Learning about Complexity and Beyond: Theoretical and Methodological Implications for the Learning Sciences

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Abstract: This paper provides an overview of a symposium that explored the implications of complexity for the field of the learning sciences. Two papers explored aspects of learning about complex systems in the domains of physics and electricity and of the mathematics of change and variation. The third paper viewed learning from a complexity perspective as an emergent phenomenon, and proposes to compliment traditional quantitative and qualitative methodologies used in learning sciences research with computational agent-based modeling methods. The fourth paper is a "theoretical case study" in which an "ontological network theory" based on scale free networks is proposed, and then used to reframe the debate in the learning sciences concerning "coherent knowledge" versus "knowledge-in-pieces" theories of conceptual change. Overall, it is hoped this session stimulated interest in new theoretical and methodological "lenses" for understanding the challenges of learning *about* complex systems and for doing research into learning *as* complex systems.

Overview

We live in an age where many 21st century scientists theoretically conceptualize and methodologically investigate complex physical and social systems in new ways that enable consideration of critical aspects of how these systems behave that have been simplified or ignored in earlier research. For example, whereas neo-Darwinian views of evolution highlighted the importance of natural selection, recent bio-complexity perspectives also stress notions of self-organization, interdependence, co-evolution, and emergent patterns (Bar-Yam, 1997; Gell-Mann, 1994; Holland, 1995; Kauffman, 1993, 1995; Simon, 1999). Other complexity concepts that scientists are using to study complex natural and even synthetic or artificial systems include multi-scale hierarchical organization, dynamical attractors, deterministic chaos, network theories, developmental trajectories, and fitness landscapes.

However, in the learning sciences, interest in complexity has to date focused primarily on issues associated with learning about complex systems, such as papers in the *learning about complex systems* strand in the *Journal of the Learning Sciences* by Sabelli (2006), Jacobson and Wilensky (2006), Goldstone (2006), Lesh (2006), Hmelo-Silver and Azevedo (2006), Hmelo-Silver, Marathe, and Liu (2007), and Goldstone and Wilensky (2008). An assertion explored in this symposium is that "concepts and methodologies from the study of complex systems raise important issues of theoretical and methodological centrality in the field of the learning sciences itself (p. 11) (Jacobson & Wilensky, 2006). Clancey (2008) has made a similar claim about the central role of complexity and systems thinking as scientific antecedents of views of situation cognition in the cognitive sciences.

The purpose of this symposium is to accept the premise that knowledge about the dynamics of complex physical and social systems *is* important for students in the 21st century to understand and to then look at empirical research into the learnability of these ideas. Two papers explored aspects of learning about complex systems in the domains of physics and electricity and of the mathematics of change and variation. Both of these papers employ agent-based models and visualizations as important interactive representational artifacts central to the respective learning interventions employed. In addition, other papers in this symposium considered ways in which theoretical and methodological perspectives from complexity may inform research in our field. The third paper in the symposium examined the methodological limitations of quantitative and qualitative methods used in the majority of learning sciences research if one views learning as an emergent phenomenon, and proposed complementing these methodologies with computational agent-based methods. The fourth paper was a "theoretical case study" that proposed an "ontological network theory" based on scale free networks, which then was used to reframe the debate in the learning sciences concerning "coherent knowledge" versus "knowledge-in-pieces" theories of conceptual change.

The papers in this symposium fit together in a complementary manner. All papers in this symposium employ various complexity conceptual perspectives such as agent interactions, self-organization, hierarchical levels, emergent properties, scale free networks, and three of the four papers explicitly use agent-based models either to facilitate learning or to enhance research. The format of the symposium followed this sequence: (a) comments on the symposium themes by the Chair (5 minutes), (b) 15 minute talks by each of the presenters (60 minutes), (c) discussant comments (10 minutes), and (e) moderated audience discussion (15 minutes). Overall, it is hoped this session stimulated interest in new theoretical and methodological "lenses" for understanding the challenges of learning *about* complex systems and for doing research into learning *as* complex systems.

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Learning About Complex Systems

The Role of Perceptual Signatures and Agent-Level Mechanisms in Understanding Emergence: An Example in Learning Electricity

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Research Goals

Our primary research goal is to investigate the effectiveness and cognitive (epistemological) implications of representing electrical conduction in a multi-agent based computational learning environment based on agent-level, intuitive mechanisms.

Theoretical Framework

It has been widely noted that knowledge in the various sub-domains of physics, including electricity, is organized around a few central principles that in turn typically require knowledge of vector algebra and calculus (Belcher & Olbert, 2003; Bagno & Eylon, 1990; Larkin et al, 1981)[1]. A design goal that often drives instructional design in electromagnetism is to organize learners' knowledge around these principles (Bagno and Eylon, 1997; Belcher and Olbert, 2003; Reiner et al, 2000). In contrast to this, the central design principle of the NIELS learning environment (NetLogo Investigations in Electromagnetism, Sengupta & Wilensky, 2005, 2008) is to represent and organize phenomena in the domain of introductory electricity in terms of a few intuitive "mechanisms" that in turn are based individual agent-level behaviors and attributes. For example, resistance is represented in terms of simple electron-atom interactions ("collisions" or "bouncing"), and electric current is represented as the emergent "flow" flow of electrons, that depends on agent-level attributes (e.g., *number* and *speed* of electrons).

Context and Methods

In this paper, we will present the analysis of 5th grade (n = 20) students' interactions with a sequence of two NIELS models (Current in a Wire model (Sengupta and Wilensky, 2008a), and Series Circuit model (Sengupta and Wilensky, 2008b)). Activity Sheets accompanying each model scaffolded learners' interactions with these models, during which they were prompted to observe the agent-level attributes and interactions, and were asked provide written explanations of the following macro-level phenomena in pre- and post-tests: a) how a light bulb works; and b) the behavior of electric current in a light bulb circuit (i.e., whether and why electric current is equal throughout the circuit with a light bulb). The data presented here includes participants' written explanations and semi-clinical interviews with a few selected students.

Data & Analysis

Post-test responses show that all students indicated that electric current would be equal on either side of the light bulb, compared to less than 20% in the pre-test. Written explanations and interview responses show that participants were able to identify both the "mechanism" that produces light, as well as the reason(s) for constancy of electric current, based on the agent-level *natural* behavior of the electrons in the circuit – "bouncing up and down", and/or "friction" with the atoms – which in turn produced heat, and then, light.

Our argument here is that the intuitive nature of these mechanisms is due to the distinct perceptual signatures of some of the key agent-level behaviors. For example, although the Current in a Wire model depict electron-atom collisions, it does not contain any cues pertaining to the temperature of the system (wire). Yet, almost all the participants in their written explanations indicated it is the collisions (and the resultant friction) that would "heat up" the wire (filament) of the bulb and that in turn generates "light." The perceptual signatures here are "heat" and "light," both of which are ubiquitous and intricate components of our repertoire of everyday interactions with the physical world. Goldstone and Wilensky (2009) argued that such perceptual signatures are characteristics of multi-agent based computational representations of the underlying mechanisms that generate emergent complex phenomena across several domains.

[1] For example, Maxwell's equations can explain a large number of different electromagnetic phenomena, and the behavior of most electric circuits can be predicted using Kirchhoff's laws.

Significance

These results suggest that representing electrical conduction in terms of intuitive, agent-level behaviors can enable learners as young as 5th graders to understand and explain (in a scientifically correct manner) the behavior of electric current in linear circuits, which misconceptions researchers have shown to be difficult for even college students to understand (Chi et al., 1994; Reiner et al., 2000; Bagno & Eylon, 1997).

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Seeing Change in the World from Different Levels: Understanding the Mathematics of Complex Systems

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In an increasingly dynamic and data-driven world, it is important for all students to be able to understand and interpret mathematical patterns over time in the context of the real-world phenomena that generate them. While there is a growing body of evidence that students as early as middle school can understand some fundamental and powerful ideas related to the mathematics of change over time in terms of real-world contexts such as motion or banking (Confrey, Maloney, & Castro-Filho, 1997; Nemirovsky, Tierney, & Wright, 1998; Roschelle, Kaput, & Stroup, 2000), as well as the sophisticated dynamics of many complex systems (Wilensky & Reisman, 2006; Wilensky & Resnick, 1999), little is known about how they might think about mathematical change as it relates to complex systems: where a number of *different behaviors and entities all contribute to a single quantity* of interest, rather than a single behavior or phenomenon. But such systems are increasingly important in all aspects of academic and everyday life. From global temperatures that are increasing exponentially due to increased individual consumption to employment patterns that affect individual workers and are influenced by consumer spending, students must be able to understand not only how to interpret rates of change in the world, but also how individual entities and their actions and interactions contribute to and are affected by those rates of change.

Knowing how students think and learn about change over time in such systems is important not only because it can help prepare students as active and informed citizens (Sabelli, 2006), but also because it can serve as a new access point to more formal mathematical topics such as calculus (Nemirovsky, Tierney, & Ogonowski, 1993; Stroup, 2002), and provide a better foundation for students entering the natural and social sciences where such systems are especially common (AAAS, 1991). That traditional calculus-based mathematics and notions of rate of change are so widely applicable and powerful, yet can so easily obfuscate the very mechanisms and elements that are at the core of those systems, presents a fundamental challenge for mathematics and science educators. In this presentation, we will explore the potential for *Agent-Based Modeling (ABM)* to provide students with an alternative, intellectually honest means to construct and analyze the mathematical trends produced by complex systems.

Agent-based modeling shifts the encoding of *quantitative change* from an aggregate-level quantitative trend (for example, the rate of change of a population count) to a collection of agent-level behaviors that produce those trends (the reproduction behaviors of individuals). As a result of this shift, agent-based modeling can represent and reflect quantitative change in a way that includes notions of randomness, sensitivity to local conditions, the role of nonuniform distributions in aggregation, and other powerful aspects characteristic of change in *systems* that are not dealt with in traditional calculus. While considerable research has investigated how computation has expanded *who* can learn the mathematics of change, less is known about how it can expand *what* can be learned about the mathematics of change.

We propose that such a practice can:

- Broaden student access to the mathematics of change and variation, by providing an alternative language with which to "speak" and "build" mathematical models of multi-agent systems that change over time.
- Make more accessible to students the connections between the mathematical model(s) of a system, and the behavior and mechanisms that comprise that system.
- Provide students with an infrastructure within which the ideas of calculus can be applied to a large class of interesting, and personally relevant, phenomena.

We will support these claims with evidence from think-aloud (Ericsson & Simon, 1984), semi-clinical (Clement, 2000) interviews conducted with 12 high school students enrolled in a precalculus course, who engaged in agent-based model building activities related to population growth and analyzed the graphs of mathematical trends produced by those models. These interviews are part of a larger design research agenda that intends to explore the potential for a constructionist, computational agent-based modeling environment to provide students a flexible, meaningful context within which students can explore the mathematics of complex systems. Findings suggest that while students were initially able to connect the behavior of a population plot to the behavior of the agent-based model, they were not able to articulate how the modeled reproductive behavior of that population, or how certain real-world factors such as a catastrophic event or individual preferences on childbearing might be manifested in the notion of "rate of change" or in the featured plots. They were also likely to attribute fluctuations in the plot to real-world events that were not included in the model, or develop incorrect mathematical explanations for real-world factors. In other words, students had great difficulty connecting the behavior of the model to mathematical ideas such as rate of change; when they tried to do so, they struggled and were often unsuccessful. After interacting with, and building their own, agent based models of population growth, students were much more likely to consider explicitly how behaviors that they knew were included in the model might play a role in the mathematical trends generated by that model, and were better able to predict mathematical trends given behaviors that were not included in the model. They were more likely to consider issues of randomness, individual heterogeneity, and the "stripped down" nature of modeling (that is, that not every real-world factor can be included in a given model) when analyzing mathematical trends and discussing mathematical models.

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Theoretical and Methodological Implications of Complexity

Learning as an Emergent Phenomenon: Methodological Implications

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In this paper, we put forth a theoretical cum methodological proposal for a line of inquiry that seeks to understand learning as an emergent phenomenon. Our theoretical and methodological arguments detail how an emergent conception of learning places limits on experimental and descriptive approaches, whether used alone or in combination. These limits are not so much a function of causality or reduction, but the need to deal with the dialectical co-existence of linearity and non-linearity that often characterizes complex phenomenon. To overcome these limits, albeit only partially, we leverage complexity theory to advance computational agent-based models as part of an integrated, iteratively validated phenomenological-ABM inquiry cycle to understand learning as an emergent phenomenon from the "bottom up."

Although there is much excitement about the possibilities that computational methods bring to the table, there remains little theoretical and methodological exposition of why and how computational methods can be integrated with existing quantitative and qualitative methods to potentially expand the research toolkit of educational researchers. How do existing quantitative and qualitative methods fall short and how might computational methods be integrated to provide better understanding of the phenomenon of learning, and vice versa? Our argument is based on the premise that learning is a complex phenomenon, which under certain conditions exhibits emergent properties. Indeed, many contexts of learning—formal or informal, groups or individuals—are in fact complex systems (Jacobson & Wilensky, 2006; Kapur et al., 2007). It is this very complexity that sets up the stage for the emergence of knowledge structures, interactional patterns, values, norms, identity, culture, and so on. Invoking emergence, however, requires that we deal with a fundamental tenet of complexity: an emergent phenomenon is ontologically and methodologically irreducible, i.e., *an emergent phenomenon is its own shortest description* (Kauffman, 1995). This simple yet powerful tenet poses serious methodological challenges. Through a careful analysis of the assumptions underpinning quantitative and qualitative methods, we will build a case that existing methods fail to adequately address the issues of *non-linearity*, *temporality*, *spatiality*, and *phase-space* that are of central to understanding emergent phenomenon. We will discuss how and the extent to which these issues can be addressed by *integrating* computational agent-based methods with existing quantitative and qualitative methods (Abrahamson & Wilensky, 2005; Blikstein, Abrahamson, & Wilensky, 2006; Goldstone & Janssen, 2005). In the final analysis, we propose an iterative process of building from and validating with phenomenological theory and data to seek a better understanding of the complex phenomenon of learning noting very well that, any method, be it quantitative, qualitative, or computational, used alone or in combination, will necessarily remain reductive.

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Ontologies as Scale Free Networks: Implications for Theories of Conceptual Change

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This paper provides a “theoretical case study” of how perspectives from complexity research might provide insights into debates of theory in the learning sciences. The debate we examine concerns the “fault line” in the field related to the “knowledge-in-pieces” versus “coherent knowledge” about conceptual change (diSessa, 2006), which extends back to the seminal monograph in *Cognition and Instruction* in which diSessa (1993) articulated his theory of phenomenological primitives (p-prims) and of “knowledge-in-pieces.”

An Ontological Networks Theory (ONT) is proposed in this paper that combines complexity views about scale-free network topologies with learning sciences perspectives about knowledge representation, conceptual change, and learning. Briefly, scale-free networks (Barabasi, Albert, & Jeong, 1999; Barabasi & Bonabeau, 2003; Steyversa & Tenenbaum, 2005; Watts & Strogatz, 1998) resemble the airline system that consists of *hubs*, which are nodes with a very high number of links, in contrast to *random networks*—such as a national highway system—that consist of *nodes* with randomly placed connections. Barabasi et al. (1999) demonstrated that the basic mechanism that produces a scale free network involves: (a) *growth* (addition of new nodes), and (b) *preferential attachment* (the probability of a new node linking with an existing node is proportional to the number of links the existing node has).

The ONT is explicitly based on these core properties of scale-free networks. We propose that the representation of knowledge about a variety of scientific phenomena consists of network configurations of nodes and hubs involving preferential attachment and selection processes. *Ontological nodes* or O-Nodes are relatively “small” domain specific ideas about natural phenomena. O-Nodes are conceptualized as being similar to the construct of phenomenological primitives or p-prims (diSessa, 1993). In contrast, *ontological hubs* or O-Hubs are highly connected nodes (i.e., hubs in scale free network theory) that we regard as similar to the psychological construct of “ontological categories” (Chi, 1992, 2005; Lakoff, 1987). (The full paper discusses the ONT in more detail, including selection processes and deactivating of nodes.)

Recently it has been argued by diSessa (2006) that several theories about how people solve problems and learn often conceptualize knowledge as being relatively stable, consistent, and “coherent.” He maintains that these “coherent knowledge” theories have been more common than “knowledge-in-pieces” theories (such as diSessa’s) in which ideas are viewed as fragmented and highly influenced by contextual cues and factors. Chi and her associates have articulated one representative theoretical view of “coherent” knowledge and conceptual change. Chi (1992) proposed a theory (which has been iteratively revised for several years, see Chi (2005)) that difficulties learners have with changing their concepts about certain types of knowledge, particularly in the sciences, may be explained as a result of ascribing the concepts being learned to inappropriate ontological categories. Chi’s basic argument is that students will need to make an ontological shift if they are to achieve conceptual change about such scientific concepts.

In this paper, we propose that the ONT may be used to reframe this debate in a principled manner. First, p-prims appear to be "node-like" in that they are described as "*Elements*: P-prims are rather small knowledge structures, typically involving configurations of only a few parts…" (diSessa, 1993, p. 111). In contrast, other major theories of conceptual change, such as by Chi, seem to describe cognitive structures such as "ontological categories" that are more "hub-like" than the "node-like" p-prims of diSessa. We believe the ONT has theoretical properties that are consistent with the major assertions and empirical findings associated with these two major conceptual change theoretical camps in the learning sciences (i.e., "coherent knowledge" versus "knowledge-in-pieces"). Further, the ONT as advantages over the learning sciences theory, such as the incorporation of a mechanism or process for how and why certain ideas link or do not link together, that is, the principle of preferential attachment, whereby more highly connected nodes (and hubs) have a higher probability of being linked to than less connected nodes. Thus new scientific ideas we might wish for students to learn would have a higher probability of linking to already formed ontological hubs (i.e., ontological categories), and thus there is a degree of "coherence" or consistency in how a conceptual network is activated, which research on conceptual change by researchers such as Chi has shown. Another potential advantage of the ONT is that as other researchers make progress on the properties and characteristics of scale-free networks mathematically and in terms of applications in other domains (e.g., neuroscience), these advances may in turn inform and enhance our understanding of processes of learning in our field. Finally, it is hoped this "theoretical case study" might be suggestive of how complexity perspectives more generally may be explored for their potential to inform other issues of theory and methodology in the learning sciences.

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