Complex Systems in Education: Conceptual Principles, Methodologies, and Implications for Research in the Learning Sciences

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Abstract. The symposium has two main goals: First, it would allow the contributors to the recent JLS special issue on complex systems in education to provide an overview of the issues raised in their respective papers as well as to discuss updated research of relevance. Second, it is hoped that this symposium will provide a forum for discussing the potential implications of complex systems perspectives for research in the learning sciences, and more generally for educational research, curriculum development, and educational policy and reform initiatives.

Symposium Overview

The Journal of the Learning Sciences (JLS) has recently inaugurated a series of research strands on timely and developing issues (Kolodner, 2003). Each of these strands is to have an orienting paper and commentaries as part of a special issue that would help contextualize and perhaps guide subsequent research papers submitted to the strand over the next few years. One of the initially identified strands is learning and school environments as complex systems, for which a special issue has recently appeared in the JLS (Azevedo & Hmelo, 2006; Goldstone, 2006; Jacobson & Wilensky, 2006; Lesh, 2006; Sabelli, 2006) that is the focus of this symposium.

As background to this session, there are four thematic perspectives that emerge from the papers. First, there is a growing body of research that is documenting how students at the pre-graduate school level can in fact learn dimensions of core knowledge that are being articulated by scientists who study complex physical and social systems. While this is an important general finding in itself, a second argument is that helping students learn complex systems principles may also address other long standing research issues and learning challenges, such as how best to help students learn knowledge in deep and meaningful ways, how to help students apply or use this knowledge in new and different contexts, and what are the boundaries of knowledge and conceptual difficulty that students at particular ages and developmental levels might be capable of learning. Third, concepts derived from a complex systems analytical perspective have the potential to provide a degree of conceptual coherence to the otherwise bewildering properties of diverse phenomena in the physical and social sciences. Thus it may be that infusing complex systems concepts into the curricular content of school subjects could form the basis of a new type of scientific literacy that also would have important implications for how curricula in the physical and social sciences are developed and sequenced across grade levels from elementary school to college. Fourth, there are concepts and methodologies being articulated by scientists in the physical and social sciences who are involved with advanced complex systems research that raise important issues of theoretical and methodological centrality in the learning sciences and in fields involved with research in education and educational policy.

Presentation Overviews

Complex Systems In Education: Importance, Implications, and Issues

Michael J. Jacobson, National Institute of Education, Nanyang Technological University

The multi-disciplinary study of complex systems in the physical and social sciences over the past quarter of a century has led to the articulation of important new conceptual perspectives and methodologies that are of value both to researchers in these fields as well as to professionals, policy makers, and citizens who must deal with challenging social and global problems in the 21st century. This presentation will: (a) argue for the importance of
learning these ideas at the pre-college and college levels; (b) discuss the significant challenges inherent in learning complex systems knowledge from the standpoint of theory and research; (c) argue that the cognitive and socio-cultural factors related to learning complex systems knowledge are relevant and challenging areas for learning sciences research; and (d) consider ways that concepts and methodologies from the study of complex systems raise important issues of theoretical and methodological centrality in the fields related to the learning sciences. Also, this paper provides a background for issues that will be considered in other papers in this session.

**Complex Systems and Reformulating Scientific Disciplines: Implications for Learning, Analysis of Social Systems, and Educational Policy**

*Uri Wilensky, Northwestern University*

A complex systems perspective has enabled scientists to study a wide variety of systems in principled ways that had not previously been possible and, in turn, this has also lead to a deepening of our understanding of the connections between scientific disciplines. However, of perhaps even greater potential impact for student learning of new scientific views of complex systems is the ability to replace traditional algebraic or mathematical formalisms with computational representations. In particular, it is now possible to understand important aspects of how systems function and dynamically change in terms of many simple rules using technologies such as cellular automata and agent-based modeling instead of through the listing of differential equations. An important advantage of this approach is that it enables scientists and learners to conceptually and visually “see” the explicit connections between the micro level behaviors and the macro level phenomena. A complex systems perspective means that in helping our students to learn important knowledge in the physical and social sciences, we no longer have to be content with descriptions of only the aggregate level of phenomena (e.g., birds flocking, neighborhood segregation patterns), but instead can also explore mechanisms related to micro level interactions (the behavior of an individual bird or individual house-dweller). An important consequence of these developments is that the reformulation of scientific disciplines (also referred to as restructurations (Wilensky & Papert, 2005)) and the use of perspectives and methodologies from work on complex systems can enable students to study advanced content in the physical and social sciences at a deep level without requiring that they have an advanced knowledge of mathematics. A related consequence is that this will enable many more students to have access to this content. This paper will provide an overview of the research at the Northwestern Center for Connected Learning and Computer-Based Modeling (CCL) that has investigated learning in the context of restructurations in fields such as chemistry, evolutionary and population biology, materials science, and electrostatics. The CCL has authored restructured curricula using agent-based models as the representational form (Wilensky, 1999; Blikstein & Wilensky, 2004; Levy, Kim & Wilensky, 2004; Sengupta & Wilensky, 2005; Wilensky & Reisman, 2006). This research has been investigating how students learn with these restructured curricula and whether students can use similar sets of computational rules and algorithms in different domains of inquiry and, if so, whether such perspectives enable students to transfer ideas across very different disciplines. Other work to be discussed in this paper includes how complex systems modeling techniques may be used to look at educational and social systems, modeling these systems, and examining the implications for policy decisions.

**Seeing Through Complex Systems**

*Robert L. Goldstone, David Landy, Ji Son, Indiana University*

A complex systems perspective offers the promise of unifying increasingly fragmented scientific communities, and also facilitating transfer of knowledge across widely dissimilar domains, one of the greatest unsolved challenges for education. We will report on the results from a series of laboratory experiments exploring transfer of complex systems principles by undergraduate students. These experiments manipulate several design aspects of the computer simulations that are used to instantiate the principles: the graphical concreteness/idealization of the simulation elements, the specificity of the words describing elements, and the amount of contextualizing information or experience given to ground the simulations. Given these experiments and our experience using these simulations, we suggest that the most effective way to promote cross-domain transfer is to get learners to automatically see new situations using perceptual processes that have been adapted to previous situations, rather than relying on generalization from equations or abstract schemas.
Core Challenges in Understanding Complex Systems

Roger Azevedo, University of Maryland

Cindy E. Hmelo-Silver, Rutgers University

Understanding and reasoning about complex systems places a huge burden on our cognitive resources and often violates our intuitions (Feltovich, Coulson, & Spiro, 2001; Narayanan & Hegarty, 1998). Yet, education about complex phenomena often ignores the phenomena themselves and instead has learners focus on memorizing the names of the parts of the system (AAAS, n.d.). Thus, it is not surprising that most people understand complex systems as collections of parts with little understanding of how the system works (Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver, Marathe, & Liu, 2004). There are some deep principles that underlie many complex systems, some of which Jacobson and Wilensky have discussed, such as structure-behavior-function and emergence (see Goldstone & Sakamoto, 2003 for others). What differentiates these complex systems from complicated systems is the heterogeneity of components and their multiple levels of organization. Supporting learning about complex systems are key research issues for the learning sciences, and we have identified several challenges that must be addressed to help students better understand complex systems. One of the major issues affecting students’ ability to learn about complex systems is their cognitive, metacognitive, and self-regulatory processes. Students’ ability to learn about complex systems and other challenging topics (Azevedo, in press; Quintana, Zhao, & Krajcik, in press) is somewhat dependent on being able to plan, sustain, and reflect on the complex mechanisms underlying learning about complex systems. There is a faulty assumption that students not only have these skills, but that they are motivated and can effectively make decisions regarding their learning (Azevedo, Cromley, & Seibert, 2004). We need to reconsider these assumptions and to examine their role in fostering students’ learning about complex systems. There are developmental issues related to the use of cognitive, metacognitive, and motivational skills required to sustain learning in specific contexts (Azevedo, in press). Studying the use of metacognitive processes in understanding complex systems is critical to understanding how we can facilitate learning about complex systems, as learners engage in monitoring multiple activities during such learning—their emerging understanding and the aspects of their learning environment. Besides learning mechanisms, there are reasoning skills that must the deployed while learning about complex systems in technology-based environments such as simulations and modeling environments. Learners need knowledge about the nature of models, domain knowledge, general cognitive and metacognitive skills and scientific reasoning skills. Without such knowledge, it is difficult to learn about a complex system through simulation and modeling. This suggests that the field must strive for explanations of the roles these underlying mechanisms and scientific skills play in supporting learning about complex systems and what kinds of scaffolding are needed.

The learning sciences is at an early stage of understanding how people think about complex systems (e.g., Jacobson, 2001; Hmelo-Silver & Pfeffer, 2004) and how they learn about such systems (e.g., Azevedo, in press-b; Charles & D’Appolonia, 2003; Wilensky & Resnick, 1999). Our presentation will highlight a number of issues that the field must better understand if we are going to support students’ learning about complex systems. Understanding these issues requires that learning scientists identify and carry out a broad research program with respect to how students and teachers learn about complex systems.

The Teaching and Learning of Complex Systems in Education: Paradigm Shifts Beyond Current Ways of Thinking

Richard Lesh, Indiana University

This presentation accepts the premise that it is important to understand how students might learn about complex systems. However, it is argued that current learning science theories are not necessarily sufficient to provide answers to most questions about the nature of the conceptual systems that students would need to develop in order 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. The paper will make four main points. First, investigations about what it means to “understand” complex systems are important in their own right because
in the 21st century such systems are becoming increasingly important in the everyday lives of 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, and 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. We are at an exciting time in which a paradigmatic shift has been occurring in many fields with respect to 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.

**Discussants**

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**References**


