Heredity, Complexity, and Surprise: Embedded Self-Replication and Evolution in CA

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Abstract. This paper reviews the history of embedded, evolvable self-replicating structures implemented as cellular automata systems. We relate recent advances in this field to the concept of the evolutionary growth of complexity, a term introduced by McMullin to describe the central idea contained in von Neumann's self-reproducing automata theory. We show that conditions for such growth are *in principle* satisfied by universal constructors, yet that *in practice* much simpler replicators may satisfy scaled-down — yet equally relevant — versions thereof. Examples of such evolvable self-replicators are described and discussed, and future challenges identified.

1 Introduction

In recent decades, the study of embedded self-replicating structures in cellular automata has developed into one of the main themes of research in Artificial Life[31,32]. A common goal motivates such research: to extract the fundamental organizing principles that govern real-world biological phenomena (and, in a wider sense, life as we know it[13]) from an abstraction of their driving biophysical processes. Central among such processes is self-replication in its variety of forms. The eminent mathematician John von Neumann was the first to suggest that essential features of such biological self-replication, with its many degrees of freedom and complex kinematics, could be usefully represented in a discrete cellular space with uniform local rules[41]. His seminal self-reproducing automata theory, which he situated "in the intermediate area between logic, communication theory and physiology"[41, p.204], set the stage for future research in artificial self-replication[16] and remains among the defining achievements of this field[17].

Following von Neumann's work of the late 1940s and early 1950s, research on CA-based self-replicators split into a number of major trends. Among these, the majority are efforts to implement regulated behavior (universal construction[8, 9,20,38,40], self-replication[5,12,14,18,22,34], self-inspection[11], functionality[7, 19,37]) manually introduced to satisfy pre-defined goals of the designer. Such goal-oriented design is important for resolving theoretical problems (bounds and limitations on self-replicating structures) and for direct application (computation, problem-solving, nanotechnology), yet does little to address the fundamental issue that shaped von Neumann's original theory. This issue centers on the

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vague and intuitive concept of "complication"[41, p.78], roughly measured in terms of the number of elementary parts of a machine or organism. Von Neumann observed that natural organisms have a surprising collective tendency to increase such complication over time. Such increases are *unexpected*, resulting from robustness and adaptability of the natural self-replication process rather than from any specific functionality. Von Neumann proved that, *in principle*, such increases are not confined to natural automata but may equally be achievable in artificial ones, in particular by one of his own creation: a complicated universal construction machine embedded in a 29-state CA system. His machine realizes an ingenious separation between static description (tape) and active translation (machine) that has since become synonymous with the concept of self-reproduction[15]. Yet while significant as a defining example, von Neumann's design has been widely critiqued for its reliance on a lengthy set of rules and expansive space. His machine and others like it are so computationally demanding as to be largely unfeasible[1]; hence simpler alternatives with comparable potential are sought.

Considerable disagreement on the topic of such simpler replicating structures has arisen over the fifty years since von Neumann first developed his theory. Such disagreement stems from conflicting definitions of "self-reproduction" and from misconceptions regarding von Neumann's original intent. Most commonly, the "self-reproduction problem"[3, p.xv] has been stated in terms of "non-trivial" self-reproduction, understood to mean reproduction of structures with some minimal level of complexity. First mentioned by Burks[4, p.49], this idea was later adopted by Langton[12] and subsequently incorporated as a guiding principle in CA-based self-replication models[31]. Langton's famous Self-Reproducing (SR) Loop, a model often mistakenly viewed as a *simplification* of von Neumann's machine, embodies a common belief derived from this way of thinking: that minimal *non-trivial* self-reproduction is *explicit* (or *self-directed*[22]) self-reproduction. Such an interpretation is natural when one focuses on engineering aspects of von Neumann's machine design, which indeed embody a highly explicit translation/transcription copy process. Yet it fundamentally overlooks an essential property stressed by von Neumann himself, namely that "self-reproduction includes the ability to undergo inheritable mutations as well as the ability to make another organism like the original"[42, p.489]. Such capacity to withstand *viable heritable mutations* was central to von Neumann's formal theory and to the evolutionary growth of complexity described therein[17,36].

In this paper, we take a new look at the history of self-replication studies in cellular automata. With hereditary variation in mind, Sections 2 and 3 review key concepts underlying von Neumann's original work, highlighting an area of the field that has received little attention. These are the recently de-

[1] Von Neumann's machine required 29 states and a highly complex set of transition rules, occupying an estimated 50,000 to 200,000 CA cells[31, p.241]. Pesavento[20] recently simulated a modified version of this CA, yet was unable (due to prohibitive computational demands) to implement even a single complete self-reproduction cycle.

veloped evolvable loop- and worm-shaped self-replicators of *marginal* hereditary and structural complexity[1,6,29,30,35], reviewed in Section 4, that straddle the boundary between von Neumann's powerful yet fragile machine and more robust yet trivial systems. In Section 5, we identify future challenges and relate their importance in the field of Artificial Life to von Neumann's original search for the evolutionary growth of complexity.

2 Embeddedness, Explicitness, and Heredity

A defining property of CA systems of self-replicators, *embeddedness* quantifies the extent to which state information of an individual is expressed in the arena of competition[2]. Taylor[36, p.216] argues that embeddedness is important because it enables "the very *structure* of the individual to be modified"[original emphasis], likely a necessary condition for open-ended evolution. Related to embeddedness is the range of possible interactions that are allowed between objects or structures. Von Neumann's machine is fully embedded; the entire specification of the machine — its various control organs, memory, and construction arm — are expressed in the cellular space itself rather than hidden in auxiliary non-interactive locations. At any time, the construction process may be modified or disrupted via local rules applied to cells adjacent to the machine. This is distinct from e.g. systems of evolutionary computer programs such as Tierra[21], popular and well-studied in Artificial Life, which assume an unlimited number of CPUs existing outside of the arena of evolution, beyond the influence of other individuals. Since CA by their nature do not "hide" any information (with the exception of the transition rules themselves), CA-based replicators are as a rule highly embedded and in general allow for direct and unrestricted interactions among them. This goes some way to explaining their popularity as a medium for the theoretical study of self-replication.

Self-replicators embedded in CA share an important defining property with biological organisms: both are fundamentally built up from — and interact through — a common material structure grounded in physical laws (i.e. CA rules). Unlike other evolutionary systems such as those of computer programs, CA-based models supply no universal structural cues: everything down to the separation between replicator and its environment is distinguished relative to the system observer. This property has the side-effect of making such systems intrinsically "messy" to analyze, yet has the potential to elevate the richness and surprise of their evolutionary dynamics to levels inherently excluded from less embedded systems. Von Neumann never witnessed such dynamics; although his system is *in principle* capable of producing them, it is *in practice* far too computationally demanding and structurally fragile to be useful in this regard. This key difference manifests the importance of developing simpler, more robust models of self-replication imbued with the potential for evolvability.

Since von Neumann's original work, the majority of discussions on such CA-based embedded models of self-replication have focused on the *explicitness* of

[2] This discussion of embeddedness is based on an analysis by Taylor[36, p.215-219].

the self-reproduction process rather than any potential *evolvability* contained therein[12,18,22,32]. Langton, who supplied possibly the most well-known argument to this effect, makes the case that

> Von Neumann's work suggests an appropriate criterion, which is all the more appropriate because it is satisfied by molecular self-reproduction: the configuration must treat its stored information in two different manners[...]: *interpreted*, as instructions to be executed (translation), and *uninterpreted*, as data to be copied (transcription).[12, p.137, original emphasis]

Although von Neumann indeed based the design of his construction machine on this translation/transcription process, and although he did emphasize the interpreted/uninterpreted distinction at the heart of his theory, this does not imply that such separations should be considered an appropriate *criterion* for self-reproduction. A criterion based on explicitness alone is, in any case, somewhat arbitrary as the transition rules of the CA will always play some role in enabling structures to copy themselves.

More appropriate as criterion is the issue of *heredity*, on the basis of which simple replicators such as Langton's Loop can be unambiguously distinguished from potentially evolvable machines such as that of von Neumann. Whereas Langton takes the translation/transcription *process* to be of primary interest, von Neumann emphasized static *descriptions*, the importance of which

> is that they replace the varying and reactive originals by quiescent and (temporarily) unchanging semantic equivalents and thus permit copying[,] the decisive step which renders self-reproduction (or, more generally, *reproduction without degeneration in size or level of organization*) possible.[41, p.122-123, emphasis added]

Such non-degenerative reproduction is an immediate consequence of construction universality, an important result recently clarified and strengthened by McMullin[17]. Yet whereas such universality is computationally demanding and biologically implausible, a less stringent yet explicit encoding — one that enables a shift in heredity from *limited* towards *indefinite* — is in fact possible and indeed has already been implemented in a number of models[1,10,26,30,35]. Such a shift enables evolutionary complexity growth, described in the next section.

3 The Evolutionary Growth of Complexity

In his recent re-appraisal of von Neumann's work, McMullin[17] summarizes three principal conditions he deems necessary to solve the problem of what he calls the *evolutionary growth of complexity.* Namely, to do so

> one would need to exhibit a concrete class of machines [...] in sufficient detail to satisfy ourselves that they *are* purely mechanistic; one would need to show that they span a significant range of complexity; and finally, one would have to demonstrate that there are construction pathways leading from the simplest to the most complex[17, p.351, original emphasis]

He goes on to show that von Neumann's machine satisfies these requirements, that it is thus capable of "incremental, bootstrapping *increases* in complexity"[17, p.354, original emphasis], and moreover that it is arguably the *simplest* machine so far capable of doing so. The proof of this result rests on the construction universality that von Neumann worked so hard to realize in his machine. Whereas the concept of complexity is notoriously ill-defined (von Neumann referred to his own understanding of it as "vague, unscientific and imperfect"[41, p.78]), this turns out not to be essential for demonstrating complexity-increasing construction pathways — the central piece of the puzzle.

Having elucidated the above result, McMullin goes on to ask the important question: "what further conditions are required to enable an *actual*, as opposed to merely *potential*, growth in complexity?"[17, p.360, emphasis added]. Von Neumann's machine does not qualify as "actual" primarily due to the fact that its structure is extremely fragile, unable to withstand minimal external perturbations. Such fragility would render any interactions — notably those between parent and child immediately following self-reproduction — highly destructive, preventing the coexistence of a population of such machines. In addition, neither current computational resources nor those of the foreseeable future hold much promise for implementing such a complicated system on any significant scale.

There is an added concern, and this relates to the concept of a *Darwinian* — as distinct from *mutational* — growth of complexity. The former entails *actual* growth and requires direction from selection pressures, whereas the latter merely implies *possible* growth and only requires the presence of construction pathways. McMullin notes that, if the former were to occur at all, they would happen "along paths in the genetic network that lead "uphill" in terms of fitness". Yet a fixed genetic network such as that of von Neumann's machines "*may* impose severe limits on the practical paths of Darwinian evolution (and thus on the practical evolutionary growth of complexity)"[17, p.358, original emphasis]. The question of whether or not a population of replicating machines, directly competing and evolving within such a network, would indeed favour increases in complexity is clearly an important one, yet one to which a complicated system such as von Neumann's provides no concrete answers.

One may thus ask: what then are the *practical* alternatives to fragile and complicated universal constructors, and are they capable of any evolutionary growth in complexity? Addressing the latter question, McMullin makes the important admission[3] that the solution he presents "may seem to imply that a *general* constructive automaton (i.e., capable of constructing a very wide range of target machines) is a prerequisite to *any* evolutionary growth of complexity. It is not."[17, p.357,original emphasis] If we are interested in studying complexity-increase during the earliest stages of life, a universal constructive automaton in any case hardly seems like the appropriate model; such a complicated machine would have to be preceded by simpler, less sophisticated replicators. It is to such simpler evolvable replicators that we turn our attention in the following section.

[3] McMullin makes this point in the context of a related discussion on genetic relativism/absolutism.

4 Evolvable Self-Replicators in Cellular Automata

A wide array of self-replicating structures have been implemented in cellular automata since von Neumann first introduced his self-reproducing automata theory. Such models are often conceptualized as situated on a linear scale of "complexity", with complicated universal constructors at one end and simple self-replicators at the other. Because the terms "simple" and "complex" are themselves so ill-defined, it is not always clear what properties should be associated with the intermediate region between these extremes. Sipper[31, p.245], for instance, situates self-replicators with added computational and functional capabilities[7,19,37] in this region. Models such as these are indeed interesting from the point of view of achieving *targeted* behaviours, but in terms of studying the evolutionary *process* itself — and in particular that of complexity-increase — they fall short of the requirements stated earlier[4]. In particular, such models lack the "surprise!"[23] element that plays a crucial role in the emergence of complexity-increasing evolution.

Taylor[36, p.200] presents an alternative 2D visualization in which each system is assigned to a point on a plane, with x and y axes representing the copying process (explicit/implicit) and heredity (limited/indefinite), respectively, of self-replicators. The diagram we have drawn in Fig. 1 is based on Taylor's and, like his, is not intended to be quantitatively accurate; rather it is a qualitative tool to better visualize certain key concepts. Von Neumann's machine, which carries out a highly explicit translation/transcription process, is also construction universal and hence appears close to the upper left (indefinite/explicit) portion of the diagram. In contrast, self-reproduction of template-based replicators[10,34] is largely implicit in "physical" rules, allowing any arbitrary string to be replicated; hence they appear close to the upper right (indefinite/implicit) portion of the diagram. Langton's Loop and other minimal self-replicators appear at the same level on the heredity scale as do trivial self-replicators; neither accommodates any hereditary variation, although Langton's CA has a more explicit translation process.

Note that certain evolving self-replicating loops and worms — not yet developed at the time when Taylor produced his thesis — are included at the center of the diagram, far from Langton's Loop along the hereditary axis. It is this central region, representing self-replicators of *marginal* hereditary and structural complexity, that is our focus. Such structures should have the following virtues: they should have some potential for hereditary variability, should be sufficiently robust to self-replicate continuously without self-destruction, and should be sufficiently simple in specification to be realized on a computer.

Chou and Reggia[6] designed the first such system while studying the emergence of CA-based self-replicating loops from a "soup" of components. Initiated with a random distribution of "unbound" cells, the soup is "stirred" (using

[4] This represents another interpretation of "complexity", namely that of *computational functionality* (or *universality*). McMullin[17, p.348-349] addresses this perspective and finds it inadequate for describing evolutionary complexity-growth.

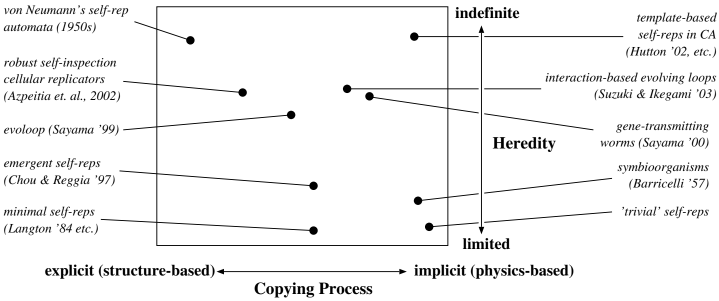

Fig. 1. Categorization of CA-based Self-Replicators.

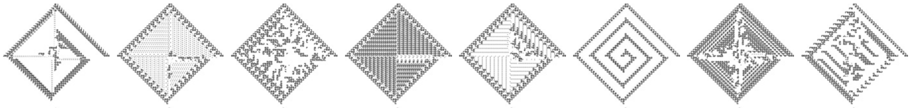

Fig. 2. Pattern formation of some different size-6 evoloop species after 5000 time steps.

only local rules) until a minimal-sized loop appears by chance. This structure is identified by local rules, certain "bound" bits are set to distinguish it, and a self-replicating loop emerges. An evolutionary cycle then commences and continues indefinitely: smaller loops, induced by "growth bits" scattered about the space, become progressively larger until the space cannot accommodate them, at which point smaller ones re-emerge. Chou and Reggia did not aim at studying an evolutionary *process* with this work but rather the *emergence* of self-replicators. Evolution in this model, explicitly induced and somewhat artificial, was not a priority. Heredity was also highly constricted, with each loop "species" defined exclusively by replicator size.

Sayama's "evoloop" model[29], developed shortly thereafter and based on his earlier self-replicating loop called the SDSR Loop[28], differs significantly in these regards. Although it borrows its basic structure from Langton's Loop, the evoloop exhibits more complex and interesting evolutionary behaviour than do earlier minimal self-replicators of its kind — behaviour traditionally assumed to require a more complicated system specification. Within this model occur evolutionary processes (viewed here as variation plus natural selection) that result exclusively from the *local*, *structural* interaction of embedded self-replicators. Such variation and selection processes are not defined a priori but rather emerge spontaneously from the low-level "physics" of the CA, a distinctly bottom-up feature that distinguishes it from earlier evolutionary models. Initially it was believed that such variation was limited to size only, but extensive and detailed studies[24] have since revealed that the genetic state-space grows *combinatorially* with loop size. Each genotype within this vast possibility space has unique growth patterns (Fig. 2) and genealogical connectivity[27], exerting a demonstrable and decisive pressure on selection and resulting in a rugged fitness landscape[26], producing a limited form of complexity-increase in hostile environments[25].

Evolutionary systems of self-replicating structures with other shapes have also yielded interesting evolutionary potential. Morita and Imai[18] were the first to develop CA-based shape-encoding worms and loops. A variety of different structural patterns can replicate successfully in this model, however collisions leading to mutations are explicitly disallowed. Sayama[30] borrowed this basic shape-encoding worm structure and adapted it to enable gene transmission through structural interaction, enabling worms to change their genotype (and phenotype) in a bottom-up way. Results from experiments with this model showed a tendency of worms to increase their average length over time, hence demonstrating a limited form of complexity-increase.

Suzuki and Ikegami[35] applied the shape-encoding mechanism to study interaction based evolution of loop structures. Although more complicated than the models already mentioned, this CA allows for a variety of different loop-shaped structures (other than the traditional square) to successfully self-replicate, mutate, and evolve, and in this respect it is quite unique. The main thrust of this work is an interaction mechanism between replicating structures that makes use of a hypercycle-like network of collision rules. Using such a network, it was found that larger, more complex loop structures emerged at the boundary between waves of superior and inferior species in a propagating hypercycle formation.

Using a novel CA system incorporating both self-inspection and genetic reproduction strategies, Azpeitia and Ibáñez[1] investigated the spontaneous emergence of robust cellular replicators (self-replicating loops). Emergence in this system is notably achieved without explicit mechanisms (e.g. "bound" or "growth" bits as in [6]). The detailed comparison of self-inspection and genetic reproduction strategies in this study is moreover unique among those we have discussed. In their conclusions, the authors note: "experiments suggest that self-inspection reproduction could be a precursory stage for the genetic one." Yet "despite having a better chance to trigger the reproduction dynamics, self-inspection would be taken over by the evolutinary advantages of genetic reproduction."[1, p.142]

Systems of template-based replicators[10,33,39] aim at simulating the emergence of living (i.e. self-replicating and possibly evolving) structures from a soup of non-living components under virtual physical laws; they hence bear similarities to the models already mentioned. Hutton[10] recently designed such a system in a CA-equivalent Artificial Chemistry (Squirm3) in which strands of "atoms" self-replicate via a set of reaction rules that apply locally throughout the space. No limitations are imposed on this replication process, hence any arbitrary strand, if immersed in a sufficiently large random soup of atoms, will self-replicate. Although the number of different possible "types" is thus quite high in this system, all strands have the same basic behaviour. Hutton discovered the emergence of self-replicators and a limited form of adaptation to the environment, although he concluded that more reactions were necessary to enable complexity growth.

5 Conclusion

The systems we mentioned in the previous section constitute a small sample of the possible marginal self-replicators that could potentially be devised in CA. Results with these models, notably the genetic diversity and complex genealogy recently discovered with the evoloop[24,26], demonstrate that complexity-increase of a limited kind is possible *in practice* using such evolvable explicit self-replicators. In many ways such models constitute the first step towards von Neumann's original goal of complexity-increase in CA, steps that he himself could never take because his model was too fragile and complicated.

Models of the kind discussed here are also important as a teaching tool. For a student who is learning about the principles of evolution, a system such as the evoloop has unique advantages over more complicated systems such as those of evolutionary computer programs. Namely, the basic mechanism for evolution (variation and selection) is in one case *emergent*, in the other case *prescribed.* Whereas the latter case *assumes* certain basic principals of biology, the former allows one to *discover* them. The analysis and insight that ultimately lead to such a discovery are at the heart of scientific thinking.

An immediate future challenge is to incorporate within CA systems of self-replicators the possibility for functional interaction potentially leading to more complex hierarchical relations between organisms. The diversity of multi-cellular life that has evolved in the biosphere is clear evidence that self-replication at concurrent multiple scales plays a critical role in the growth of complexity. Although the emergence of self-replication has been shown[1,6,10], self-replication of macro-scale replicators from simpler micro-scale ones has not[5]. The study of self-replication and evolution — and in particular the search for complexity-increasing evolution — would likely benefit from work in this direction.

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[5] Barricelli's early work with symbioorganisms[2] is however an important first step in this direction.

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