Capra Course

Summary of Lecture 3:

Order and Complexity in the Living World

(with references to the corresponding sections in the textbook *The Systems View of Life* by Capra and Luisi)

In Lectures 3 and 4, I apply the systemic perspective to the understanding of the origin and evolution of life. To do so, we need to shift to a different level of description. The theory of autopoiesis defines life as a particular pattern of organization — a self-generating network within a boundary of its own making — but it does not give us a detailed description of the processes that occur within this self-generating network in terms of physics, chemistry, and genetics. This level of description is necessary to understand the evolution and the origin of life.

Today, there is a broad consensus among biologists that long before the emergence of the first living cell there was a type of molecular evolution, also known as "prebiotic" evolution, in which the transition from nonliving to living matter was brought about by a gradual and spontaneous increase of molecular complexity.

At first glance, this seems to be in contradiction with the second law of thermodynamics, but there are in fact quite a few processes in nature where there is a spontaneous increase of molecular complexity without any violation thermodynamics. These processes are known as "self-organization," because the resulting structures are organized by the "internal rules" of the system, not by anything outside. A simple and well-known example is the formation of soap bubbles when you shake a mixture of soap and water. The resulting structures form spontaneously because they are thermodynamically more stable than the original ingredients. *(Section 8.1)*

There are many such examples, which are well known to all chemists. They are known as static self-organization, because once the self-organization has taken place — once the bubbles have formed — the structure does not change anymore; there is chemical equilibrium. For the systems view of life, the much more interesting examples of self-organization are what is called dynamic self-organization. Their key characteristic is that these systems operate far from chemical equilibrium. Ilya Prigogine called them "dissipative structures" to indicate that they are stable but also change all the time. A water vortex is a simple example of a dissipative structure. Water particles flow through it continuously, yet the overall structure remains stable. Metaphorically, we can also visualize a cell as a whirlpool — a stable structure with matter and energy continually flowing through it. *(Section 8.3)*

Prigogine's critical insight was that systems operating far from equilibrium need to be described in terms of nonlinear equations. Therefore, the formalism of nonlinear dynamics, or complexity theory, became very important for him. He used this new mathematics to formulate a nonlinear thermodynamics of dissipative structures, for which he was awarded the Nobel prize.

To conclude this lecture, I discuss what is perhaps the most important discovery in the theory of dissipative structures and, in my view, the most important discovery in complexity theory. The dynamics of dissipative structures specifically include the spontaneous emergence of new forms of order. When the energy of the flow increases, it may happen that the system as a whole encounters a point of instability, known technically as a "bifurcation point," where it can branch off, or "bifurcate," into an entirely new state. *(Section 8.2)*

This spontaneous emergence of new order at critical points of instability, which is nowadays often referred to just as "emergence," is the key characteristic of dynamic self-organization, and is in fact one of the hallmarks of life. It has been recognized as the underlying dynamic of development, of learning, and of evolution. In other words, creativity — the generation of new forms of order — is a key property of all living systems. Nature always reaches out into new territory to create novelty.

The detailed theory of emergence shows that the instabilities and sudden jumps to new forms of order are the result of small fluctuations that are amplified by feedback loops, until the system as a whole becomes unstable. When that happens, it may fall apart because of the instability, but much more frequently it will not break down but break through to a new state of order.

The process of emergence has happened in evolution from the beginning of life. All the structures that were created in this way are all so-called "emergent structures." In fact, biological life itself is the ultimate emergent structure. None of the basic constituents of a living cell are alive by themselves. But when they all came together in a particular pattern of organization, billions of years ago, life emerged and has continued to unfold, producing countless new emergent structures. This continual unfolding of life — in other words, evolution — is the subject of the following lecture.