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Designs for learning about climate change as a complex system

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ABSTRACT

This paper reports on a study in which students used agent-based computer models to learn about complex systems ideas of relevance to understanding climate change. The experimental condition used a *Productive Failure* (PF) learning design in which ninth grade students initially worked with agent-based computer models to solve challenge problems followed by teacher instruction about targeted climate and complexity ideas. In contrast, the comparison condition employed a *Direct Instruction* (DI) learning design in which the teacher instruction was provided initially, followed by the students working on the same computer models and challenge problems as the experimental group. The students in the PF group scored significantly higher on the post-test on measures of climate and complex systems explanatory knowledge and near and far knowledge transfer. Theoretical and practical implications of these findings are considered.

The study of complex physical and social systems is increasingly important in 21st century science (Arthur, Durlauf, & Lane, 1997; Bar-Yam, 2003; Colwell, 2013; Epstein, 2006; Gell-Mann, 1994; Kauffman, 1995; Ziemelis, 2001). Briefly, complex systems consist of agents or elements that interact with each other and their environment in ways that may often be described in terms of relatively simple rules. Through mechanisms such as feedback and sensitivity to initial conditions (chaos), these interactions generally lead to self-organization at a micro level of a system and emergence of new patterns at a macro system level. Further, once patterns emerge at a macro level of a system, these may in turn provide positive or negative feedback that could influence agent behaviors at a micro system level. Commonly cited examples of complex systems include the formation of flocks of birds, herds of elephants, and schools of fish; adaptations of the immune system to changing viral and bacterial threats; economic adaptations of markets; dynamics of social networks and the world-wide web; and spiral and elliptical galaxies. Mitchell (2009) notes that many core complexity constructs—such as nonlinearity, decentralized control, networks, and emergence in hierarchical levels in systems—are being increasingly used by both scientific communities and the general public.

Learning about complex systems has been done primarily at university and graduate school levels, however, there have been calls to teach complexity ideas in science classes for students at pre-university levels (Jacobson & Wilensky, 2006; Sabelli, 2006). The value of learning about complex systems relates both to the importance of these ideas in modern science as well as for the potential of complexity ideas to provide conceptual interconnections across different science subjects as a new perspective about scientific literacy (Jacobson, 2001). Related, Goldstone and Wilensky (2008) have argued that “complex systems theory opens up new ways of organizing science according to underlying principles, not according to established disciplines such as biology, physics, chemistry, and psychology” (p. 507). Most recently, we are also seeing conceptual perspectives related to complex systems being emphasized in science education policy reform documents, such as the Next Generation Science Standards (NGSS) (National Research Council, 2012, 2013). However, many complexity ideas are challenging to learn (Jacobson & Wilensky, 2006; Wilensky & Jacobson, 2014) and instructional approaches for teaching this kind of knowledge effectively are just emerging.

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The main goal of the research reported in this paper is to contribute to the issue of effectively teaching complex systems ideas in K-12 classes from the perspective of the potential need for new instructional approaches for this new content. We report on classroom-based research with ninth grade students in which they used agent-based computer models to learn a core set of complex systems ideas as part of a unit dealing with climate change, earth systems, and sustainability in which different learning design approaches were used.

We next discuss research related to learning about complex systems, climate systems, and climate change as well as identify issues in this literature. We then report on a study in which two contrasting learning design approaches were used: (a) *Productive Failure* (PF) (Kapur, 2010; 2012; Kapur & Bielaczyc, 2012), and (b) *Direct Instruction* (DI). Implications of this work are then considered regarding ways to teach complex systems ideas and core disciplinary ideas as well as more general theoretical and practical issues in the field.

1. Literature review

1.1. Learning about complex systems: an overview

Although complex systems are commonly experienced, research indicates that there are significant differences in the ways that experts and novices think about and represent knowledge about complexity. For example, the first published study of expert-novice complex systems problem solving (Jacobson, 2001) documented that novices, who were undergraduate university students who had not formally studied complexity, were found to solve a set of problems about different types of complex systems (e.g., how do ants forage for food, can a butterfly influence the weather) with ideas such as *actions* being *linear*, *order* resulting from *centralized interactions*, and *system processes* as being *events* (i.e., they have a beginning, middle, and end (Chi, Slotta, & de Leeuw, 1994)). In contrast, complexity experts solved these problems with ideas such as *actions* being *nonlinear*, *order* being an emergent property of *decentralized interactions*, and *processes* being in *dynamic equilibrium.* In other research, Hmelo-Silver and colleagues (Hmelo-Silver, Marathe, & Liu, 2007) demonstrated that novices think about complex systems in terms of lower level attributes of structures, whereas experts focus on causal behaviors and functions of the system. More recent research has explored other factors that cognitively might influence the understanding of complex systems, such as the work by Chi, Roscoe, Slotta, Roy, and Chase (2012).

In some of the earliest research to investigate learning about complexity ideas (Resnick & Wilensky, 1993; Wilensky & Resnick, 1999), students used agent-based models programmed in NetLogo or StarLogo to explore different examples of complex systems that illustrated ideas such as self-organization or emergent properties. However, students were found to have difficulties in understanding the behavior of certain complex systems models due to what Wilensky and Resnick referred to as a Deterministic-Centralized Mindset (DCM), which is a cognitive bias that assumes the behavior of agents in a system is fully predictable rather than probabilistic, and that order in the system is centrally imposed by a leader or designed by a single entity rather than resulting from de-centralized interactions.

Reviews of research in Jacobson and Wilensky (2006) and Wilensky and Jacobson (2014) have identified a range of studies that demonstrated that pre-university students could in fact learn complex systems ideas. Common across these studies was the use of computational representations of complex physical or social systems and engaging students in problem solving or inquiry types of experiences (Charles, 2002; Resnick, 1994; Wilensky & Reisman, 2006).

Jacobson, Kapur, So, and Lee (2011) investigated the use of scaffolding that supported contrasting and comparing different model-based complex systems cases. It was found that there was significant learning of key complexity ideas about how complex systems function, which was also associated with higher performance on novel complex systems problem solving tasks.

In addition, research has been exploring how standard science topics in physics, chemistry, and biology may be learned in terms of core conceptual principles associated with complex systems. For example, the research of Sengupta and Wilensky (2009) employs agent-based models in order to help students learn different aspects of the physics of electricity where the behavior of electrons in a circuit was modeled and conceptualized in terms of complex systems principles. This research demonstrated that students showed an understanding of electricity when the ideas of emergent properties were made salient in the agent-based models and how macro level properties such as voltage or current "emerged" from the micro level interactions of electrons and atoms. Research along these lines is important as it suggests a way to address an issue about where to integrate complex systems ideas into the curriculum, which is to infuse complex system ideas into the teaching of regular science topics, rather than just "adding" complexity as a separate subject to be learned.

In addition to the issue of learning complex systems ideas, there is a related concern of students being able to transfer or use these ideas in new situations or to solve new problems. Considerable research suggests that students have difficulty in spontaneously transferring what they have learned, especially to different domains (i.e., far transfer) (Bransford, Brown, Cocking, & Donovan, 2000). Goldstone and Wilensky (2008) have argued that the research agenda of learning about complex systems should be fused with the research agenda of describing ways of achieving scientific transfer. We concur and hope that research into the learning of science subjects in terms of complex systems principles—as explored in this paper—might make solid dual contributions to the literature of learning about complex systems and of learning for transfer.

1.2. Learning about climate systems and climate change

We are starting to see new national guidelines for science curricula and standards in countries such as Australia (ACARA, 2013) and the United States (National Research Council, 2012, 2013). One new disciplinary area that is receiving greater emphasis beyond traditional topics in biology, chemistry, and physics involves *earth systems*, with new topics such global climate systems, including the carbon cycle and interactions involving the biosphere, lithosphere, hydrosphere, and atmosphere, and understanding how human activity affects the global climate system.

However, there has been relatively little research to inform approaches to help students learn about scientific knowledge about climate systems. To date, research in this area has been primarily descriptive of the important scientific ideas associated with global warming and climate change, and what ways students currently think about these topics. Regarding the former, Jarrett, Takacsa, and Ferry (2011) conducted a Delphi study of 19 academics, researchers, and high-school teachers who have expertise in global climate systems, as well as a comprehensive literature review. A set of 10 major ideas related to understanding climate change were identified: *carbon cycle and fossil fuels, electromagnetic spectrum, interactions between greenhouse gases and electromagnetic radiation, natural climate variability in the past and relationship to CO2 levels, differences between weather and climate, proportions of greenhouse and non-greenhouse gases in the atmosphere, radiative forcing*