The Web of Life

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Introduction

In February 1943, the Austrian physicist Erwin Schrödinger, one of the founders of quantum theory, gave a series of three lectures at Trinity College in Dublin with the title "What is Life?". These lectures changed the course of the life sciences. In the lectures, and in the subsequent book with the same title, Schrödinger advanced clear and compelling hypotheses about the molecular structure of genes, which stimulated biologists to think about genetics in a novel way, and in so doing opened a new frontier of science, molecular biology.

Molecular biologists have discovered the fundamental building blocks of life, but this has not helped them to understand the vital integrative actions of living organisms. Twenty-five years ago, one of the leading molecular biologists, Sidney Brenner, made the following reflective comments:

In one way, you could say all the genetic and molecular biological work of the last sixty years could be considered a long interlude... Now that that program has been completed, we have come full circle and back to the problems left behind unsolved. How does a wounded organism regenerate to exactly the same structure it had before? How does the egg form the organism?... I think in the next twenty-five years we are going to have to teach biologists another language... I don't know what it's called yet; nobody knows... It may be wrong to believe that all the logic is at the molecular level. We may need to get beyond the clock mechanisms.[1]

Since the time Brenner made these comments, a new language for understanding the complexity of living systems Ñ - that is, of organisms, social systems, and ecosystems - has indeed emerged. You may have heard about some of the key concepts of this new way of understanding complex systems - chaos, attractors, fractals, dissipative structures, self-organization, and so on.

In the early eighties, I conceived a synthesis of these new discoveries, a new conceptual framework for the scientific understanding of life. I developed and refined my synthesis for ten years, discussed it with numerous scientists, and have recently published it in my new book, *The Web of Life*.

The intellectual tradition of systems thinking, and the models of living systems developed during the early decades of the century, form the conceptual and historical roots of the new scientific framework that I want to present to you tonight. In fact, my synthesis of current models and theories may be seen as an outline of an emerging new theory of living systems. What is now emerging at the forefront of science is a coherent scientific theory that offers, for the first time, a unified view of mind, matter, and life.

Since industrial society has been dominated by the Cartesian split between mind and matter and by the ensuing mechanistic paradigm for the past three hundred years, this new vision that finally overcomes the Cartesian split will have not only important scientific and philosophical consequences, but will also have tremendous practical implications. It will change the way we relate to each other and to our living natural environment, the way we deal with our health, the way we perceive our business organizations, our educational systems, and many other social and political institutions

In particular, the new vision of life will help us build and nurture sustainable communities - the great challenge of our time - because it will help us understand how nature's communities of plants, animals, and microorganisms - the ecosystems - have organized themselves so as so maximize their ecological sustainability. We have much to learn from this wisdom of nature, and to do so we need to become ecologically literate. We need to understand the basic principles of ecology, the language of nature. The new framework I present in my book shows that these principles of ecology are also the basic principles of organization of all living systems. I believe therefore that The Web of Life provides a solid basis for ecological thought and practice.

Emergence of systems thinking

Let me begin my outline of the new understanding of life with a brief historical perspective on the tradition of systems thinking. Systems thinking emerged during the 1920s simultaneously in three different fields: organismic biology, gestalt psychology, and ecology. In all these fields scientists explored living systems, i.e. integrated wholes whose properties cannot be reduced to those of smaller parts. Living systems include individual organisms, parts of organisms, and communities of organisms, such as social systems and ecosystems. Living systems span a very broad range, and systems thinking is therefore by its very nature an interdisciplinary, or better still, "transdisciplinary" approach.

From the beginning of biology, philosophers and scientists had realized that the form of a living organism is more than shape, more than a static configuration of components in a whole. The first systems thinkers expressed this realization in the famous phrase, "The whole is more than the sum of its parts."

For several decades, biologists and psychologists struggled with the question: in what sense exactly is the whole more than the sum of its parts? At that time, there was a fierce debate between two schools of thought, known as mechanism and vitalism. The mechanists said: "The whole is nothing but the sum of its parts. All biological phenomena can be explained in terms of the laws of physics and chemistry." The vitalists disagreed and maintained that a nonphysical entity Ñ a vital force, or field Ñ must be added to the laws of physics and chemistry to explain biological phenomena.

The school of organismic biology emerged as a third way out of this debate. Organismic biologists opposed both mechanists and vitalists. They agreed that something must be added to the laws of physics and chemistry to understand life, but that something, in their view, was not a new entity. It was the knowledge of the living system's organization, or, as they put it, of its "organizing relations."

The systems view of life was formulated first by the organismic biologists. It holds that the essential properties of a living system are properties of the whole, which none of the parts have. They arise from the interactions and relationships between the parts. These properties are destroyed when the system is dissected, either physically or theoretically, into isolated elements. Although we can discern individual parts in any system, these parts are not isolated, and the nature of the whole is always different from the mere sum of its parts. It took many years to formulate this insight clearly, and several key concepts of systems thinking were developed during that period.

The new science of ecology, which began during the 1920s, enriched the emerging systemic way of thinking by introducing a very important concept, the concept of the network. From the beginning of ecology, ecological communities have been seen as consisting of organisms linked together in network fashion through feeding relations. At first, ecologists formulated the concepts of food chains and food cycles, and these were soon expanded to the contemporary concept of the food web.

The "Web of Life" is, of course, an ancient idea, which has been used by poets, philosophers, and mystics throughout the ages to convey their sense of the interwovenness and interdependence of all phenomena. As the network concept became more and more prominent in ecology, systems thinkers began to use network models at all systems levels, viewing organisms as networks of organs and cells, just as ecosystems are understood as networks of individual organisms. This led to the key insight that the network is a pattern that is common to all life. Wherever we see life, we see networks.

Characteristics of systems thinking

Let me now summarize some of the key characteristics of systems thinking. Living systems are integrated wholes, and thus systems thinking implies a shift of perspective from the parts to the whole. The whole is more than the sum of its parts, and what is more is relationships. So systems thinking is thinking in terms of relationships. The shift from the parts to the whole requires another shift of focus, from objects to relationships.

Understanding relationships is not easy for us, because it is something that goes counter to the traditional scientific enterprise in Western culture. In science, we have been told, things need to be measured and weighed. But relationships cannot be measured and weighed; relationships need to be mapped. So here is another shift: from measuring to mapping.

When you map relationships, you will find certain configurations that occur repeatedly. This is what we call a pattern. Patterns are configurations of relationships that appear again and again. The study of relationships, then, leads to the study of patterns. Systems thinking involves a shift of perspective from contents to patterns.

Moreover, mapping relationships and studying patterns is not a quantitative but a qualitative approach. Indeed, in the new mathematics of complexity "qualitative analysis" is now used as a technical term. So systems thinking implies a shift from quantity to quality.

Finally, the study of relationships concerns not only the relationships among the system's components, but also those between the system as a whole and surrounding larger systems. Those relationships between the system and its environment are what we mean by context. The word "context," from the Latin *contexere* - "to weave together," also implies the idea of the web and is perhaps the most appropriate to characterize systems thinking as a whole. Systems thinking is "contextual thinking."

There is another important strand of systems thinking, to which I shall return later. It is thinking in terms of processes, which historically emerged somewhat later. So systems thinking means both contextual thinking and process thinking.

Classical systems theories

The key concepts of systems thinking were developed during the 1920s and 1930s. The 1940s, then, saw the formulation of actual systems *theories*. This means that systems concepts were integrated into coherent theoretical frameworks describing the principles of organization of living systems. These theories, which I call the "classical systems theories," include general systems theory and cybernetics.

General systems theory was formulated in the 1940s by Ludwig von Bertalanffy, an Austrian biologist who set out to replace the mechanistic foundations of science with a holistic vision. Like other organismic biologists, Bertalanffy believed that biological phenomena required a new way of thinking. His goal was to construct a "general science of wholeness" as a formal mathematical discipline.

Bertalanffy's greatest contribution, in my view, was the concept of an "open system" as a key distinction between biological and physical phenomena. Living systems, he recognized, are open systems, which means that they need to feed on a continual flux of matter and energy from their environment to stay alive.

These open systems maintain themselves in a balanced state far from equilibrium, characterized by continual flow and change. Bertalanffy coined the German term *Fliessgleichgewicht* ("flowing balance") to describe such a state of dynamic balance. He recognized that such open systems cannot be described by classical thermodynamics, which was the theory of complex systems available at his time, and he postulated that a new thermodynamics of open systems was needed to describe living systems.

Ludwig von Bertalanffy's concepts of an open system and of a general systems theory established systems thinking as a major scientific movement. In addition, his emphasis on flow and flowing balance introduced process thinking as a new and important aspect of systemic thought. He was not able to write down the new thermodynamics of open systems he was looking for, because he lacked the appropriate mathematics for that purpose. Thirty years later, Ilya Prigogine accomplished this feat, using the a mathematics of complexity that had been formulated in the meantime.

Cybernetics, the other classical systems theory, was formulated by an inter-disciplinary group of scientists, including the mathematicians Norbert Wiener and John von Neumann, the neuroscientist Warren McCulloch, and the social scientists Gregory Bateson and Margaret Mead.

Cybernetics soon became a powerful intellectual movement, which developed independently of organismic biology and general systems theory. The central focus of the cyberneticists was the attention to patterns of organization. In particular, they were concerned with patterns of communication, especially in closed loops and networks. Their investigations led them to the concepts of feedback and self-regulation, and then, later on, to self-organization.

The concept of feedback, one of the greatest achievements of cybernetics, is intimately connected with the network pattern. In a network, you have cycles and closed loops; and these loops can become feedback loops. A feedback loop is a circular arrangement of causally connected elements, in which an initial cause propagates around the links of the loop, so that each element has an effect on the next, until the last "feeds back" the effect into the first element of the cycle.

The feedback phenomenon is extremely important for living systems. Because of feedback, living networks can regulate themselves and can organize themselves. A community, for example, can regulate itself. It can learn from its mistakes, because the mistakes will travel and come back along these feedback loops. So, the community can organize itself and can learn. Because of feedback, a community has its own intelligence, its own learning capacity.

So, networks, feedback, and self-organization are closely linked concepts. Living systems are networks capable of self-organization.

The new mathematics of complexity

And now I come to the most important point of my brief historical review. There is a watershed in systems thinking between the classical systems theories of the 1940s and the theories of living systems developed during the past 25 years. The distinctive feature of the new theories is a new mathematical language that allowed scientists for the first time to handle the enormous complexity of living systems mathematically.

We need to realize that even the simplest living system, a bacterial cell, is a highly complex network involving literally thousands of interdependent chemical reactions. A new set of concepts and techniques for dealing with that enormous complexity has now emerged, which is beginning to form a coherent mathematical framework. Chaos theory and fractal geometry are important branches of this new mathematics of complexity.

The crucial characteristic of the new mathematics is that it is a nonlinear mathematics. In science, until recently, we were always taught to avoid nonlinear equations, because they are very difficult to solve. For example, the smooth flow of water in a river, in which there are no obstacles, is described by a linear equation. But when there is a rock in the river the water begins to swirl; it becomes turbulent. There are eddies; there are all kinds of vortices; and this complex motion is described by nonlinear equations. The movement of water becomes so complicated that it seems quite chaotic.

In the 1970s, scientists for the first time had powerful high-speed computers that could help them tackle and solve nonlinear equations. In doing so, they devised a number of techniques, a new kind of mathematical language that revealed very surprising patterns underneath the seemingly chaotic behavior of nonlinear systems, an underlying order beneath the seeming chaos. Indeed, chaos theory is really a theory of order, but of a new kind of order that is not visible to the naked eye but is revealed by this new mathematics.

When you solve a nonlinear equation with these new techniques, the result is not a formula but a visual shape, a pattern traced by the computer. So, the new mathematics is a mathematics of patterns, of relationships. The so-called "attractors" are examples of these mathematical patterns. They picture the dynamics of a particular system in terms of visual shapes.

During the 1970s, the strong interest in nonlinear phenomena generated a whole series of new and powerful theories that describe various aspects of living systems. These theories, which I discuss in some detail in the book, form the components of my own synthesis of the new conception of life.

A new synthesis

I have come to believe that the key to a comprehensive theory of living systems lies in the synthesis of two approaches to our understanding of nature that have been in competition throughout our scientific history - the study of pattern (or relationships, order, quality) and the study of structure (or constituents, matter, quantity).

The emergence and refinement of the concept of "pattern of organization" has been a central theme in systems thinking. The early systems thinkers defined pattern as a configuration of relationships. The ecologists recognized the network as the general pattern of life. The cyberneticists identified feedback as a circular pattern of causal links; and the new mathematics of complexity is a mathematics of visual patterns.

So, the understanding of pattern is of crucial importance to the scientific understanding of life. But that is not enough. We also need to understand the system's structure. To show you how the pattern approach and the structure approach can be integrated, let me now define these two terms more precisely.

The pattern of organization of any system, living or nonliving, is the configuration of relationships among the system's components that determines the system's essential characteristics. In other words, certain relationships must be present for something to be recognized as - say - a chair, a bicycle, or a tree. That configuration of relationships that gives a system its essential characteristics is what I mean by its pattern of organization.

Let me illustrate this with a bicycle, because it is easier with a nonliving system. If I took all the parts of a bicycle - the saddle, the handle bars, the frame, the wheels, and so on - and put them here in front of you in a heap, you would all say: This is not a bicycle; these are the parts of a bicycle. How do I turn them into a bicycle? By putting them together *in a certain order*! This order, this configuration of relationships among the parts, is what I call the pattern of organization.

To describe the bicycle's pattern of organization, I can use an abstract language of relationships. I don't need to tell you whether the frame is made of heavy iron or light aluminium, what kind of rubber went into the tires, and so on. In other words, the physical materials are not part of the description of the pattern of organization. They are part of the description of the structure, which I define as the material embodiment of the system's pattern of organization.

Whereas the description of the pattern of organization involves an abstract mapping of relationships, the description of the structure involves describing the system's actual physical components - their shapes, chemical compositions, and so on.

Well, this is all quite simple with a bicycle. You can visualize its pattern of organization, you can draw a sketch of it, you can get the actual materials and build the bicycle according to your design sketch, and then the bicycle will just stand there and will not do much on its own.

With a living system, the situation is very different. Every living system, as I mentioned before involves thousands of interlinked chemical processes. In a living system, there is a ceaseless flux of matter; there is growth, development, and evolution. From the very beginning of biology, the understanding of living structure has been inseparable from the understanding of metabolic and developmental processes.

This striking property of living systems suggests process as a third criterion for a comprehensive description of the nature of life. The process of life is the activity involved in the continual embodiment of the system's pattern of organization. Thus the process criterion is the link between pattern and structure.

The process criterion completes the conceptual framework of my synthesis. All three criteria are totally interdependent. The pattern of organization can only be recognized if it is embodied in a physical structure, and in living systems this embodiment is an ongoing process. One could say that the three criteria - pattern, structure, and process - are three different but inseparable perspectives on the phenomenon of life. They form the three conceptual dimensions of my synthesis.

What this means is that, in order to define a living system - in other words, to answer Schrödinger's question, "What is Life?" - we have to really answer three questions: What is the structure of a living system? What is its pattern of organization? What is the process of life? Let me now answer these questions in that order.

Dissipative structures

The structure of a living system has been described in detail by Ilya Prigogine in his theory of dissipative structures. Like Ludwig von Bertalanffy, Prigogine recognized that living systems are open systems that are able to maintain their life processes under conditions of non-equilibrium. A living organism is characterized by continual flow and change in its metabolism, involving thousands of chemical reactions. Chemical and thermal equilibrium exists when all these processes come to a halt. In other words, an organism in equilibrium is a dead organism. Living organisms continually maintain themselves in a state far from equilibrium, which is the state of life. Although very different from equilibrium, this state is nevertheless stable: the same overall structure is maintained in spite of the ongoing flow and change of components.

Prigogine called the open systems described by his theory "dissipative structures" to emphasize this close interplay between structure on the one hand, and flow and change (or dissipation) on the other.

According to Prigogine's theory, dissipative structures not only maintain themselves in a stable state far from equilibrium, but may even evolve. When the flow of energy and matter through them increases, they may go through points of instability and transform themselves into new structures of increased complexity. This phenomenon - the spontaneous emergence of order - is also known as self-organization. It is the basis of development, learning, and evolution.

Autopoiesis

Let me now turn to the second perspective on the nature of life, the pattern perspective. The pattern of organization of a living system is a network of relationships in which the function of each component is to transform and replace other components of the network. This pattern has been called "autopoiesis" by Humberto Maturana and Francisco Varela. "Auto", of course, means "self", and "poiesis" - which is the same Greek root as in the word "poetry" - means "making". So autopoiesis means "self-making." The network continually "makes itself." It is produced by its components and in turn produces those components.

Cognition - the process of life

Let me now turn to the third conceptual dimension of my synthesis, the process aspect. The understanding of the life process is perhaps the most revolutionary aspect of the emerging theory of living systems, as it implies a new conception of mind, or cognition. This new conception was proposed by Gregory Bateson and elaborated more completely by Maturana and Varela, and it is known as the Santiago theory of cognition.

The central insight of the Santiago theory is the identification of cognition, the process of knowing, with the process of life. Cognition, according to Maturana, is the activity involved in the self-generation and self-perpetuation of living networks. In other words, cognition is the very process of life. "Living systems are cognitive systems," writes Maturana, "and living as a process is a process of cognition."

It is obvious that we are dealing here with a radical expansion of the concept of cognition and, implicitly, the concept of mind. In this new view, cognition involves the entire process of life - including perception, emotion, and behavior - and does not necessarily require a brain and a nervous system. In the human realm, cognition includes language, conceptual thought, self-awareness, and all the other attributes of human consciousness.

The Santiago theory of cognition, I believe, is the first scientific theory that overcomes the Cartesian division of mind and matter, and will thus have the most far-reaching implications. Mind and matter no longer appear to belong to two separate categories, but can be seen as representing two complementary aspects of the phenomenon of life - the process aspect and the structure aspect. At all levels of life, beginning with the simplest cell, mind and matter, process and structure, are inseparably connected. Mind is immanent in living matter as the process of self-organization. For the first time, we have a scientific theory that unifies mind, matter and life.

Transcript taken from: http://www2.tcd.ie/Physics/Schrodinger/Lecture3.html

1. Brenner quote from Judson HF, The Eighth Day of Creation, Simon and Schuster, NY, 1979 pp 209,220