The search for a First Cell under the Maximalism Design principle

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1 introduction

We often assume that evolution proceeds from simple to complex in various levels of description, e.g. morphology and behavioral structures. An example can be found in a suture line pattern of ammonites or the increment of the genomic size from prokaryotes to eukaryotes. In the simulation of artificial life, we tend to simulate how simple creatures develop into complex ones. Increasing complexity corresponds to the direction of evolution (or time so to speak) similar to the second law of thermodynamics. It should be noted that high entropy is not equal to high complexity, as we think living systems absorb the entropy (i.e. neg-entropy) by increasing their structural complexity.

Recently, there have been many attempts to make a minimal cell in the nano and micro scales. Here the possible minimal cell would be a liposome that contains a minimal metabolic cycle for self-maintenance and self-replication [7, 9, 13]. However, none of these attempts have succeeded so far. In this paper, we propose the concept of first cell versus the minimal cell.

We consider the problem of creating a minimal cell as a model for the origin of life from several different perspectives: 1) the human developmental process, 2) a generator of complexity and 3) the maximalism design principle. Human developmental processes do not go merely from simple to complex, but it often shows a U-shaped curve [12, 14] with respect to its performance. We will compare the evolutionary process with the developmental process. Second, we will discuss the necessary complexity of a first cell. We will take a classical example of cellular automata to discuss the class 4 type complexity and discuss the initial configuration as a part of developmental dynamics. Finally, we will discuss our recent experiments on self-moving droplets and propose a new design principle for making a sufficiently complex cell, the first cell, instead of making a minimal cell.

2 U-shaped development

Contrary to the classical view of human development (i.e. a stage-like progress view), the recent observation [14] reveals that development shows a U-shaped curve in infant capabilities (Fig.1). Namely, skills and pattern of human infants are better at the first phase then drop to a certain level and again recover to a qualitatively better level. This inverse phase change is observed in many aspects in developmental stages such as body movement, face recognition, speech processing capabilities and so on.

Some researchers try to explain the U-shaped development in terms of nonlinearity of the collective dynamical systems underlying the developmental process. For example, Gershkoff-Stowe and Thelen [2] used the dynamical systems perspective to explore the U-shaped development in infants' stepping, object reaching and naming. Taga et al. [16] studied the infant's general movement (i.e. free movement of hands and feet) to qualitatively measure the movement in terms of dynamical systems. The infant's complex and diverse pattern is lost around the age of 2 months but recovered at the age of 3 years. This has been modeled as freeing and freezing the effective degrees of freedom in the course of development. The difference between the complexity at the initial phase of development and the recovering phase is that movement becomes more flexible and controlled in the recovering phase, with the general movement more periodic-like by age 2. This phase change, Taga et al, called a "freezing and freeing" of the degrees of freedom in a brain-body system.

Evolution might have proceeded in a similar way, and therefore the modern cell and the first cell both can be complex but radically different. In case of human development, we think that the U-shaped curve is driven by the inter/intra organization of interaction patterns of the brain system. The separate regions in the brain must be re-organized to communicate with each other (intra organization) and must be adjusted in response to the environmental complexity (inter organization). We can also have a same scenario for the development of early cell systems. A first cell can be highly self-regulated, and therefore it is less dependent on the environment but still able to interact with the environment. The intra organization at this early stage is highly dependent on self-assembly and self-organization. As it develops, a cell becomes more dependent on the environment and the level of robustness becomes lower as it develops its inter organization. Then the cell becomes robust again with more dependence on the environment that the cell itself helped to shape and as the environment shapes the cell. Namely,

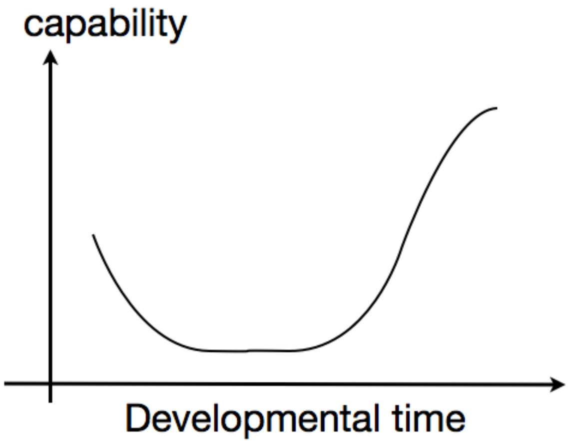

Figure 1: Illustration of the U-shaped curve. A certain capability vs. developmental time.

a cell internalizes complexity within the cell in the initial phase but externalizes complexity to the environment in the later phases. The viability or robustness of a cell may have demonstrated a U-shaped curve in the course of evolution. This is due to an inverse analogy of Earnest Haeckel's famous phrase "ontogeny recapitulates phylogeny", but also due to our belief that there should be universal dynamics that governs developmental processes and open-ended evolution (i.e. evolution that eventually creates novel patterns [1]).

3 Measuring Complexity

Among the many different definitions of complexity, the Kolmogorov formulation of complexity is the most basic and well studied. It is specified by the minimum length of description (for the universal Turing machine) of the target object. A random string has the highest complexity as it cannot be compressed into a shorter message. By using this notion of complexity, we can simply classify the different complexity generated by different rules or dynamics. Steve Wolfram distinguished two classes of rules that i) generate complexity from complex initial states and ii) generate complexity from the simple initial states [18]. In the example of one-dimensional elementary cellular automata (i.e. two states per each spatial site and only a single

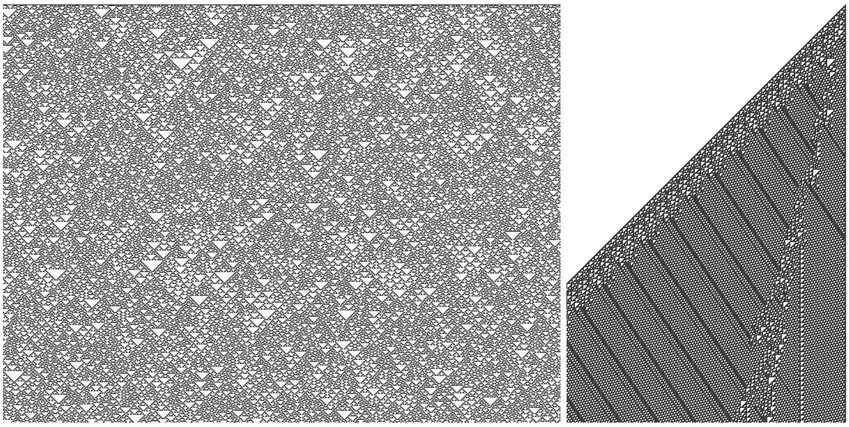

Figure 2: Difference between the space time patterns from the 1-dimensional rule 22 (left) and 110(right). The horizontal direction is space and the vertical direction is time.

neighbors), rules like 90 or 18 can only generate complex patterns by having complex initial strings. Rules like 30 or 110 generate complex patterns from a single black state string (Fig.2). In particular, rule 110 is an example of class 4 behavior, that is, it produces a system that varies between periodic and chaotic behaviors.

In the case of the game of life, the situation becomes more complicated. Some initial states lead to complex ever-changing patterns but similar initial states collapse into simple fixed patterns. We have not found any conditions that evolve towards higher complexity. Although the rule of the game of life is so simple [1], the behavior can be unexpectedly complex, such as class 4 type behavior.

Usually, we separate the equation from its variables or rules from its states. But in case of the game of life, we should not separate them. The states constitute dynamics, as a certain state enables certain type of dynamics. This may be also true for the first cell. A certain type of chemical initial states may lead to complex protocellular stages.

The design of the initial genesis state of the primordial chemical system is still unknown, just like in case of the game of life. For a laboratory experiment, the practical usage of a pipette in preparing the initial chemical conditions from a prescribed protocol is common. Preparing the initial state for a chemical game of life is not possible using traditions chemical methods and protocols. We need an external criterion to design the initial state to allow open-ended evolution. The whole process is not automatic. It requires constant perturbation from the outside, while at the same time the process is under the control of the self-organization of the chemical system. In the other words, the whole process is both deterministic and contingent at the

[1] a state of a cell becomes black only if it is already black and has 2 or 3 black states as neighbors or it is white and has exactly 3 black states as neighbors

Figure 3: The spatial configuration of the new universal constructor designed by Tim Hutton.

same time. We will come back to this point in the end.

4 Maximalism Design principle

The design of life-like behavior has been the challenge of artificial life for last two decades. We have developed many different languages and dynamic processes for making artificial life systems. One of the most well studied themes is self-replication of units in a cellular-automata (CA) like space. John von Neumann designed the intricate 29 state CA to model the universal constructor, which generates any structure written on a tape consists of 2-dimensional bit pattern [17]. Recently, several new CAs have been designed that have the same universal capability with reduced forms (Fig.3). A difficulty of this self-reproducing CA is that it has almost no robustness. Any bit flip of the initial state will cause a fatal error and the initial state will never be recovered.

If we prepare many initial tapes and let them compete, usually simpler and faster self-replicating units will dominate the whole space. Bigger and complex reproducing units have slim chance to out perform the smaller units. There are only a few exceptions to this trend. Chris Saltzburg et al. [10] have found that there exist a minimal self-replicating pattern that increases complexity. Suzuki and Ikegami have found that spatial spiral pattern generates complex replicators in the peripherals of spiral arms [11]. But none of them have shown open-ended evolution, i.e. evolution which eventually creates new species and patterns.

This failure of synthesizing an evolutionary pathway towards increasing complexity casts doubt on the power of self-organization alone to drive evolution. Certainly nonlinear science has demonstrated beautiful examples of

Figure 4: The self-organized population of the oil droplets.

self-organization, but these demonstrations are restricted to typical physical chemical processes. Life is everywhere but its initiation from non-living matter and processes is an atypical phenomenon.

We should change our design principle and should start from a complex initial pattern rather than simple and fast replicators. In the case of the game of life, gliders as a pattern do emerge from the random initial configuration, but in order to have some large complex patterns we have to carefully tune the initial pattern. Currently for the chemical experiments, we are at the level of creating simple chemical gliders in our systems.

We have conducted a following chemical experiment: add oleic anhydride oil phase to highly alkaline water phase (pH 12) to see how the hydrolysis of the anhydride proceeds in a glass plate. Immediately the oil begins to react with the water causing the oil phase to break up into smaller spherical droplets, several to hundreds of microns in diameter. These droplets are like gliders in the game of life moving freely in the space and interacting with each other (Fig.4). Different from the game of life, the droplets can change direction spontaneously and coming into contact they never fuse together. In other words, they are far more robust than gliders. Also the droplets have finite life spans of less than 30 minutes and are sensitive to factors in the external environment such as pH. We argue that the mechanism of the movement is caused by the coupling of the hydrolysis reaction at the interface with the fluid dynamics of the droplet. Because of this coupling, chemical reaction lasts much longer than without the coupling [8]. This is a "half living" state as it sustains the non-equilibrium state by its own self-regulation.

A key point is that the environmental conditions (such as pH, product concentration, Reynolds number,,,) are self-organized by the system itself rather than being prepared by the experimenter. If we try to obtain the same behavior by preparing the oil phase in high pH water along with some product of the reaction, the moving droplets never appear. The moving state, i.e. chemical gliders, appears through radical self-construction of the environment. We state that we cannot rely on the power of self-organization in searching for the origin of life. This is because both self-organization and the rich complex initial state are required. The ratio of the two is determined by the "rareness" of the event. Self-organization tends to simplify the final outcome limiting it to a low degree of complexity, while the low complexity assures the robustness of the outcome. The rich and complex initial state prevents the system from falling into a simple state. Therefore, we call our principle the Maximalism design principle.

The Maximalism design principle on one hand proposes that a minimal cell representative of the origin of life on Earth cannot be found using traditional laboratory approaches and protocols, and on the other hand the concept challenges today's experimentalists to design more complex initial states. The complex initial state may evolve into a 'half living' state possessing some of the desired properties of life, such as replication, movement, homeostasis, etc (see e.g. [4]). The experimentalist will then be challenged to understand how the system patterns and organizes itself to produce the 'half living' state, first by observation and then by rigorous sampling through complex parameter space. The complex interplay between the self-assembled structures and the environments that they create may lead to the understanding of the inter and intra organization of the system as it evolves. If a minimal cell is constructed from a simple initial state, this will likely be accomplished using high influxes of matter (high concentration of building blocks) as well as highly energetic compounds (such as highly activated chemical precursors). When considering the origin of life, both conditions seem highly contrived. In addition, the longevity of the life-like processes may be highly limited due to a less than complete embodiment of complex truly living system. A true understanding of the origin of life may require a different approach as suggested here.

5 conclusion

Is life a contingent or deterministic phenomenon? This was a topic discussed recently at the international workshop on the open questions on the origins of life in San Sebastian, Spain (May, 2009). Stuart Kauffman [5] argues that adjacent possible is what he sees as a generic principle in evolutionary processes. He claims that "biospheres on average keep expanding into the adjacent possible" and the rate of exploring the adjacent possible should be balanced with the "internal gating mechanism". Our design principle is to increase the number of the adjacent possible from the very beginning.

Figure 5: An art film "The way things go" by Peter Fischli and David Weiss (1987) . These snapshots are taken from the movie.

The self-organization starts to happen in this open-ended space and thus may generate a rare event. Life emerges at the edge of self-organization and complexity. In other words, we have to blend the contingency and the deterministic processes in searching for the rare event. This is aptly illustrated in the famous art piece " The way things go" by Peter Fischli and David Weiss (1987).

The two artists made a half-hour movie of an unlikely chain of events, e.g. a tire pushes a steel drum so that a toy car with a small candle starts to run and igniting a fuse.... The chain of events is not a chain of inevitable causes but a freezing chain of accidents. Only the inevitable physical causes there can be found in between successive events. On the other hand, the chain of unrelated events is an automatic and deterministic process in the sense it doesn't depend on a coin tossing. It may be akin to saying that a chaotic orbit itself is deterministic and its inherent instability is only detectable by adding a noise from without. If the evolution of life is similar to this chain of unrelated events, searching for the first cell doesn't solve the problem how the evolution proceeds from there. In this sense, what we do is to design adjacent possible events step by step from the first cell to modern life forms. Not a single path but a bundle of evolutionary paths can be our research target.

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