Self-Organizing Systems: A Unifying Paradigm for Science Education

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> "Nature, in the systems view, is a sphere of complex and delicate organization. Systems communicate with systems and form supersystems. Strands of order appear and out of increasingly complex levels of organization novel properties emerge." (Lazslo, 1947, p. 74)

Abstract

For the past 20 years science education standards have advocated the use of crosscutting concepts to communicate that science is a unified endeavor. One of the crosscutting concepts that survived multiple iterations of standards is the idea of systems. This paper extends the fundamental idea of systems in multiple fields and at multiple scales to the concept of self-organizing systems (SOS)—a universal process that results in the emergence of new structures, properties, and processes. The purpose of the paper is to serve as a springboard for discussion among high school science teachers who are willing to step outside the traditional boundaries of their discipline to explore the concept of self-organizing systems as a means of helping their students achieve a coherent science-based world-view.

Key Words: High School, Multi-disciplinary Approach, Systems Approach, Nature of Science, Integrated Science

Introduction

As science teachers our aim is to help our students understand the big ideas that cut across and unify all of the sciences. But our predecessors have already dissected the body of scientific knowledge into distinct parts. Reductionism started there. We, ourselves, are products of the system that makes of us teachers of Biology, Chemistry, Physics, or (less frequently) Earth and space science.

Despite fragmentation of the various fields of science, each of the documents that have attempted to describe what all students should know have included a few essential ideas about the nature of science, variously called "themes," "unifying principles," and more recently "crosscutting concepts." A crosscutting concept that survived the test of time is *systems.* In describing what it refers to as *Systems and System Models A Framework for K-12 Science Education* (NRC, 2012) urges that students should learn about systems beginning in elementary school: "Starting in the earliest grades, students should describe objects or organisms in terms of their parts and the roles those parts play in the functioning of the object or organism, and they should note relationships between the parts" (NRC, 2012, p. 93)

The *Framework* includes the idea that systems have boundaries, inputs, outputs, and flows, that systems interact with other systems, that systems exist at vastly different scales, and that students should use models and simulations to represent systems. It also notes a new aspect of systems not mentioned in the previous documents: emergence —"the properties and behavior of the whole system can be very different from those of any of its parts, and large systems may have emergent properties, such as the shape of a tree, that cannot be predicted in detail from knowledge about the components and their interactions." (NRC, 2012, p. 92)

A Broader Vision of Systems

Although nature is one place, we have divided her into subjects in order to fit into the constraints of the high school curriculum. Since the subjects have different names and are taught at different times, few students see the connections among them. The systems view of nature, in particular the knowledge of self-organizing systems (SOS), has the potential to establish a vision of the universe as an interconnected whole. We claim that science teachers can help students achieve that unity and view nature whole without adding significantly to their teaching load.

The vision of self-organizing systems has its roots in the voice of Julian Huxley who wrote that the underlying process of all nature is evolution: "if we define evolution as a self-operating, self-transforming process that in its course generates both greater variety and higher levels of organization. It has three phases, inorganic or cosmological, the organic or biological, and the human or psychosocial." (Huxley, 1957)

Today we can extend Huxley's vision through the scale of physical size, starting with the self-organization of quarks and electrons into atoms; of atoms into molecules; of molecules into compounds; of compounds into cells — and leaping over the many self-organizational steps involved in the emergence and development of life, both individual and societal – we can see self-organization in the formation of stars, planetary systems and galaxies. The universe itself is a huge self-organizing system.

A Few Words to Activate the Systems View

System: a group of parts so linked together by interactions that the group functions as a whole. Any group of interacting parts constitutes a system. This applies to quarks and gluons functioning as a proton as well as galactic superclusters.

Self-organization: a broad range of pattern-formation processes in both physical and biological systems that occur through interactions internal to the system, without any intervention by external influences. (Camazine, 2003, p. 7)

Complexity: Although there is no consensus on the exact meaning of this term, a common meaning may serve: something is complex when there are a great number of interacting elements with many interconnections. (Golden, 1997, p. 24)

Emergence: the process whereby new and unexpected structures, processes and properties come into existence from the synergetic combination of simpler structures and processes. (Golden, 1997, p. 32)

Organizing principle: those forces and/or processes, which are necessary to bring and hold parts together to form systems. Examples include gravity, electromagnetism, evolution, chemical bonding, and convection.

Although much is to be learned about how novel structures and properties emerge, some parts of the process seem obvious. Fundamental organizing principles (laws of nature) operate on matter and energy, creating the systems that we observe today. Over time these systems become more complex. There is a tendency in the universe for systems to combine with other systems and produce new states of organized complexity. This is a
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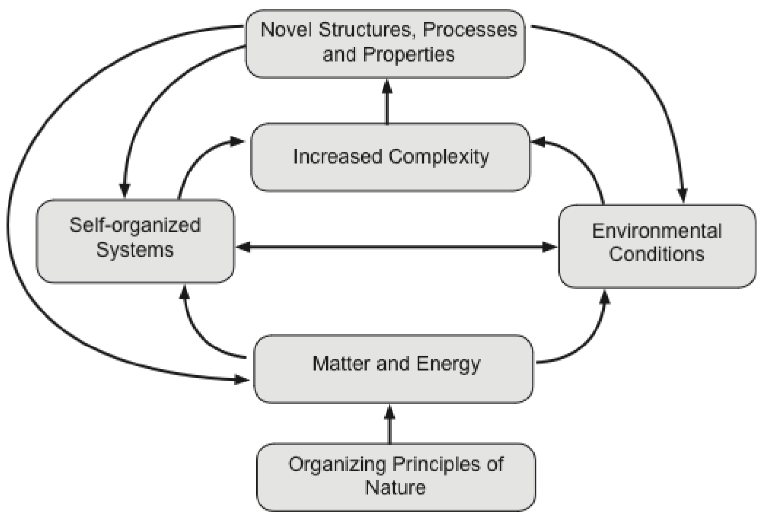

Figure 1. The process of emergent evolution

Emergent evolution, what an evocative phrase! Evolution as used here is more than Darwinian. It is not limited to living organisms but rather incorporates them and relates to the formation of everything. The novel structures, processes and properties produced through emergent evolution have feedback effects on matter and energy, which can result in new self-organized systems of further increased complexity. Changes that work tend to continue. Those that fail disappear. The survivors produce changes in the environment, which trigger changes in systems. This feedback process is self-sustaining as long as there is input of energy. It brings new things into the universe.

Applying the concepts in the classroom

With the terms system, self-organization, complexity, emergence, and organizing principle floating in the air almost any topic in the science classroom can be seen as a system. MConsider atoms self-organizing into molecules. The property we call sweetness is nowhere to be found in carbon, hydrogen or oxygen atoms but through organization the property emerges. Molecules combine to form cells. Neurons self-organize into a vast complex collection we call the brain and, finally, consider the novel emerging property called consciousness.

We science teachers, more than teachers of other disciplines, are engaged in teaching how systems work. What is science itself but the search for organizing principles (scientific laws) and obtaining the knowledge of how they function in the world? The great organizing principle of gravity constructs the cosmological universe. By ruthless elimination the organizing principle of evolution produces the different species of living things so exquisitely suited to their environment. The self-organization of protons, neutrons and electrons produce the order of the periodic table of the elements. The way of nature is self-organization.

A biology teacher just finishing a unit on cell structure might review the day's lesson by asking: What are the parts of the cell? How does the function of each part contribute to the overall function of the cell? (self-organization) What can the cell do now that it couldn't do before the parts got to work together? (emergence of new properties) Is there some general principle here that works to organize living structures and make them functional in their environment? (organizing principle – evolution) Students can describe how the cell now has the potential to join with other cells and form larger structures with new functions (a living organism – some of them with the new property of consciousness).

A chemistry teacher completing a discussion of le Chatelier's principle can ask her students how this principle might apply to systems other than chemical ones. How, for example, it might apply to a biological system? Or to a cosmological system?

A physics teacher after teaching about the functions of resistors, capacitors and transistors can ask: What new property emerges when the parts are arranged in a particular way? The resonant frequency of the circuit is an emergent property. A reference to the fact that both temperature and pressure are emergent properties of a collection of gaseous molecules can point to the self-organizing systems view.

Conclusion

It is hard to conceive of any structure that performs a function that is not a system. "Everything is connected to everything else" seems almost true. Gravity is ubiquitously involved in the organization of all of the macro-world and the laws of electromagnetism hold the micro-world together. Biology is all about self-organized systems. When students recognize how new things come into being the world becomes a different place. Many seemingly disjointed effects can more easily be related to their causes. The role of science in general becomes clearer.

"The study of scientific fact contributes to the growth of knowledge but the study of scientific principle contributes to the development of understanding." (Zwick, 2013) In later life a student may be able to apply the systems view of things to a seemingly intractable problem and recognize how a novel and unexpected result emerged.

Some students may be fortunate to experience the kind of epiphany E. O. Wilson describes when he suddenly saw evolution as the grand organizing principle of all life. (Wilson, 1998) Ideas of self-organizing systems, emergence and organizing principles can provide a unifying theme to science teaching. And, most importantly, evoke in students' minds a coherent view of nature.

Readers who wish to dive deeper into self-organizing systems can download a PDF monograph on self-organizing systems by author Richard Golden at http://self-organizing-systems.net.

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