997 and 2004 Evolution of Parallel Cellular Machines: The Cellular Programming Approach, :Springer-Verlag

[9] Taylor, T.1999. Creativity in evolution: Individuals, interactions and environment.In P. Bentley & D. Corne (Eds.), Proceedings of the AISB'99 Symposium on Creative Evolutionary Systems, The Society for the Study of Artificial Intelligence and Simulation of Behaviour.Edin burgh: Morgan Kaufman

[10] Turing, A, 1952 "The Chemical Basis of Morphogenesis," Philosophical Transactions of the Royal Society of London , Series B, No. 641, Vol. 237, pp. 37-72

[11] Wolfram S. 2002 A New Kind of Science, Wolfram Media, Inc., Champaign, Illinois.