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Modeling Students Modeling Abilities: The Teaching and Learning of Complex Systems in Education

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The Tao that can be told is not the eternal Tao. (Lau Tsu, Tao Te Ching)

The word Tao usually is translated as way or path, but it refers to the deep structure of patterns and regularities beneath surface-level experiences. Similarly, Taoists use the terms naming or telling to refer to nearly any formal statement, proposition, or rule. So, for our purposes here, a particularization of Lao Tsu’s famous saying might be: The structure of things that can be reduced to a formal statement, proposition, or rule is not the true structure of things. … This is, or should be, the central challenge that confronts learning scientists who hope to create models of the models (and/or underlying conceptual systems) that students develop to make sense of complex systems that occur in their lives. The challenge occurs because of the following mismatch. On the one hand, many currently prevailing cognitive science theories continue to rely implicitly (if not explicitly) on mechanistic information processing metaphors in which everything that students know is reduced to lists of condition–action rules. On the other hand, the most fundamental (systemic) characteristics of complex systems cannot be explained (or modeled) using only a single function—or even a list of functions; they arise from interactions among lower order/rule-governed agents—which function simultaneously and continuously, and which are not simply inert objects waiting to be activated by some external source. It is here where I think learning scientists could really have an impact, especially in understanding how to teach and learn about complex systems.
Jacobson and Wilensky’s article provides a review of the literature by several researchers who have been seeking to understand students’ sense-making abilities related to complex systems, and Wilensky’s NetLogo Project (http://ccl.northwestern.edu/netlogo/) and Web site provide an excellent set of resources to introduce learning scientists to the important characteristics of this class of systems. In particular, the Web site provides a variety of understandable and powerful examples of concepts such as emergent properties, self-organization, and levels or hierarchies of interacting agents associated with complex systems. Though I agree with Jacobson and Wilensky on the importance of understanding how people learn about complex systems, I do not view current learning science theories as being sufficient to provide answers to most questions about the nature of the conceptual systems that students would need to develop to understand complex systems. In contrast, I believe that the most exciting point about learning science investigations of complex systems is precisely that such research is likely to require a variety of significant paradigm shifts beyond current ways of thinking. Furthermore, I believe that these paradigm shifts should have implications for learning and problem solving related to a wide range of constructs and situations where relationships to systemic understandings are far less obvious than in the case of complex systems.

To support these claims, it is useful to distinguish among three kinds of complex systems: (a) “real life” systems (or simulations of such systems) that occur (or are created) in everyday situations; (b) conceptual systems that humans develop to design, model, or make sense of the preceding “real life” systems; and (c) models that researchers develop to describe and explain students’ modeling abilities. These three types of systems correspond to three reasons why the study of complex systems promises to be especially productive for researchers who are attempting to advance theory development in the learning sciences. First, in a technology-based age of information, complex systems are important objects of study in their own right—not only because such systems are important “objects” that impact the lives of ordinary people, but also because (mis)understandings about them underlie a great many beliefs, principles, policies, and processes that need to be understood for informed citizenship—and for ethical behavior in complex societies. Second, precisely because knowledge about such systems is not likely to be reducible to lists of simple closed-form functions, investigations of what it means to understand such systems should provide productive venues to advance relevant learning science theories. Furthermore, complexity theory introduces a wealth of language, models, metaphors, and tools that provide alternatives to traditional rule-based ways of thinking about the nature of knowledge, learning, and problem solving. Third, the kind of “systemic understandings” that are highlighted in the context of complex systems also are involved in the development of many other types of concepts, skills, principles, beliefs, and attitudes, and problem solving processes that are not as obviously systemic in nature.
WHAT ARE DISTINCTIVE RELEVANT CHARACTERISTICS OF COMPLEX SYSTEMS?

One of the simplest examples of a complex system is a double pendulum—a dynamic version of which can be seen at http://www.maths.tcd.ie/~plynch/SwingingSpring/doublependulum.html. A significant fact about double pendulums is that each of their two components obeys simple rules; yet, when the components function simultaneously and interact, the interactions lead to chaotic (unpredictable) behavior. A second fact is that, for these interactions to occur, the components need to be dynamic and continuously functioning. That is, they are like living entities (which act on other things) rather than being simply machine-like objects (which are acted on). They are not simply inert objects waiting to be turned on; they are actively functioning and “seek out” interactions. The point here is not that the agents in complex systems need to have the kind of “life spirit” that is associated with biological organisms. The points are that (a) properties of a system that result from interactions among its agents are not the same as properties that can be logically deduced from properties of the agents, and (b) properties that result from interactions do not occur in systems where the relevant agents are not “in action” (rather than being inert and waiting to be “turned on”).

In fact, most “complex systems” that readers are likely to encounter on Web sites or in print are similar to the double pendulum in the sense that they are only complex at the uppermost level. That is, the systems themselves are complex even though their constituent parts obey fairly simple functional rules. Such systems can be referred to as being “simply complex” to contrast them with the kind of “deeply complex” systems that abound in “real life” systems (such as ecological systems, economic systems, or biological systems). . . . In deeply complex systems, neither the systems-as-a-whole nor their constituent parts obey simple functional rules. In fact, additional layers of complexity tend to emerge as far down as researchers are able to crank their microscopes of inquiry—perhaps because the “agents” within the system often are living organisms or ecosystems governed by wetware that obeys logics that are distributed, multimedia, and fuzzy, and that, in general, are not characterized by simple, linearly combined, or concatenated hardware/software-based rules.

In spite of obvious differences between realistically complex systems and their counterparts in toy worlds, models that researchers develop to explain peoples’ thinking about the latter should provide useful ways of thinking-about-thinking for more realistic systems. One reason this is true is because similar factors (such as emergent properties, self-organization, and levels or hierarchies of interacting agents) tend to occur in both types of systems. Also, research on complex systems is filled with examples illustrating the point that more complex or elaborate systems are not always more difficult to describe or explain mathematically. For example, in the literature on complex systems, the three-bodies problem (which in-
volves an idealization of the interactions of the sun, earth, and moon) continues to be an unsolved problem in mathematics, whereas *the n-bodies problem* was solved long ago.

WHAT ARE REASONABLE ASSUMPTIONS ABOUT THE NATURE OF CONCEPTUAL SYSTEMS THAT HUMANS DEVELOP TO MAKE SENSE OF COMPLEX SYSTEMS?

In virtually every field where ethnographic studies have been conducted to compare experts and novices, results have shown that experts not only *do* things differently from novices, but they also *see* things differently. Therefore, to understand what it means to understand complex systems, key questions for learning scientists to ask are *What is the nature of the conceptual systems that are needed to interpret (describe, explain) experiences involving complex systems? How do these conceptual systems develop? How can development be facilitated and assessed?*

In mathematics and science, conceptual systems that humans develop to make sense of their experiences generally are referred to as models. A naive notion of models is that they are simply (familiar) systems that are being used to make sense of some other (less familiar) systems—for some purpose. For example, a single algebraic equation may be referred to as a model for some system of physical objects, forces, and motions. Or a *Cartesian Coordinate System* may be referred to as a model of space—even though a *Cartesian Coordinate System* may be so large that it seems to be more like a language for creating models rather than being a single model in itself. But in any case, the main point of this initial conception of a model is that, in mathematics and science, modeling is primarily about purposeful description, explanation, or conceptualization (quantification, dimensionalization, coordinatization, or in general mathematization)—even though computation and deduction processes also are involved. An obvious shortcoming of the preceding conception of a model is that it puts far too much emphasis on the external or observable manifestations of models, whereas, from the point of view of learning scientists, the most interesting aspects of models are the underlying conceptual systems that they embody.

*What are reasonable assumptions to adopt (or avoid) about the nature of these conceptual systems?* Modern learning scientists have been breathing new life back into a variety of perspectives that were emphasized long ago by *American Pragmatists* such as Dewey, James, Meade, and Pierce—but that often have been neglected during the era when mechanistic *information-processing* descriptions of cognition were preeminent. For example, (a) Dewey and Meade emphasized that conceptual systems are human construct, and that they also are fundamentally social in nature. (b) Pierce emphasized that the meanings of these constructs tend to be distributed across a variety of representational media (ranging from spoken language, written
language, to diagrams and graphs, to concrete models, to experience-based metaphors)—each of which emphasize and ignore somewhat different aspects of the constructs they are intended to express and/or the “real life” experiences they are intended to describe. (c) Dewey emphasized that knowledge is organized around experience at least as much as around abstractions—and that the ways of thinking that are needed to make sense of realistically complex decision-making situations nearly always must integrate ideas from more than a single discipline, or textbook topic area, or grand theory. (d) James emphasized that the “worlds of experience” that humans need to understand and explain are not static. They are, in large part, products of human creativity. So they are continually changing—and so are the knowledge needs of the humans who created them. (e) Dewey emphasized that, in a world filled with technological tools for expressing and communicating ideas, it is naive to suppose that all “thinking” goes on inside the minds of isolated individuals. For example, at least since the age of written media, mathematicians have been off-loading formerly internal functions. Furthermore, models and other conceptual tools seldom are worthwhile to develop unless they are intended to be sharable (with other people) and reusable (in other situations beyond the one in which they were created).

The preceding observations stress the fact that, even though the models and conceptual systems that humans develop to make sense of complex systems must have some properties in common with the systems they are intended to describe or explain, they do not need to be like internal copies of the external systems that they are used to describe—no more so that equations are photograph-like copies of the systems they describe. Nonetheless, to have adequate explanatory power, useful models of complex systems should be based on at least three assumptions and principles: (a) Their most important properties cannot be derived from a list of simple functional rules, (b) knowledge about them tends to be both situated (e.g., organize around experience as much as around abstractions) and distributed (e.g., socially, representationally, and epistemologically), and (c) they meaningfully capture and illuminate some properties of the world.

WHAT CHARACTERISTICS OF COMPLEX SYSTEMS ARE PRIORITIES TO UNDERSTAND IN A TECHNOLOGY-BASED AGE OF INFORMATION?

As we enter the 21st century, many of the most powerful “things” that impact the lives of both professionals and ordinary people are systems—ranging from communication systems, to economic systems, to ecological systems, to the kind of systems that underlie the design of complex artifacts such as continually adapting learning organizations. Some of these systems occur naturally, whereas others are created by humans. Some are mathematically complex, whereas others are not. And some go
beyond being complex to also involve self-regulation and continual adaptation. That is, they are both complex and adaptive systems. … But, in any case,

- In an age of increasing globalization, local decisions often impact remote locations where reactions may lead to feedback loops whose second-order effects dwarf local first-order effects. So people who understand and anticipate such situations are less likely to be victimized by unforeseen events.
- In knowledge economies, the most important resources that many companies or individuals possess often consist of conceptual systems for creating, manipulating, predicting, and (perhaps) controlling a variety of different kinds of complex systems. For example, in the past, a key attribute of a prototypically successful business was to have a large inventory of resources on hand, whereas today, an essential goal of many knowledge industries is to have absolutely no merchandise sitting in warehouses or on shelves. The goal is to make the connection as rapid, efficient, and effective as possible between suppliers and consumers. So powerful models (and the underlying conceptual systems that they embody) for designing or making sense of complex systems are, in themselves, important “pieces of knowledge” that are valued highly.
- In learning organizations, the conceptual systems that humans develop to make sense of their experiences also are used to mold and shape the world in which these experiences occur. In other words, humans are continually projecting their conceptual systems into the world. So the world that needs to be understood is not one that has remained unchanged since the beginning of recorded history. It is a world that is continually and rapidly changing, for these reasons: (a) The understandings and abilities that are needed to make sense of such situations also are changing and (b) the kind of knowledge and information that is most powerful often involves models for creating, manipulating, and making sense of complex systems.

All of the preceding situations involve emergent properties of complex systems. That is, they involve properties that only become meaningful in the context of some functioning system-as-a-whole. For example, if we study traffic patterns in a city, then gridlock (or the wave-like patterns of traffic flow) are properties of the system-as-a-whole. They occur because of the way automobiles interact. Similarly,

- Objects such as leverage points, discontinuity points, and attractors acquire significance only due to their functions within systems-as-a-whole.
- Irreversibility/reversibility, feedback loops, and resonances are characteristics of systems-as-a-whole; they are not characteristics of isolated agents or objects within the systems.
- Patterns, regularities, invariance properties, and force fields are properties of systems-as-a-whole; they are not properties of isolated agents or objects within the systems.
• Optimization, minimization, maximization are goals within systems of interactions.

In each of these cases, the whole is more than the sum of its parts. So the key to understanding what it means to understand emergent properties of complex systems is, in part, to understand what it means to understand the systems-as-a-whole from which they gain their meanings; this is true even for systems that do not qualify as being mathematically complex. Therefore, if investigations of complex systems clarify what it means to understand emergent properties, and if emergent properties are important even for systems that are not mathematically complex, then the significance of research on complex systems should extend to these latter types of situations.

It is my belief that investigations of what it means to “understand” complex systems has important implications for other kinds of concepts and abilities. For example, Piaget’s research provides a wealth of examples of emergent properties that occur in the context of systems that are not mathematically complex. Piaget’s famous “conservation tasks” (about quantities such as number, area, volume, or mass) are about invariance properties of specific systems of operations and/or relations. In other words, conservation tasks are about properties whose significance only occurs if children’s thinking is based on well-organized systems of operations and relations. Consequently, such invariance properties are emergent properties of the relevant systems; for this reason, the aim of Piaget’s research was to clarify the nature of these systems. In contrast, many cognitive scientists interpreted Piaget’s tasks as if they involved nothing more than some curious type of rule-based learning. So when these researchers “taught” the rules without doing anything to help children develop the relevant underlying conceptual systems, their results tended to be similar to what happens when a teacher attempts to teach rules about inertia without helping students develop relevant conceptual systems that involve systems of forces. That is, the rules only apply to a very restricted set of situations, and they seldom generalize beyond these situations.

Mathematical constructions are similar to, and yet significantly different from, psychological developments. For example, whereas mathematicians have the luxury of beginning with undefined terms, human learners do not. Nonetheless, in both cases, all of the mathematical meanings of mathematical “undefined terms” come from the systems in which they are embedded. Similarly, using conservation tasks that consist of concrete and acted-out versions of the preceding axioms, Piaget demonstrated that the notation of a unit (of number, length, area, volume, etc.) is not the starting point for the development of students’ early quantitative understandings. Instead, concepts of units evolve simultaneously with the development of relevant operational/relational systems-as-a-whole.

Piaget’s general intent was to demonstrate that one of the foremost characteristics that distinguish mathematical concepts from those in other sciences is that vir-
tually all mathematical concepts involve emergent properties of conceptual system-as-a-whole. That is, (a) mathematics is not just about learning lists of rules and (b) thinking mathematically is about describing (or conceptualizing) situations at least as much as it is about processing information (which already has been mathematized).

**SUMMARY**

In this brief review, I have built on the Jacobson and Wilensky article by emphasizing four points. First, investigations about what it means to “understand” complex systems is important in its own right because, in the 21st century, such systems are becoming increasingly important in the everyday lives or ordinary people. Second, investigations of such systems should have implications far beyond the topic of complex systems because “systemic understandings” that are highlighted in the context of complex systems also are involved in the development of many other types of concepts, skills, principles, beliefs, attitudes, and problem-solving processes that are not as obviously systemic in nature. Third, investigations of what it means to “understand” such systems should provide productive venues to advance learning science theories precisely because knowledge about such systems is not likely to be reducible to lists of simple closed-form functions. Fourth, complexity theory introduces a wealth of language, models, metaphors, and tools that could provide very productive alternatives to traditional rule-based ways of thinking about the nature of knowledge, learning, and problem solving (more details about each of these topics can be found in a book on *Foundations for the Future in Mathematics & Science Education*). We are at an exciting time in which a paradigmatic shift has been occurring in many fields regarding complex systems. Learning scientists are uniquely positioned to understand the implications of this shift, especially as it relates to facilitating the learning of and about these complex systems as well as how complex systems principles can inform our understanding of how people learn.

**REFERENCE**