What is the nature of "life"? Kouhei Fukai

The process by which biological systems came into being on earth continues to be a central question in biology. Of course, there is currently no way to know directly what happened 3 billion years ago. All we can do is to seek the conditions under which the system of life can emerge and evolve. To discuss the origin of biological systems, we have to define "life". To define "life" is no easy task and it is difficult to construct the universal definition to everyone. However, the following two conditions may be widely accepted.

i) to have the ability of self-reproducing

ii) to have the ability to inherit mutations

What is important here is that the system that meets i) and ii) can evolve. The cycle of reproduction and mutant follows the emergence of complex and diverse individuals. However, it is far from clear how such a system that has the conditions i) and ii) could emerge and what is the feature of the dynamics of the evolution.

The most influential theory about the origin of life is the "RNA world hypothesis". The RNA world hypothesis suggests that life on Earth began with a simple RNA high molecule that could copy itself and have high catalytic activity. In other words, it meets the two conditions above. In this theory, the accidental emergence of the "First RNA" is the very our ancestor. However, the RNA world hypothesis has many problems. For example, it is not clear how likely the RNA high molecular with the two conditions is to occur.

Let's look at this issue from a different perspective, in mathematical language and computers. Jon von Neumann was interested in the self-reproducing dynamics in the biology system and was trying to find out the mathematical model with the properties of evolutionary-capable systems in the 1940s. After trying various models of dynamical systems, von Neumann finally came up with "cellular automaton (CA)", which is the dynamical system defined by the states on boxes with a simple rule of dynamics. Von Neumann made a self-reproducing system with CA and these artificial life phenomena were simulated on the computer. His work became the pioneering research of artificial life research (ALife). Before we talk about his great work of von Neumann's self-reproducing automata, let me explain the basics of CA.

The most simple and instructive example of CA is two-states one-dimensional CA. Only a broad overview is given here. This model was defined on the boxes aligned in a horizontal row. Each cell can take the state "0" or "1". The states evolve with time according to a simple rule. The rule is defined on the three consecutive boxes. The configurations of the three consecutive boxes are "000", "001", …, "111" and each of the 8 configurations evolves to "0" or "1" in the next time step according to the specified rule. There are $2^8 = 256$ rules and they are classified into 4 classes. Class 1: rapidly converge to a homogeneous uniform state. Class 2: rapidly converge to a repetitive or stable state. Class 4: appear to remain in a random state, chaos. Class 4: form areas of repetitive states, but also form complicated structure. The most interesting class is class 4, which is between complete chaos (class 3) and repetitive pattern (class 2). This is why class 4 is called "Edge of Chaos". The rule classified in class 4 is a rare case, only two among the 256 rules. This pattern of class 4 is often seen in the natural world, for example, the pattern of a shell (Fig.1). Moreover, it is proved that we can "build a computer" in the class 4 world! (This property is called “Turing complete”.) Therefore class 4, “Edge of Chaos", is thought to have a relation with "life" and to be an interesting research topic.

Let’s return the story to von Neumann’s self-reproducing automaton. Von Neumann considers CA on two-dimensional cells with 29 states. In the 1940s, von Neumann found that when the initial state is set appropriately, the system evolves with the self-reproducing feature. The structure of self-reproducing automaton reminiscents of DNA and their reproduction system. This discovery was before Watson and Crick found the DNA in 1953! The basic concept is the same as the previous example. The details of the rule of von Neumann’s self-reproducing automata are complex and are not present here, but what is surprising is that von Neumann finds the rule and the self-reproducing feature only by the analysis with paper and pencil! (Is he really human...?) It was not until 1995, 38 years after his death that the actual numerical experiment was done, and people watched Neumann’s self-reproducing automata reproduce itself actually in the real world. Another noteworthy thing is Neumann’s self-reproducing automata is also “Turing complete” likewise class 4, in other words, we can build a computer in this self-reproducing automaton world.

However, self-reproducing automaton is vulnerable to noise. When a little mutation occurs, this automaton loses the feature of “Turing complete”. This makes the stable evolution difficult and having this fault is not enough for the conditions of evolution ii). It is future work to construct self-reproducing automaton which is robust against noise. If such an automaton is developed, mankind will know the answer to the question “what is the nature of life?”, which is a very important question to all humans.

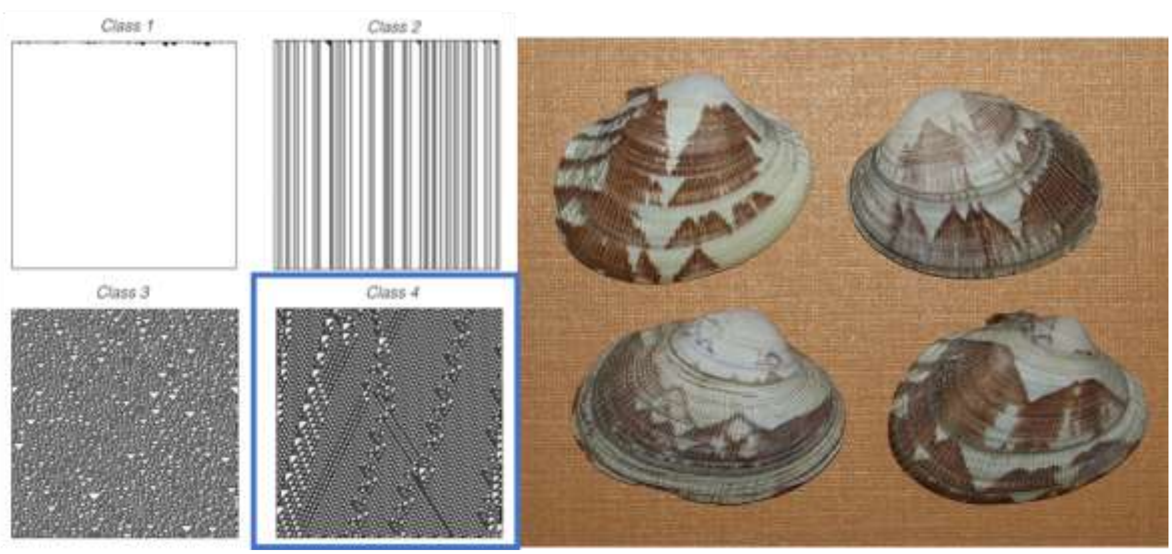

Fig. 1: The 4 class of one-dimensional CA and the shell pattern. The shell pattern looks like the pattern of class4…? (Cited from [G. Vladimir Phys. Rev. E, **88** 042814 (2013)])