Complex Systems and Learning: Empirical Research, Issues, and "Seeing" Scientific Knowledge with New Eyes

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Abstract: The purpose of this symposium is to move beyond speculations about how knowledge about complex systems might be important for students to understand to focus on empirical research into the learnability of these ideas. For example, do complex systems ideas represent learning challenges that are qualitatively different than learning other scientific knowledge? What are the differences in pre-conceptions students have about complex systems phenomena and more expert scientific ways of thinking in these areas? What are the profiles of successful and less successful ways of learning about complex systems conceptual perspectives? Can complex systems provide conceptual perspectives for cognitively "seeing" physical and social sciences subjects in new and interconnected ways? It is hoped the papers in this session will provide insights into these questions and other theoretical and research issues in the learning sciences.

Symposium Overview

Michael J. Jacobson

There have been recent papers in journals such as The Journal of the Learning Sciences and Cognitive Science as well as various sessions at conferences such as American Educational Research Association, International Conference of the Learning Sciences, and Cognitive Science over the past few years that have considered different aspects of how ideas and conceptual perspectives related to the multi-disciplinary study of complex physical and social systems might be of importance in the field of education. Issues have been considered such as whether complex systems ideas might constitute important new knowledge K-16 level students should learn, what might be the challenges to be faced in helping students learn emerging scientific knowledge, or how these analytical and methodological perspectives might be used to inform our understanding of the dynamics of complex educational systems. The purpose of this symposium is to move beyond speculations about how knowledge about complex systems might be important for students to understand to focus on empirical research into the learnability of these ideas, as well as to consider issues of theoretical importance to the field of the learning sciences.

Implementing Multi-Agent Modeling in the Classroom: Lessons from Empirical Studies in Undergraduate Engineering Education

Paulo Blikstein and Uri Wilensky

This paper reports on a four-year empirical study of MaterialSim (Blikstein & Wilensky, 2004), an undergraduate material sciences learning environment based on multi-agent computer modeling built in the NetLogo (Wilensky, 1999b) simulation environment. This design-based research builds on previous studies that have suggested the benefits of complex systems, multi-agent and/or cellular-automata simulation for understanding how a variety of complex behaviors in science derive from simple, local rules (Langton, Minar, & Burkhart, 1995; Wilensky, 1999a; Wilensky & Reisman, 2006; Wilensky & Resnick, 1999; Wolfram, 2002). The design of MaterialSim emerged from a literature review on engineering and materials science education (e.g., Hurst, 1995; Lamley, 1996; Russell & Stouffer, 2005; Thornton & Asta, 2005), classroom observations, and extensive interviews with students. Our observations, supported by the literature review, indicated that students' understanding of the subject matter was problematic, and that the conventional teaching strategies and resources were not up to the challenge of the content being taught. Particularly, university-level Materials Science is exceptionally complex and interconnected, but the traditional teaching strategies are fragmented and "linear": Students are presented with different scientific phenomena, one at a time, with their respective sets of equations and mathematical models. In this "many-to-one" framework, many context-specific equations and models are necessary to explain one single phenomenon. The result, as our studies have suggested, is fragmented, overly specific, and inflexible knowledge, which students cannot utilize to explore new areas within the subject matter.

MaterialSim's design, conversely, follows a "one-to-many" framework (Blikstein & Wilensky, 2006), in which students are led to identify, by exploring previously-built NetLogo models, some common principles across entire content sections of a course. These few principles can be used to understand *many* different phenomena. After having mastered those basic principles, students are asked to author a new computer model of their choice. A core feature of this design, then, is that students can apply a small number of models to capture fundamental causal structures underlying behaviors in a range of apparently disparate phenomena within a domain. For example, the free-energy minimization model allows students to understand crystal nucleation and growth, solidification, annealing, recrystallization, phase transformations, diffusion, and many other phenomena in Materials Science, which are traditionally taught as separate topics, each with their own models.

Four user studies were conducted, in 2004, 2005, 2006, and 2007, with a total of 39 Material Science undergraduate students enrolled in an introductory Materials Science course. The first three studies were conducted in the lab, but the last study took place in a regular classroom, as a for-credit assignment. In this last implementation (n=18), each student was assigned the task of programming an agent-based model of any relevant topic in the course, run the model, collect data, and compare their results with published data. Students were given one month to complete the assignment and took approximately 20 (± 6) work-hours on average to complete it. Students were observed during three activities: learning the NetLogo language, learning how to build computer models with NetLogo, and running/analyzing multi-dimensional experiments with their own models. We videotaped all student sessions and captured their computer interactions. The first author also attended the Microstructural Dynamics undergraduate course, collected and analyzed class materials and related literature. At the end of the quarter, students filled up questionnaires about their motivation, their modeling experience, and time investment in different phases of the project.

The data demonstrate the usefulness of the complex systems perspective infused into MaterialSim design. All 18 students were able to successfully complete their models and data validations, most of which were able to identify agent rules with applicability in more than one phenomenon, and students' self-reported ability to create computer models increased significantly. We posit that, whereas the conventional, many-to-one approach leads to the accumulation of inert models, the one-to-many multi-agent simulation approach provided students with useful generative models to reflect on the unifying principles of the phenomena studied, and enabled them to build new models. However, the environment in an undergraduate engineering course presented challenges not present in the lab studies we had previously conducted. For example, issues such as time investment, intrinsic/extrinsic motivation, the usefulness (for students) of learning a new computer language, and the perceived usefulness of the activity to their school performance had to be constantly negotiated. From this experience, we identified design principles and important challenges for researchers making the transition from complex-systems-in-the-lab to implementations in regular classrooms.

Selected References

Blikstein, P., & Wilensky, U. (2004). *Materialsim: An agent-based simulation toolkit for learning materials science.* Paper presented at the International Conference on Engineering Education, Gainesville, Florida, USA.

Blikstein, P., & Wilensky, U. (2006). *From inert to generative modeling: Two case studies of multiagent-based simulation in undergraduate engineering education.* Paper presented at the Annual Meeting of the American Educational Research Association, San Francisco, CA.

On Learnability of Electricity as a Complex System

Pratim Sengupta and Uri Wilensky

Electricity has been a topic of much interest to learning scientists and science educators over the last three decades. The Pfund and Duit (1998) bibliography documents around 1200 studies that investigate students' misconceptions in the domains of heat, light, and electricity. Recently, a number of proposals elaborate the need for introducing students to microscopic level models of electricity (Eylon & Ganiel, 1993; Chabay & Sherwood, 1995, 2002; White, Frederiksen, & Spoehr, 1993; Sengupta & Wilensky, 2006). The goal of such models is to enable students to relate the macroscopic phenomena (such as electric current and voltage) in terms of interactions between microscopic objects (e.g., electrons, ions). However, there is little agreement on the instructional strategies involved in implementing these ideas in classroom contexts. Chi and Leeuw (1994) suggested that naïve and expert cognition in the domain of electricity are incompatible with each other, as experts and novices pertain to different and incommensurable ontologies of knowledge. They proposed that instruction in this domain should "shun" any materialist allusions, and instead focus on process-based descriptions of electricity. Bagno and Eylon (1997) argued for a "principle-based" instructional strategy that provides students with a microscopic understanding of electromagnetism through canonical principles from the domain of classical mechanics. White and Frederiksen (1993) demonstrated the use of agent-based simulations in which students were shown interactions between collections of charges as well as introduced to equational forms of representations to bridge the macro- and microscopic levels of description. Clement (1993, 1998) and Clement and Steinberg (2002) advocated the use of analogical thinking in a non-computational learning environment to foster student understanding of phenomena related to electricity. Also, it is noteworthy that these instructional studies typically focused on advanced high school and/or undergraduate students.

In our research, we investigate issues related to *learnability* of phenomena in the domain of electricity when they are represented as complex, dynamical systems. We situate our discussion in the context of NIELS (NetLogo Investigations in Electromagnetism; Sengupta & Wilensky, 2006), a multi-agent based, computational learning environment consisting of a suite of models authored in NetLogo (Wilensky, 1999) and demonstrate that such representations can lower the learning threshold of at least the introductory level phenomena in the domain of electricity so that students as young as 5th graders can understand them. NIELS models represent phenomena in the domain of electricity in an *emergent* (Wilensky & Resnick, 1999) fashion – e.g., aggregate level phenomena such as electric current and resistance *emerge* due to simple interactions (push, pull, simple collisions) between thousands of individual level agents (atoms, electrons) inside a conductor. Students interact with these models through scaffolded and open-ended activities that often involve a combination of simple perceptual actions (e.g., counting, observing or inferring trajectories, etc.), thereby leveraging their *core knowledge systems* (such as objects, number and motion), which are present even in infants (see Spelke & Kinzer (2007) for a review). Results from implementation of NIELS models in fifth, seventh, and twelth grades and in undergraduate classes indicate that through such activities, learners across a wide spectrum of ages activate their existing repertoire of object-based knowledge elements due to perceived contextual cues in the NIELS models. These object-based knowledge elements are acquired through our earliest interactions with the physical world (diSessa, 1993; Papert, 1980, Piaget, 1969), and therefore, are easily accessible to students as young as 5th graders, perhaps, even younger.

Furthermore, our results reveal that naïve students, prior to their interaction with NIELS, tended to assign the attributes (e.g., mass, flow) of objects at the individual level (i.e., electrons and atoms) to the aggregate-level, emergent phenomena such as current and resistance. Wilensky and Resnick (1999) have termed this tendency to assign agent-level attributes to the macro-level emergent phenomena as "slippage between levels." These perceived attributes at the aggregate level then activate object-based knowledge elements in the learner's mind and this produces the commonly noted "misconceptions". It is noteworthy that these are the same knowledge elements that are activated primarily due to micro-level cues in the NIELS models in course of the students' interaction with NIELS, and as our results show, give rise to an expert-like understanding of electricity. Therefore, one can say that these knowledge elements are not the wrong cognitive resources to activate, but rather due to the perceived contextual configurations at a *different level* of description of the phenomena, an otherwise useful knowledge element can be inappropriately activated in the learner's mind, thereby leading to a "misconception".

In conclusion, our results indicate that representing electricity as a dynamical complex system allows us to reconceive the process of learning of the revenant phenomena as *a levels-based re-organization* of the learner's existing object-based knowledge elements (Sengupta & Wilensky, 2006, 2007, 2008 (in progress)), as opposed to a radical conceptual change (Chi, Slotta & Leauw, 1994; Slotta & Chi, 2006). Furthermore, our results also indicate that NIELS models, through its use of activities that leverage *core knowledge systems,* lower the learning threshold and enable much younger kids (5th graders) to learn the same content typically taught in high school and undergraduate levels.

References

diSessa, A. (1993). Towards an epistemology of physics. *Cognition & Instruction, 10*, 105-225.

Eylon, B-S. & Ganiel, U. (1990). Macro-micro relationships: the missing link between electrostatics and electrodynamics in student reasoning. *International Journal of Science Education*, 12, 79-94

Fredericksen, J., White,B., & Gutwill, J.(1999). Dynamic mental models in learning science: The importance of constructing derivational linkages among models. *Journal of Research in Science Teaching, 36*(7), 806-836.

Levy, S.T., & Wilensky, U. (2008). Inventing a "Mid-level" to make ends meet: Reasoning between the levels of complexity. *Cognition and Instruction, 26(1),* 1-47.

Papert, S. (1980). *Mindstorms: Children, computers and powerful ideas.* Basic Books, NY.

Reiner, M., Slotta J. D., Chi T., H., & Resnick L., B. (2000). Naïve physics reasoning: A commitment to substance-based conceptions. *Cognition and Instruction, 18*(1), 1-34.

Sengupta, P., & Wilensky, U. (2005). *N.I.E.L.S: An emergent multi-agent based modeling environment for learning physics.* Paper presented at the 4th International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2005), Utrecht, Netherlands.
Sengupta, P., & Wilensky, U. (2006). *NIELS: An agent-based modeling environment for learning electromagnetism.* Paper presented at the annual meeting of the American Educational Research Association (AERA 2006), San Francisco, CA.
Wilensky, U. (1999). *NetLogo. http://ccl.northwestern.edu/netlogo.* Center for Connected Learning and Computer-Based Modeling. Northwestern University, Evanston, IL.
Wilensky, U., & Resnick, M. (1999b). Thinking in levels: A dynamic systems perspective to making sense of the world. *Journal of Science Education and Technology, 8*(1).

Problem-based Hypermedia and Agent Based Modeling: Shifting Ontologies about Complex Systems

Michael J. Jacobson, Hyo-Jeong So, and June Lee

This presentation discusses a study of a problem-based hypermedia environment, the Complex Systems Knowledge Mediator (CSKM) (Jacobson, 2008), which was designed to provide cases about different types of complex systems in order to help students learn conceptually challenging but increasingly important ideas about complexity (Jacobson & Wilensky, 2006). The CSKM incorporated five NetLogo (Wilensky, 1999) agent-based computer models—Ants, Traffic Jams, Slime Molds, Segregation, and Wolf-Sheep Predation—into hypermedia cases for which conceptual, ontological, and problem solving scaffolds were developed. Scaffolds that consisted of mini-lessons for four main complex systems concepts as well as case-specific explanations of these concepts were authored for the CSKM materials: *agents and rules*, *feedback, self-organization*, and *emergent properties and levels*. In addition, similar scaffolds were authored for four ontological beliefs that were based on previous expert-novice study research (Jacobson, 2001) related to (a) *system control (centralized versus centralized-decentralized)*, (b) *actions (random versus random-predictable)*, (c) *causality (single versus single-multiple)*, and (d) *processes (events versus event-emergent*). (1)

A study was conducted in which 60 undergraduate university students were randomly assigned to three treatment groups that varied the types of scaffolding. The Full Scaffolding group used the NetLogo models in conjunction with text-based scaffolding about complexity ontological ideas such as *decentralized control* and *random actions* and higher order complexity concepts such as *self-organization* and *emergence* whereas the Conceptual Scaffolding group was the same but without the ontological scaffolding. The third group only used the hypermedia cases with the NetLogo models but received no other ontological or conceptual scaffolding. The common CSKM design features that all three groups experienced were the five complex systems cases with embedded NetLogo agent-based models and a set of problem-solving activities that required contrasting and comparing the different cases in order to answer the problems, such as: How is it possible for a system to function in an orderly manner when the agents in the system behave randomly?

The CSKM was used in three sessions of approximately two hours each. Learning was assessed using a range of declarative and problem solving measures on the pretest and the posttest. Two raters used a rubric for factual accuracy and writing quality to code the open-ended declarative knowledge and problem solving responses. In addition, the complex systems problem solving responses were coded using a *complex systems ontology framework* (CSOF) rubric (Jacobson, 2001); for example, "Clockwork" ontologies such as *central control of system* or *linear action effects* or "Complexity" ontologies such as *order from decentralized interaction* in a system or *nonlinear action effects* (e.g., the "butterfly effect").

In terms of the main findings of this study, all participants in the three groups significantly increased their declarative knowledge scores from pretest to posttest ($F(1, 57) = 168.90$, $p<.001$, $\eta p^2 = 0.75$). An ANOVA on the posttest found there was a significant difference between the three groups ($F(2, 57) = 5.23$, $p<.001$, $\eta p^2 = 0.16$), with Full Scaffolding being significantly higher than the NetLogo treatment ($p<.001$), but no significant differences between the Full Scaffolding and Conceptual Scaffolding groups. Problem solving ontology scores based on five ontology ideas (*non-reductive understandings of phenomena, decentralized control*, *random agent actions, dynamic or emergent processes*) were calculated. All three groups showed significantly higher Clockwork ontology scores (M=0.18, SD=0.14) than Complexity ontology scores (M=0.11, SD=0.13) on the pretest ($F(1, 57) = 6.00$, $p<.05$, $\eta p^2 = 0.09$), and by the posttest there were no significant changes in the continued use of Clockwork ontology ideas. However, the participants had higher mean number of Complexity ontology ideas in the posttest (M=0.23, SD=0.15) than in the pretest (M=0.11, SD=0.13), and this was a significant and moderate effect size difference ($F(1, 57) = 56.71$, $p<.05$, $\eta p^2 = 0.40$).

Further it was found that on average, all participants significantly increased from pretest to posttest in terms of four of the five complexity ontology ideas (*non-reductive understandings of phenomena, decentralized control*, *random agent actions, dynamic or emergent processes*); but no significant shift for the *nonlinearity* ontology (which suggests this is a more difficult idea to deeply understand). A composite variable of the averages of these four ontology posttest scores was created and significant correlations between the composite ontology score and the open-ended posttest responses to the two transfer problems were found ($p<.01$). Given the positive relationship between complex ontologies and problem solving, participants were re-grouped according to their complexity ontologies scores on the posttest. The scores ranged from 0 to 0.7, and three groups were created: low (scores less than 0.24, n=24), medium (scores between 0.24 to 0.34, n=23), and high scorers (scores more than and equal to 0.35, n=13). One-way ANOVAs were run to see whether there were any significant group differences on the declarative knowledge, problem solving, and total test scores. Results showed a significant group difference on the problem solving performance in the posttest ($F(2, 57)=9.39$, $p<.001$). Post hoc tests revealed that participants with low complexity ontologies scores had significantly lower scores on the solutions to the complex systems problems compared to the medium ($p<.05$) and high complexity ontology groups ($p<.001$).

It appears that the primarily textual scaffolding about ontological and complexity concepts the Full Scaffolding group received and the complexity concepts only scaffolding for the Conceptual Scaffolding group contributed to gains in the declarative knowledge understanding about complex systems for these participants. However, the finding that higher complexity ontologies scores were significantly associated with higher performance on two of the far transfer complex systems problem solving tasks is potentially important. We believe there are two main reasons for this finding. First, all three groups used the complex systems cases with the embedded NetLogo models, which have certain representational and interactive affordances for depicting dynamic aspects of different types of complex systems. It may be that the NetLogo modeling activities allowed the participants to perceptually attend to and interactively explore properties of how complex systems behave that in turn allowed them to begin to construct new complexity ontologies that they did not seem to have at the pretest. Second, the CSKM hypermedia system has design features that support problem-solving activities in which facets of the different cases may be contrasted and compared, which has been found to lead to significant knowledge transfer in earlier research (Jacobson & Archodidou, 2000; Jacobson, Maouri, Mishra, & Kolar, 1996; Jacobson & Spiro, 1995). Thus it may have been the experiences with the NetLogo models in the cases may have helped the students construct new Complexity ontologies such as *decentralized control* and *random agent actions* in conjunction with the efficacy of contrasting and comparing cases for promoting transfer, as suggested by Gentner and associates (Gentner, Loewenstein, & Thompson, 2003) in their theory of analogical encoding. However, it was also found that the participants *continued* to have ontological commitments to the Clockwork ontologies in the posttest problem solutions as well. Future research into these issues is clearly needed. The implications of this study for learning about complex systems knowledge and for theoretical issues in the field of the learning sciences such as conceptual change are further considered in the conference presentation.

Endnotes

(1) The characterization of complexity ontologies as being dialectical in nature (e.g., actions in a complex system may have both *random and predictable* dynamics) is one that contrasts with a dichotomous view of complexity ontologies (e.g., actions are *predictable* as a naïve view versus actions are *random* as a complexity view). The dichotomous view of complexity is more common in published research to date on learning about complex systems, including work by the first author, however the rationale for a *dialectical* view of the ontologies of complexity is being articulated in two manuscripts in preparation (Jacobson & Kapur, 2008; Kapur & Jacobson, 2008).

References

Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95*(2), 393-408.

Jacobson, M. J. (2001). Problem solving, cognition, and complex systems: Differences between experts and novices. *Complexity, 6*(3), 41-49.

Jacobson, M. J. (2008). Hypermedia systems for problem-based learning: Theory, research, and learning emerging scientific conceptual perspectives. *Educational Technology, Research, and Development, 56*, 5-28.

Jacobson, M. J., & Archodidou, A. (2000). The knowledge mediator framework: Toward the design of hypermedia tools for learning. In M. J. Jacobson & R. B. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 117-161). Mahwah, NJ: Lawrence Erlbaum Associates.

Jacobson, M. J., & Kapur, M. (2008). *Ontological network theory and learning about complex systems*. Manuscript in preparation.

Jacobson, M. J., Maouri, C., Mishra, P., & Kolar, C. (1996). Learning with hypertext learning environments: Theory, design, and research. *Journal of Educational Multimedia and Hypermedia, 5*(3/4), 239-281.

Jacobson, M. J., & Spiro, R. J. (1995). Hypertext learning environments, cognitive flexibility, and the transfer of complex knowledge: An empirical investigation. *Journal of Educational Computing Research, 12*(5), 301-333.

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *The Journal of the Learning Sciences, 15*(1), 11-34.

Kapur, M., & Jacobson, M. J. (2008). *On the nature of complexity*. Manuscript in preparation.

Wilensky, U. (1999). Netlogo. Evanston, IL: Center for Connected Learning and Computer-Based Modeling. http://ccl.northwestern.edu/netlogo.

Actions Across Levels (AAL): A Multiple Levels Perspective On What It Means To Make Sense Of Complex Systems

Sharona T Levy and Uri Wilensky

Framework

Furthering our understanding of what it means to make sense of complex systems is becoming a pressing imperative, as educational systems begin incorporating such constructs into standard curricula (Jacobson, 2006; Wilensky, 1999; Levy & Wilensky, under review). Work to date on the topic has focused on understanding of the system's structural aspects (Hmelo-Silver & Pfeffer, 2004) or the underlying epistemologies and ontologies (Wilensky & Resnick, 1999; Jacobson, 2001; Chi, 2005). This work builds upon previous work, delineating how people reason about complex systems. We propose a framework, Actions Across Levels (AAL), for understanding and investigating how people reason about complex systems. This framework describes possible participating cognitive processes and consists of two dimensions: description levels and actions undertaken while interpreting systems (Figure 1).

The notion of *levels* is a central component in agent-based approaches, specifying both *individual agents* and the *overall system*'s emergent and aggregate behavior (Bar-Yam, 1997). Thus, one dimension in the AAL framework is the description level: agent (individuals), aggregate (system) or a mélange of the two (AA, agent-aggregate complementarity, when both description levels are incorporated in reasoning about the system; Stroup & Wilensky, 2003).

The second dimension introduces three actions, involved in reasoning about systems. *Rule-making*: connecting conditions and actions, which govern agents' behaviors as they respond to their environment or internal states; relating global changes and affected properties; or combinations of the two; *Paralleling*: simulating multiple agents acting and interacting concurrently; *Chaining*: observing or deriving a sequence of states, temporal changes in the system and/or its elements. No claim is made regarding whether all cognitive processes actually take place, nor in what order.

Level / Action	Agent	AA* (both)	Aggregate
Rule-making	*Forming agent rules*: agents behaviors depending upon local and internal conditions	*Forming rules* in which (1) local behaviors are impacted by global properties; (2) global behaviors depend on local properties and events.	*Forming rules for the whole system*: impact of global variables upon aggregate states and properties
Paralleling	*Concurrent behaviors of several agents*: Different agent behaviors are dependent on varying local environments; local patterns may emerge.		
Chaining	*Sequencing a chain of agent behaviors* through time: an individual's history	*Sequencing a chain of states* that involve both agent and aggregate description levels.	*Sequencing a chain of systemic states*: the aggregate evolution through time

Figure 1. Actions Across Levels (AAL) framework.

Research and Findings

In previous work, we investigated ten sixth-grade students' reasoning about ordinary social complex systems, such as scattering in preparation for calisthenics in gym class, discovering a pervasive strategy: "mid-level construction" (Levy & Wilensky, 2008). We had found that students invent intermediate groups in a variety of forms along one of two trajectories: starting from the agents and grouping; or starting from the aggregate and partitioning. This strategy reduces the amount of information in the system, while preserving its multi-component, dynamic and interacting nature, serving explication of the system under scrutiny. The students presented diverse mid-level forms: clustering agents into groups ("clustering"), detaching groups in parallel from a central cluster ("groups"), moving the agents in a staggered form, each group at a different time ("outsides first"), rows of agents, subdivision into groups that behave according to different rules.

In the current study, we further explicate this strategy by coding the above interviews using the AAL framework. The students' utterances during the interview were coded according to the seven categories (Figure 1) and analyzed for relative frequencies.

We have located group-wide strengths regarding the different cognitive processes: while agent rule-making is most commonly exercised (*M*=27%, *SD*=7), mentally simulating the system's evolution - chaining at all levels is least frequently (*M*=6%, *SD*=6 for agents, *M*=8%, *SD*=5 for aggregate); paralleling and aggregate rule-making are of intermediate strengths (*M*=17%, *SD*=11, *M*=16%, *SD*=12 respectively), however with a greater variance among the students. Moreover, we have found associations between individual students' strengths and the specific forms of "mid-levels" they created, as described above. Strong (32%) paralleling is associated with a pattern involving several groups acting concurrently ("groups"), but not with a pattern in which groups' actions are staggered over time ("outsides first") (8%). Strong aggregate rule-making is associated with the "outsides first" pattern (29%) but not with the others (14% for both). AA chaining is associated mainly with "clustering" (18%), less so with "groups" (12%) or "outsides first" (4%).

Discussion

We discuss these findings with respect to support for the AAL framework, reported difficulties and possible supports in learning and teaching complex systems. In the introduction, we proposed a two-dimensional framework for describing the cognitive processes that may take place while reasoning about complex phenomena: "Actions across Levels" (AAL). We have presented evidence to support the utility of the AAL framework by locating instances of each component in the students' utterances, as well as diverse strengths and their association with different reasoning strategies. We have found that for all the students, agent rule-making was prominent. Chaining (or sequencing events) was the least dominant. This confirmed our assumption that the task describing social settings was well suited to students' everyday agent-based reasoning. As a group, the students' main resource was agent rule-making. Mentally simulating the unfolding of events was a challenge.

Mid-level construction was used to test the framework. Given the small sample, we do this carefully, and claim only to trends. We found that variation among the AAL components is related to the particular forms of mid-levels; stronger actions were used to construct mid-levels. "Clustering" in an individual-to-mid-level trajectory was related to stronger Paralleling or AA chaining, central features of agent-based reasoning. The other patterns were formed in a population-to-mid-level trajectory. The "groups" pattern, a parallel detachment of groups from the central cluster was related to stronger Paralleling, while lacking the Chaining features that access the system's evolution; staggering the groups ("outsides-first") was related to stronger Aggregate chaining and Aggregate rule-making, which support such temporal patterns, but lack the system's parallel interactions. Educational implications of this research point a way to analyzing both strengths and difficulties encountered by students while reasoning about complex systems, as related curricula become more prevalent.

References

Bar-Yam, Y. (1997). *Dynamics of complex systems*. Reading, Mass.: Addison-Wesley, The Advanced Book Program.

Chi, M.T.H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences*, *14(2),* 161-199.

Hmelo-Silver, C.E., & Pfeffer, M. G. (2004). Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions. *Cognitive Science*, *28,* 127-138.

Jacobson, M. J. (2006). Hypermedia systems for problem-based learning: Theory, research, and learning emerging scientific conceptual perspectives. Manuscript submitted for publication.

Levy, S.T. & Wilensky, U. (under review). Navigating the complexities of the particulate world: Learning with the Connected Chemistry curriculum.

Levy, S.T., & Wilensky, U. (2008). Inventing a "Mid-level" to make ends meet: Reasoning between the levels of complexity. *Cognition and Instruction, 26(1)*, 1-47.

Wilensky, U. & Stroup, W. (2003). Embedded complementarity of object-based and aggregate reasoning in students developing understanding of dynamic systems. Paper presented at the annual meeting of the American Educational Research Association, Chicago, IL, April 1-5.

Wilensky, U. (1999).GasLab: An extensible modeling toolkit for exploring micro- and macro- views of gases. In N. Roberts, W. Feurzeig, & B. Hunter (Eds.), *Computer modeling and simulation in science education* (pp. 151-178). Berlin: Springer Verlag.

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems perspective to making sense of the world. *Journal of Science Education and Technology, 8(1),* 3-19.