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Inventing a "Mid Level" to Make Ends Meet: Reasoning between the Levels of Complexity

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There has been a body of emerging research describing students' understanding of complex systems. This research has primarily studied students understanding of complex phenomena in science. However, complex phenomena are also pervasive in everyday life. Children observe and participate in them daily. How do they reason about such ordinary complex phenomena? In this study, we investigate students' reasoning about everyday complex phenomena. We report on interviews and a classroom participatory simulation with ten sixth-grade students about ordinary events that could be construed as emergent, such as social situations in which the social pattern emerges from the participating students' individual actions. We have observed a widespread student-initiated strategy for making sense of complex phenomena. We call this strategy "mid level construction," the formation of *small groups* of individuals. Students form these mid-level groups either by aggregating individuals or by subdividing the whole group. We describe and characterize this mid-level strategy and relate it to the students' expressed understanding of "complex systems" principles. The results are discussed with respect to (a) students' strengths in understanding everyday complex social systems; (b) the utility of mid-level groups in forming an understanding of complex systems; (c) agent-based and aggregate forms of reasoning about complex systems.

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INTRODUCTION

Consider the following expressions: “the rich get richer and the poor get poorer,” “the rumor spread like wildfire,” or “birds of a feather flock together.” Although each describes a different phenomenon, they share some characteristics: they describe systems undergoing change; these systems are usually made up of many individuals displaying a variety of behaviors; and, yet, they exhibit a predictable pattern as a group. We also know that there is no “conductor” directing or leading the individuals during the process of change. Such systems fall into the domain of “*complex systems*” and the group level patterns arising from the interactions among the individuals are referred to as “emergent phenomena.”

These expressions are familiar to us from ordinary life experience. However, there is a considerable body of research literature that describes significant difficulties most people have in explaining how such processes occur and in predicting how they will develop over time. In this article we explore young students’ reasoning about familiar complex systems, asking: How do we make sense of ordinary complex phenomena?

The domain of “complex systems” has evolved rapidly in the past 15 years, developing novel ideas and tools, and new ways of comprehending old phenomena. Complex systems are made up of many elements (often referred to as “agents”), which interact among themselves and with their environment. The interactions of numerous elements result in a higher-order or collective behavior. Although such systems are not regulated through central control, they self-organize in coherent global patterns (Holland, 1995; Kauffman, 1995). A focal concept in our work and a fundamental property of complex systems is *emergence*. Emergence is the process by which collective behavior arises out of individuals’ properties and interactions, usually in non-obvious ways. The properties of a system’s patterns cannot be reduced to just the properties of its individual elements (e.g., Bar-Yam, 1997, p. 10; Holland 1998). These patterns are often counterintuitive and unexpected (Casti, 1994; Strogatz, 2003; Wilensky & Resnick, 1999). For example, we can see many cars moving along a road in one direction. At the same time, we may also spot traffic jams forming and dispersing, shifting their peak location. The cars are the elements in this system. Traffic jams are *emergent* patterns. They are formations made up of individual cars. However, they do not share the properties of individual cars. Surprisingly, although the cars are moving forward, the traffic jams are moving backward (Resnick, 1994; Wilensky & Resnick, 1999). Traffic jams result from the local *interactions* among the individual cars and with the road. These interactions depend on the cars’ changing speeds and the distances between successive cars. When cars get too close to each other, they slow down, and traffic jams form. However, one cannot “reduce” the traffic jam and explain it solely through the properties and actions of the individual cars. In an important sense, a traffic jam is not made up of cars, but is a wave, described by the density of the cars on the road (Bar-Yam, 1997; Wilensky & Resnick, 1999). Its backward motion is a property of the group (or "aggregate"), which is not manifested by the individuals (or "agents").

How do we grasp and reason about emergent phenomena? Is this solely the realm of specialized knowledge and learning? Or, do we have some nascent strengths at our disposal that empower us in interpreting and predicting such processes?

A number of studies have shown that people misunderstand emergent phenomena (EP) along a variety of dimensions (Hmelo-Silver & Pfeffer, 2004; Jacobson, 2001; Wilensky & Resnick, 1999). Much of the research to date suggests that only through carefully designed educational interventions, do individuals come to understand complex phenomena (Charles & d'Apollonia, 2004; Klopfer, 2003; Penner 2000; Resnick & Wilensky, 1993, 1998; Slotta & Chi, 2006; Wilensky, 1997b; Wilensky & Reisman, 2006; Wilensky & Stroup, 2003). Some researchers describe novices as entrenched in epistemological stances that run counter to the epistemological basis necessary to interpret such emergent processes (Chi, 2000, 2005; Jacobson, 2001).

However, complex phenomena are pervasive in our ordinary experience, particularly in the social world. We observe and participate in them daily. It stands to reason that such experience with ordinary complex phenomena endows people with some cognitive resources that can be brought to bear on understanding complex scientific phenomena. We therefore set out to study students' reasoning about familiar complex phenomena, the resources they marshal to understand such ordinary EP and whether these resources might be recruitable for learning about EP in other domains.

In this article, we will demonstrate that students do have resources to bring to bear for making sense of ordinary complex phenomena. In particular, we will demonstrate that an important such resource is what we call a "mid-level" construction. When students are asked to develop models about familiar complex systems, their models contain multiple levels of description that are bridged by constructing an intermediary—the mid-level.

Consistent with theorists in the constructionist and strong constructivist traditions, we show that not only do students have such sense-making resources, but that these resources are continuous with cognitive resources used to make sense of simpler phenomena and are also recruitable for making sense of complex phenomena. This is analogous to Papert's pioneering demonstration that children can recruit ordinary body knowledge to learn geometry (Papert, 1972, 1980), Confrey's work on students' understanding of division building on their intuitive notions of splitting (Confrey, 1995), and diSessa's work on children's physical intuitions (diSessa, 1988, 1993). In diSessa's work we see p-prims gleaned from ordinary experience recruited to make sense of formal physics. And although these p-prims may lead students to construct incorrect explanations of the physics, diSessa and colleagues demonstrated that the remediation for these incorrect explanations does not require jettisoning the p-prims but rather organizing them in a different way so as to construct correct explanations (diSessa, 1993; Smith, diSessa, & Rochelle, 1993). By relying on this continuity between intuitive and formal scientific knowledge rather than replacing intuitive knowledge with correct formal explanations, we enable students to construct coherent worldviews rather than employing dichotomous epistemologies for ordinary and scientific knowledge (Hammer, 1995).

Herein, we will show one prominent strategy that students use to make sense of complex systems: formation of mid-level groups—groups that are in between the level of the individual and the level of the EP.

In previous work (Wilensky, 1999a, 2003; Wilensky & Resnick, 1999), we have conducted theoretical analysis and empirical investigations into explanations of EP, in which we identified two description levels and two associated modes of reasoning that students utilize when trying to explain complex systems. The two levels are the micro and macro levels: the micro level involves the behavior of individuals or agents, and the macro level relates to the group properties. The two forms of reasoning are agent-based and aggregate reasoning. Agent-based reasoning is typically expressed in terms of rules or conditions and actions for individual behavior. The group patterns arise through interactions among the agents as they act out the rules in parallel. Aggregate reasoning is expressed in terms of group properties, populations, and flows between groups or rates of change of a population. Traditional science education and science research has emphasized the aggregate form, which is instantiated, for example, by differential equations. Elsewhere (Wilensky & Reisman, 2006), we have argued for the power and importance of the neglected agent-based form and its advantage of greater learnability. Wilensky and Stroup (2003) have argued that both forms of reasoning are necessary and complementary in mature reasoning about EP. In this article, we look more closely at how these two forms of reasoning are reflected in the students' creation of a "mid level" construct to animate and describe change in a system.

BACKGROUND

Previous Work on Understanding Emergent Phenomena

Previous studies on reasoning about complex systems and EP provide us with several valuable insights. In general, this body of research points out various biases, which divert people from attending to bottom-up processes of emergence. In some of the articles, educational interventions have been shown to change this state of affairs. Students' understanding of diverse EP is promoted via innovative instructional interventions, such as constructing and exploring agent-based computer models (Ioannidou, Repenning, Lewis, Cherry, & Rader, 2003; Klopfer, 2003; Levy, Kim, & Wilensky, 2004; Repenning, Ionnidou, & Zola, 2000; Resnick, 1994; Wilensky, 1995, 1997a, b, 1999a; Wilensky & Reisman, 2006; Wilensky & Resnick, 1999) and through role-playing participatory simulations (Colella, 2000; Klopfer, Yoon, & Perry, 2005; Resnick & Wilensky, 1998; Soloway et al., 2001; Wilensky & Stroup, 1999a, c, 2000).

Resnick and Wilensky (1993; Wilensky & Resnick, 1995, 1999) have described a pattern of thinking that makes it difficult for people to make sense of EP. They call this thinking pattern: the "deterministic-centralized mindset" (DC mindset). In this mindset, when people see a group of individuals arranged in some pattern, they tend to assume the pattern arises through the control of one individual or results from centralized control even when such coordination and control does not exist. When they try to explain such patterns, people make use of deterministic causal explanations, and do not invoke the role of stochastic processes in creating patterns. For example, in work with students who were constructing multi-agent models, Wilensky and Resnick found that students initially assumed "point-level" causes for traffic jams (such as accidents or radar traps). Through building models, debugging and explaining, they constructed a "decentralized" understanding of these systems with distributed causation and an appreciation for the role, played by the random entry of cars into the highway. Penner (2000) has found a similar bias among middle-school students as they reason about flocking geese and traffic jams at the start of an educational intervention. The authors show how educational interventions, especially the construction of models, can help overcome this initial bias. Jacobson (2001) has observed the "DC mindset" among university students, novices in the field of complexity, as they reasoned through eight different emergent processes.

Wilensky and Resnick (1999) have pointed to "levels confusion," where the attributes of one level are "copied" onto another level. In one study, they showed subjects a simulation of slime mold cells aggregating into clusters. The subjects were asked to reason about the process by which the cells form clusters, seemingly new entities. In addition to DC control assumptions, they found that many students (and researchers) failed in recognizing the distinctiveness of these two levels of description. The subjects predicted that if the slime-mold cells were provided with more "noses" (or a better sense of smell), the clusters of cells would be fewer and larger. In fact, the emergent pattern is that they gather into more and smaller clusters. Wilensky and Resnick attribute this prediction to explanations that assign intentionality to the individual cells, assuming they *want* to form clusters; so with a better sense of smell they would be better at clustering. In fact, the cells follow pheromone gradients and a better sense of smell results in a greater "stickiness" among the cells, stabilizing previously unstable smaller clusters of cells. Ascribing the group-level results, clustering, to the individual cells is an example of a "levels confusion." They found such levels confusions to be the norm in reasoning about EP.

Hmelo-Silver and Pfeffer (2004) have proposed a framework for exploring and designing learning environments to support students' understanding of complex systems: Structures, Behaviors, and Functions (SBF). They used this framework to examine students' and experts' representations of an aquatic system from the perspective of the parts, or the structural elements of the system, the elements' behaviors or mechanisms and the functional aspects of the system. They found that the students focused on the structures, providing little functional or mechanistic descriptions. In contrast, the experts invoked all three SBF components in their explanations.

Jacobson (2001) compared novices' (university students) and experts' (complexity scientists) descriptions of a variety of eight EP, such as: ants foraging for food and the formation of traffic jams. He employed a set of eight component beliefs to describe their mental models. Among these beliefs, he found that a smaller sub-set were distinct between the two groups. He found that the novices tended towards a "clock-work" mental model, characterized by centralized control, predictability, linearity and a reductive approach. By contrast, the experts displayed a "complex systems" mental model that includes features such as decentralized control, multiple causes, randomness, equilibration processes, and a non-reductive approach.

The eight EP that Jacobson employed in his study cover a wide range of domains. However, these phenomena were in the main, non-familiar, invisible, or partially invisible. For example, the EP included various evolutionary processes, ants foraging for food and slime mold transformations between single-celled and multi-cellular organisms. These examples are prominent in the complex systems literature. However, younger students and novices do not typically have the prior knowledge, which is necessary to see how emergence can account for these phenomena. Some of the constituent elements may be hidden (pheromones for slime-cells or ants) or the underlying mechanisms may be unknown (genetic mutations as a randomizing mechanism in evolution). This unfamiliarity with the domain knowledge may be one source of the difficulties reported earlier.

In exploring students' understanding of emergence, Penner (2000) tried to eliminate this confounding factor by using Cellular Automata, where no domain-specific knowledge is necessary. The rules of the game are explicit and the context was equally unfamiliar to all the students with whom he had worked. The students applied the rules to the game, and observed the emergent patterns.

Our motivation for this study emerged in reaction to this research. Our hunch was that because students experience EP in their everyday life, they probably have at their disposal intuitive strategies for making sense of them. Using knowledge-poor problems to explore students' reasoning about emergent systems may not tap into students' possibly richer understanding of EP, which may be more sophisticated and powerful.

Our approach in this study was to interview the students about situations that can be described as ordinary everyday situations that they know well, but which can also be described as emergent. In this way, we wished to explore whether similar biases occur when students reason about familiar social situations, which they observe or participate in regularly. Moreover, we aimed to uncover students' strengths in reasoning about EP, which might then be recruitable when delving into less familiar settings.

Agent-Based and Aggregate Forms of Reasoning

In our work with learners to date, we have found that many of the most fundamental issues related to making sense of complex systems center on the interaction of agent-based and aggregate forms of reasoning. This central issue will resurface throughout the article as students' intuitive strategies in making sense of EP fall into two modes, which are related to these two forms of reasoning. There has been a longstanding literature (Bateson, 1972; Bertalanaffy, 1968; Laszlo, 1991; Schelling, 1978) on the relations between micro- and macro-levels of description dating back at least as far as Aristotle's famous dictum: "the whole is more than the sum of the parts." New computational tools afford a more powerful and fluid exploration of the interaction between agent-based and aggregate forms of reasoning.

A number of theorists have approached the challenge of exploring the relationship between these two levels of description and the associated forms of reasoning. Four main approaches have been developed to organize and articulate the relationships between agent-based and aggregate reasoning.

The first approach is based on a notion of "difference in scale" (Lemke, 1999); another is based on a notion of "incommensurability" or an ontological divide (Chi, 2000, 2005); a third is based on a notion of a developmental trajectory, starting with agent-based reasoning, moving to aggregate reasoning (Wilensky, 2006; Wilensky & Papert, 2006; Wilensky et al., 2005); and the fourth is based on the notion of "complementarity" (Wilensky & Stroup, 2003).

The Scale Approach

Lemke (1999) provided a scale-driven framework for organizing levels of description. Differences in scale are typically organized in terms of size or temporality; the fundamental processes are invariant, but they act at different scales of magnitude or time. Newton's laws, for example, operate over a range of scales of size and so the distinction between a galaxy and a drop of water (in so far as their behavior is actually governed by these laws) is just the physical scale. Although Lemke did not explicitly address the issue of the associated forms of reasoning, his approach suggests that there is no elementary difference in reasoning associated with different levels of description, the same fundamental processes are operating at each level. In this view, emergent phenomena do not require an essentially different mode of reasoning so much as comfort with multiple scales and transition between scales. This approach would also seem to suggest a pedagogic strategy of emphasizing the similarity between these two levels and focusing our pedagogy on issues of scale.

The Incommensurability Approach

In contrast, Chi (2000, 2005) described a fundamental divide between agent-based and aggregate forms of reasoning about EP as they belong to distinct ontological categories of reasoning about processes of change. She described two schemas for processes: one for direct processes (e.g., blood circulation) and one for emergent processes (e.g., diffusion). She argued that understanding cause–effect relationships at the local level does not necessarily afford an understanding of the global patterns without an appropriate schema.

Chi maintained that direct processes are easier to understand and more amenable to change because people are predisposed to view all processes as direct. She argues that direct and emergent processes have a different ontological status and that difficulty arises when learners fail to adequately differentiate these ontological categories. She has compared the differences between these processes to gender differences: the person you see is either male or female.[1] It is a categorical judgment, not a continuum: emergent processes are fundamentally different and cannot be explained with "direct" schemas. As a result, she concludes that when students misattribute properties of one schema (the schema for direct processes) to concepts from another ontologically distinct schema (the schema for emergent processes), then students will never understand the concepts deeply. Chi concludes that instructional interventions, aimed at developing the emergent schema, should not build from existing naïve conceptions of direct causality, as they are incompatible.

The Developmental Approach

Since 1989, Wilensky and colleagues have explored students' agent-based reasoning and how it can develop through the practice of agent-based modeling (Centola, McKenzie, & Wilensky, 2000; Resnick & Wilensky, 1993, 1998; Wilensky, 1993, 1997a, b, 1999a; Wilensky & Reisman, 2006; Wilensky & Resnick, 1995, 1999). Wilensky has argued that traditional science curriculum has emphasized aggregate forms of reasoning. The rate-based reasoning inherent in calculus colors science curriculum at all levels. Wilensky suggested that educational modeling tools such as STELLA (Richmond & Peterson, 1997) and Model-It (Jackson, Stratford, Krajcik, & Soloway, 1996) have removed the calculus formalism but

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[1] In a personal communication with the second author.

have retained the rate-based aggregate forms of reasoning. He has argued that agent-based reasoning is developmentally prior to aggregate reasoning as it is embodied and leverages children's intuitions about their own bodies, perceptions, decisions, and actions. In this view, the disconnect between students' natural agent-based reasoning and the aggregate forms they encounter in school creates a barrier to students' understanding of science. He has argued for the restructuration (Wilensky, 2006; Wilensky & Papert, 2006; Wilensky et al., 2005) of traditional science content to employ agent-based representational forms instead of aggregate forms. Lehrer and Schauble (2006) emphasized the importance of agent-based representational tools, set within inquiry- and modeling-based learning environments, in eliciting young students' existing intuitions about EP and recruiting them for further learning. Wilensky and colleagues have shown that students can make sense of more advanced content at a younger age using such agent-based forms (Centola, McKenzie, & Wilensky, 2000; Wilensky, 1993, 1997a, 1999a; Wilensky & Reisman, 2006). He has argued that after considerable experience with agent-based reasoning and agent-based modeling, students are developmentally ready to "summarize" the results into an aggregate form of reasoning. This approach differs from Lemke in that it posits fundamental differences between the forms of reasoning, but differs from Chi in suggesting that these differences can be bridged. The two forms of reasoning are not fundamentally incommensurable; indeed, agent-based reasoning, in addition to being a powerful model of reasoning in its own right, is also an important developmental precursor to aggregate reasoning.

The Complementarity Approach

Wilensky and Stroup (2003) have argued for the complementarity of the two perspectives and forms of reasoning. In contrast to Lemke, they see a fundamental distinction between the two forms of reasoning that cannot be reduced to issues of scale. Properties of the system are distinct from properties of its elements. In contrast to Chi, they argued that these forms of reasoning are not incompatible, but rather mutually informing and reinforcing. They show students, engaged in participatory simulation activities, coordinating these forms of reasoning to gain multi-perspectival understanding. They argue that it is through the coordination of these two forms of reasoning that a mature understanding of EP develops. Markers of sophisticated EP reasoning are an interpenetration of these two reasoning forms. They call this perspective "Agent-Aggregate Complementarity" (aka "AA complementarity").

The consequent pedagogic strategy is to provide situations and environments where both these perspectives can be developed and opportunities for students to coordinate and bridge the two forms of reasoning.

In this article, we seek to elaborate on the AA complementarity framework and focus on some of the developmental pathways to such complementarity. We have particularly focused on the roles of agent-based and aggregate forms of reasoning in students' sense-making of these phenomena. These four approaches will be explored in the remainder of the article, as we will provide evidence and support for some over others. Although we do address Lemke's scale framework, our primary focus will be on the latter three frameworks that all posit significant differences in reasoning about simple versus complex phenomena, and in particular, we take issue with Chi's claims of incommensurability.

Everyday Complexity

The most common examples of ordinary complex phenomena are in the social world. For example: a sixth-grade classroom goes out on a break to the playground. One can see boys and girls congregating in same-sex groupings. Explaining such a pattern does not require a centralized planned organization. It is enough to think of a small set of simple rules: each individual prefers to be with other individuals of the same gender. If you are by a group of mostly the opposite gender, you move away. If you are by a group of primarily the same gender as yours, you stick around. The emergent pattern is a gender-segregated community of sixth-graders. However, no one has instructed them to separate in this way![2]

We wish to take note of two points regarding the aforementioned example, foreshadowing the current study. (1) *Familiarity*: Sixth-grade students experience this scenario frequently. They can see the behaviors of their classmates and are probably aware of their own motivations in this process. They can observe individual behaviors, small group interactions, and large group patterns. While scanning the playground, they can see most of their classmates clustered in groups as well as their own clique; (2) *An intermediate level*: Typically the discussion of EP refers to two levels of description—the micro-level of individuals and the macro-level of the whole group (Bar-Yam, 1997; Schelling, 1978; Wilensky & Resnick, 1999). In this example, we can see the formation of an intermediate level: small clusters of children. Some researchers (e.g., Bamberger, 1996; Dopfer, Foster, & Potts, 2004; Lemke, 2001) have argued that such intermediate levels are important for understanding many systems. Lemke has suggested that interactions at the lower level are constrained by some higher level, so that only some interaction patterns

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[2] This example, based on the work of the economist Thomas Schelling (1978), has been well studied. A NetLogo model of this phenomenon, the "Party" model (Wilensky, 1997a) allows you to change the "tolerance" slider governing how many opposite-gender individuals in your group will cause you to become unhappy and move away. It turns out that even a small amount of intolerance produces high degrees of segregation. Note that the explanation is also neutral with respect to whether the movement is directed or random—either way the segregation appears. The individuals can be described as operating according to simple "happiness seeking" rules. The emergent pattern is a gender-segregated community.

are possible. One of these patterns can be a new stable, emergent intermediate level of organization. In this article, we will show the significance of such "mid levels" as they play into students' reasoning about familiar complex phenomena.

Research Questions

Our goal in the research study reported on herein was studying students' reasoning about ordinary complex phenomena in which they participate in everyday life contexts. We were motivated to understand the resources students utilized in these contexts and whether these resources would be helpful to us in designing more effective learning environments.

We ask the following research questions:

1. What characterizes students' reasoning about everyday emergent phenomena along dimensions that distinguish "complex systems" reasoning from other forms of reasoning?

In this study, we have found an unanticipated strategy that students used to reason through the dynamics of a complex phenomenon: they created an intermediate level, made of several groups. Thus, the following research questions relate to this finding and elaborate on it:

2. What characterizes students' construction of mid-level groups to reason about emergent phenomena?
3. How do the characteristics of the students' construction of mid-level groups relate to their overall reasoning about emergent phenomena in terms of "complex systems"?

METHOD

Participants

The data we report on in this article was collected from a school implementation conducted at an inner-city public school in northern Chicago that targets, attracts, and celebrates diversity. Out of the total body of students, 25.4% were Limited English Proficient and 62.7% were Low Income. The demographic distribution is multicultural and includes: White 25.7%, Hispanic 24.5%, African American 23.7%, and Asian 23.7%.

Out of a sixth grade class of 27 students, 10 students were selected for the interviews via stratified random sampling. The teacher rated the students' academic success on a three-point scale, and five students of each gender were randomly selected to represent the class distribution of academic achievement.

Setting

This work took place in a sixth grade classroom that was an implementation site for the ISME project (Integrated Simulation and Modeling Environment). Over the course of the four-month implementation, the research team conducted several HubNet-based participatory simulation activities (Wilensky & Stroup, 1999a; based on NetLogo, Wilensky, 1999b). The students were interviewed twice during the implementation. The data reported on herein were taken from the first set of interviews conducted after the first such activity, the Disease participatory simulation (Wilensky & Stroup, 1999b).[3,4]

The interviews lasted 30–45 minutes and were conducted in the teachers' lounge or the vice-principal's office. Three graduate students, full participants in planning and enacting the activities interviewed the students. The interviews were videotaped (total of approximately 13 hours) and transcribed.

Tasks

A protocol for the interviews was created, piloted, and refined. It included three tasks in the first interview and four in the second interview. In each interview, one item was related to the participatory simulation that preceded it. With respect to the other items, our goal was to elicit the students' best agent-based and aggregate reasoning by selecting scenarios for which a lack of specialized prior knowledge would not hinder the students' thinking. In these items, neither the individual level nor the population level is concealed. The goals and behaviors of the agents are clear and do not need to be inferred. The group-level phenomena are observable and readily describable. The students can explain how the system changes starting from either level of description. Thus, the target system has multiple entry levels. We selected situations in which the agent is the student: in a group scatter for gym class or the spreading of a rumor in a school. At the same time, the group "metrics" and evolution are not hidden. The size of the group is such that students can experience it in familiar scales of magnitude. Given that the agent is the student, we conjectured that the individual agents would be easy to reason about, and could be a resource in thinking about the group's dynamics. The approach was

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[3] Our analysis of the interview items assumes that student responses represent their pre-intervention thinking and were not greatly influenced by their participation in the one PSA. We have repeated the interviews in the following year before conducting any PSA. Preliminary analysis of the following year's interviews suggests that student reasoning before any experience of PSAs is consistent with the results presented herein.

[4] Subsequent to these interviews, the research team conducted several more participatory simulations including Gridlock (Wilensky & Stroup, 1999c) and SAMPLER (Abrahamson & Wilensky, 2004).

to provide a wide array of stimuli that would gradually bring forth their thoughtful reasoning about the system's evolution over time.

In the current analysis, we focus on one key item, the "Scatter" activity. We introduce a skeletal "Scatter" scenario:

> *At the beginning of a Physical Education class, the students are standing close together. The teacher tells the students to scatter so they may perform calisthenics. What happens? Can you describe and explain?*

During a 15–18 minutes exchange, the interviewee is asked to describe and explain the process by which the students scatter.

We developed a progressive taxonomy that guided the interviewers in questioning the students. All interviewers reviewed this taxonomy and agreed to introduce questions from each of these categories as appropriate to draw out student thinking. The taxonomy is comprised of four categories of questions, for which we provide examples:

1. *Elaborating description of the entry level*: What do you mean when you say. . . ? Is there anything else you want to add? Can you describe for me some more the part where. . . .? How does . . . happen?

Upon completion, the level that has not been described is introduced:

2. *Introducing agent level*: What did each kid need to do in order to scatter? What are some different things different kids did?
3. *Introducing group level*: If you were up really high, and could watch your class scatter—what would you see from above when they're scattering? How would you describe this to someone who wasn't there?
4. *Connecting levels ("what-if" questions, introducing local and global perturbations of the system)*: What would happen to the group if there were one annoying kid that always stayed close to another one? What if you're in a smaller room? If there was a big puddle and nobody can stand there?

We also provided coins that students used to model the system's evolution. In some of the cases, of their own volition, or offered by the interviewers, the students drew pictures to describe the system at different stages.

The "scatter" scenario offers multiple features and phenomena that can be experienced, observed, and explained at both the agent and aggregate levels of description: clustering while spreading, irregular jagged individual routes on the background of collective outbound flow, emergent formation of rows when a maximum inter-student distance is imposed (e.g., the students do not want to be too far from the teacher), as well as several ways to describe the global behaviors: time till the students settle down, density gradients, collective mobility of the individual student, and average distance from the center of spread. The richness of this scenario together with its familiarity were criteria in selecting it to elicit students' reasoning.

All student interviews were captured on videotape, transcribed, coded, and analyzed as will be described in what follows.

Analysis

The videotapes of the interviews were transcribed and then analyzed. The analysis of the interviews encompasses three parts. In the first part, we determine the extent to which students' reasoning reveals elements of "complex systems" thinking. In the second part, students' construction of mid-level groups is described and characterized. In the last section, we relate the results from the first two parts, exploring associations between the students' formation of "mid levels" and their reasoning about complex systems.

In a research seminar led by the second author, several in-depth discussions were held regarding the categories of analysis for this study, based on prior questions regarding agent-based and aggregate reasoning. The first author laid out the coding scheme, which was extensively discussed in the group until convergence was attained. The first author implemented the coding scheme.

Beliefs of "Complex System" Thinking

What characterizes students' explanations of everyday EP along dimensions that distinguish "complex systems" reasoning from other forms of reasoning? Do the students employ "complex systems" ideas when reasoning through the scatter of a gym class? To determine this, we use a framework, which is based on Jacobson's (2001) scheme for analyzing experts' and novices' beliefs when explaining various emergent processes. From these Jacobson rubrics, we include only those four, which were correlated with each other and distinguished between novices and experts. We also added one more rubric that assesses whether the student clearly distinguishes between the two levels of description or confuses among them (Wilensky & Resnick, 1999). Each interview is examined for evidence of the following elements of "complex systems" reasoning: (1) Distinction between levels; (2) Decentralized control; (3) Unpredictability; (4) Equilibration process; (5) Small actions–Big effects.

In Table 1, these dimensions are defined and examples are provided. We contrast between a "complex systems" model and a "clockwork" model when reasoning about systems, based on Jacobson's (2001) previous work.

The total score we use for each student is the number of "complex systems" components (out of five) that she has expressed in the "Scatter" interview item.

TABLE 1
Component Beliefs Regarding Emergent Phenomena: Definitions, Examples and Comparison

	"Complex Systems" Beliefs		*"Clockwork" Model Beliefs*	
Dimension	*Definition*	*Example*	*Definition*	*Example*
Levels[a]	*Distinction between levels:* Student[b] behaviors are distinct from those of the class. Different descriptors, rules, and patterns are assigned to each level.	. . . how do I think like the bird or like the kids? I think like the kids mostly because the bird is just seeing what's going on, but he doesn't know how we're thinking or which way we're planning to go. He just sees the action going on.	*Confusion between levels:* Student behaviors are identified with those of the class. Descriptors, rules and patterns from one level are inappropriately assigned to another level.	A hypothetical example (none were found in the data): describing individual students as "spreading out."
Control	*Decentralized:* The students navigate locally to find a free space. The implicit form characterizes the description of the system; the explicit form is a direct reference to the lack of centralized control.	Explicit: In reality, nobody is controlling them to go anywhere. They just go on, not by number. They're controlling themselves so everyone goes all together. Implicit: . . . people don't move the same amount. According to the areas around them. . . They don't really know until they come up real close to somebody. Then they know to move apart. . . . Sometimes it's one, sometimes it's a couple of them, sometimes it's the whole class that move at the same time.	*Centralized:* A single source of control governs the scattering students' actions.	Everyone is coming out of the middle. The teacher tells them to go to different areas, and he's going to instruct them from these different areas.

(Continued on next page)

TABLE 1
Component Beliefs Regarding Emergent Phenomena: Definitions, Examples and Comparison *(Continued)*

	"Complex Systems" Beliefs		*"Clockwork" Model Beliefs*	
Dimension	*Definition*	*Example*	*Definition*	*Example*
Agent actions	*Unpredictable:* An individual student's motion is unpredictable, even when initial conditions are known.	[Interviewer: And who moves when?] Uhh.. Well, I mean it's not like in order or anything. . . . Like we don't have any order. People just decide to stretch out. We just get up and move.	*Predictable:* Individual students' motion can be predicted from initial conditions.	[Interviewer: Do they all move the same amount?] Yea kinda. Yea basically.
Ontology	*Equilibration:* A process by which the system gradually stabilizes is described.	People probably will still keep moving around, because they're not settled. . . . You keep on moving until everybody is spread out and then they are not really close to each other.	*Static structures, Events:* No equilibration process is mentioned or described	[d]
Effects of local perturbations[c]	*Small actions—Big effects:* A ripple effect throughout the system may result from a small perturbation.	So if somebody comes here, then they may tell them to move so, if they come closer to a person, then the person might move by another person, and that's how it gets all mixed up all over again, so it takes a while for us to scatter.	*Small actions—Small effects:* Small local rearrangement results from a small perturbation.	Um, these two people are going to stay here. And all these people move around, and this person just moves a little to over here and then they're all scattered around and this person . . .

Note. The framework was developed in the Jacobson (2001) study.

[a] The "levels" dimension is not included in the Jacobson (2001) framework.

[b] Reference to "student" is to students participating in the imagined "Scatter" scenario, rather than to the interviewees.

[c] The interviewees were asked what would happen if one or two students refused to move.

[d] No example is provided, as the category is defined by the non-existence of a particular element.

Characterizing "Mid-Level" Construction

We focus here on a pervasive pattern that we have found: the invention of a "mid level." This strategy takes a variety of forms and plays into reasoning in different ways. Although our interviews explicitly prompted descriptions of the two focal levels, an un-prompted level frequently arose: *The students used sub-groups to reason through the process of change.* Given the supports and prompts in the interviews, we did not anticipate this student-initiated description. For example, when describing the spread of a rumor, one student included in his account cliques, with the rumor spreading from a single student to a clique. In this analysis we wish to characterize the construction of mid-level groups.

We describe the pattern qualitatively through examples and quantitatively by frequencies, regarding the following dimensions:

1. *Frequency*: How many students constructed mid-level groups? How many distinct mid-level forms did they construct?
2. *Trajectory*: From which level are the sub-groups formed: from the whole group or from the individuals in the group? In some cases, the large group is subdivided into small groups, such as rows, and the small groups are treated as homogeneous entities that move as a single entity. This is termed a "population-to-mid-level" trajectory. In other cases, local interactions among students are described, resulting in groups, such as clusters. We call this an "agent-to-mid-level" trajectory. Based on the student's description, we note how the mid-level groups are formed, subdividing or clustering, and code accordingly.
3. *Number of units in a group*: We are interested in this number as signaling a transition between what can be reasoned about causally and quantitatively and a more qualitative mode of describing the system. To identify these numbers, we used the verbal transcripts, as well as the interviewees' coin formations and drawings. We noted the number of units in a group in two distinct ways depending on the trajectory. When the trajectory is to form mid-level groups by aggregating individuals, the number refers to the number of individuals in a group. When the trajectory is to form mid-level groups by breaking up the larger group, the number refers to the number of mid-level groups in the population.
4. *Core or Peripheral*: Some of the sub-groupings were very short-lived and did not serve in later reasoning. These are distinguished from mid-level constructions that form the backbone of the student's reasoning. This dimension serves us in judging the centrality of mid-level formation in students' reasoning. We test this by omitting the particular mid-level section from the student's overall description and determining whether the line of reasoning still holds or whether it breaks down.

5. *Specific manifestation of mid levels*: Students constructed mid levels in a variety of ways. The specifics of the particular mid-level groupings for each student were classified and described.

Relating "Mid-Level Construction" to "Complex Systems" Thinking

How do the attributes of mid-level construction relate to the explanation of scattering in terms of complex systems?

We examine whether the score on the five elements of complex systems thinking is associated with the way mid-level groups are formed. We focus particularly on the trajectory dimension as this most clearly enables us to examine the relationship between the two forms of reasoning about systems (agent-based, aggregate) and a more general understanding of complex systems.

RESULTS

The results are described in three main sections. In the first section, the students' expression of the five aspects of "complex systems" is examined. The second section illustrates "mid-level construction" both qualitatively and quantitatively. In the third section we seek possible associations between the results in the first two parts: "complex systems" reasoning and particular qualities of "mid-level construction."

Beliefs of "Complex Systems" Thinking

Research Question 1: What characterizes students' reasoning about everyday emergent phenomena along dimensions that distinguish "complex systems" reasoning from other forms of reasoning?

How do the students portray the change in a scattering class? For each student, five component beliefs were coded as either a "complex systems" model or as a "clockwork" model (Jacobson, 2001), as described earlier. Table 2 and Figure 1 note the number of students who expressed "complex systems" beliefs when explaining the scatter of a class at gym.

We conclude:

1. A bi-modal distribution of scores can be seen, peaking at a lower value of 2/5 and at the higher value of 4/5.
2. Most of the students employ distinct descriptions for the individuals and for the group and view the locus of control as decentralized.

TABLE 2
Distribution of Complexity Elements in Students' Explanations of the "Scatter" Scenario

Complexity Element	*Number of Students*[a]
Distinct levels	9
Decentralized control	8
Unpredictability	7
Equilibration processes	5
Small actions—Big effects	1

[a] Maximum number of students is ten.

3. Two elements were observed for only some of the students: acknowledging the stochastic nature of the process (unpredictability) and including equilibration processes. Only one student described system-wide effects resulting from a local perturbation.
4. We note that the students who expressed the less frequent elements referred to the more frequent ones as well.

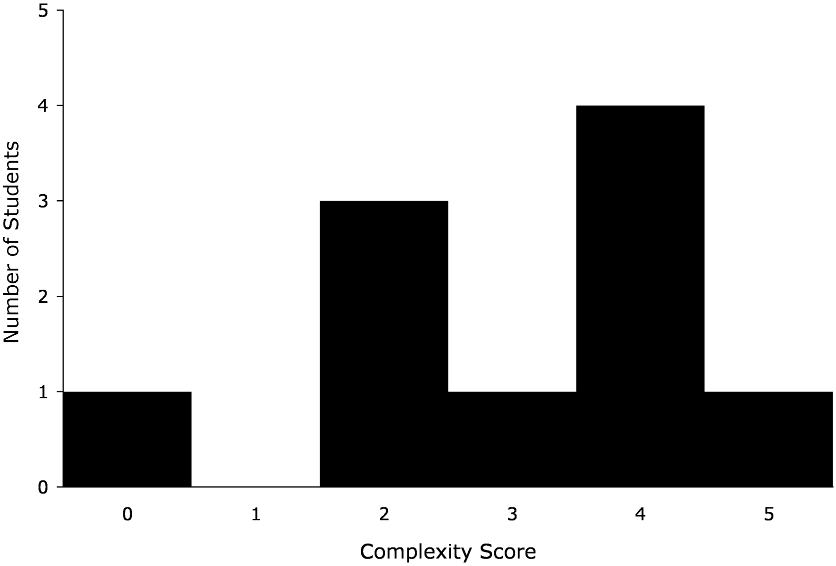

FIGURE 1 Histogram of students' "complex systems" scores, a count of the number of complexity elements expressed in the "Scatter" scenario.

Characterizing “Mid-Level Construction”

In this study, we have found a strategy that students use to reason about emergent phenomena: they create an intermediate level, grouping agents into small groups. Thus, the following research questions relate to this finding and elaborate upon it. *Research Question 2: What characterizes students’ construction of mid-level groups to reason about emergent phenomena?*

We report on an analysis of mid-level construction, which was extracted and magnified from the students’ explanations of an EP: the scattering of students in preparation for calisthenics, rumors, and the spread of disease.

In the first section, we describe a variety of situations in which we have observed students forming mid-level groups. In the second part, we turn to a quantitative account of these results.

Mid-Level Construction: Qualitative Description

In this section, we present illustrative examples in which students formed mid-level groupings. These are excerpts taken from transcripts of the interviews and from one classroom conversation. The excerpts will be discussed shortly, to highlight some features that are later analyzed in quantitative form.

Disease: Conversation in a classroom. The following conversation takes place in a sixth-grade classroom during a sequence of activities involving the Disease participatory simulation (Wilensky & Stroup, 1999b), which models the spread of disease in a population. The specific context is deer in the wild, among which chronic wasting disease is spreading. Wilensky and Stroup have developed collaborative simulation environments in which students can participate as agents in a group simulation. These participatory simulation activities seek to bridge the agent and aggregate forms of reasoning. While the students each operate their own agent, the group patterns are explored and designed using a variety of strategies (Wilensky & Stroup, 1999a). During these activities, the students invented experiments of various kinds. Most of the time was spent negotiating the next experiment and planning it, or interpreting the simulation that had taken place.

The students are planning an experiment that compares disease propagation among deer when they know who is sick, and when they do not know who is sick. In the HubNet Disease activity, a turtle’s sickness is denoted by a red dot. As a participant, you can see yourself, but also those around you. If you are healthy, you may want to avoid the turtles with the red dots. The simulation supports this comparison, as you can switch off the red-dot representation.

The following conversation takes place before running the experiment. The students are engrossed in the process of predicting: When will the deer get sick faster?

Molly: *They stay away when you know who's sick. When you don't know, if someone touches your turtle [i.e., deer], then you go for someone else.*

Veronica: *I agree with half of what you say. When you're sick, you stay away. When you don't know: the deer* ***play and share with other deer****, and then they get sick.*

Tamara: *If you're a baby deer, you stay with your family,* ***in a pack****. You don't know who to avoid and then you get sick faster.*

Veronica: *If you're feeling like an outcast, you* ***try to be with the other deer*** *and you get them sick.*

The students are reasoning about the propagation of disease in two cases: when you know, versus when you do not know, who is sick. They all predicted that the disease would spread faster when the deer do not know who is ill. As the students share their views, they elaborate on each other's stories, enriching the threadbare simulation with various spins on the agent motivations and actions, forming a common narrative frame. This story-making is powerful. The students leverage these stories to make predictions regarding the whole population—moving from story to simulation of the disease propagation and predicting the related group metric (faster or slower spread of the disease).

While making perfect sense within the context of animals caring for each other and protecting their young, this is also an instance of "mid-level construction." Tamara (all names have been changed) has introduced the idea that deer congregate in packs.

Molly introduces a deer/agent rule: when the deer know who is sick they stay away from each other; however, when the deer do not know who is sick they touch each other. This contact serves to propagate the disease. Following Molly, Veronica forms a new situation by changing one of the agent rules: she agrees with Molly that deer keep away from the sick ones when they know who is sick; however, when the deer are unaware of who is ill, they congregate—playing together and sharing. The deer are attracted to each other; they are not moving randomly as individuals. As a result of this attraction, the meetings between deer become more frequent. She surmises that the aggregate pattern will be a faster spread of the disease. It is unclear whether these are dyadic or larger congregations. Tamara elaborates on this idea, introducing the mid-level grouping: the deer socialize in packs, caring for their young. At this point, Veronica's ambiguous idea of congregation has transformed into mid-level groups: families or packs. This assemblage is not one group clustering together, but several separate groups. This closeness breeds a faster overall spread of disease. It is easier for her to see how the disease propagates faster in a small tight group. Veronica takes issue with Tamara's narrative of deer congregating in packs, restricting its applicability. Some of the deer are not in packs. There are "outcast" deer that are searching for friends. These are loners who transfer disease as they try to join the packs.

We can see that constructing mid-level groups is not an artificial addition to the modeling of EP, but an integral and natural process that exhibits many forms. Although "cliques" or "packs" constitute a natural social context, they also provide a smaller-scale system, in which emergent processes can be determined more easily and then generalized to the whole population.

Thus the students' explanations and descriptions can be seen as operating at three levels of description: an *agent*, or a single deer, which may be sick or healthy who is either keeping away or seeking the company of others; the *mid-level group*, or the pack, which protects the individual deer, is dense, and thus susceptible to a quick spread of disease among its members; and the *whole population*, for which the rate of propagating disease is assessed.

We note the empathy Veronica expressed in this conversation, possible echoes of personal social experiences. When referring to the deer, the students shift between "they" and "you" throughout. It is evident in Veronica's compassion for the lonely deer, Tamara's concern for the young deer in the pack and the social language Veronica employs ("play and share") to describe the congregating deer. It would seem that the students are drawing on their own social experiences in families or with peers, forming analogies with the deer in the simulation, that further their understanding of interactions in the system. In this vignette, the students are leveraging their social knowledge to make inferences regarding the rates at which the disease spreads.

Rumor. In this excerpt, the interviewer asks Tom about the spread of a rumor in school:

Interviewer: *Then lets make believe there's a rumor. Lets make believe that somebody discovered that Miss Ray (the homeroom teacher) dresses up as a clown and makes children laugh in the vacations.*
Tom: *He says it to a group of friends that he hangs with. It isn't in a relation of one-to-one. It's more like one to three or four.*
Interviewer: *He tells how many?*
Tom: *Three–four... and they, they say it to three-four* ***and so on and so forth****.*
Interviewer: *How long does it take for all the class to know?*
Tom: *I say that two–three days.*
Interviewer: *Tell me how this rumor is moving around the class?*
Tom: *He tells three-four kids that he hangs with. The next day they* ***scatter*** *it to three–four kids.*

Tom explains that the spread of rumors in the school does not take place in a "one-to-one" interaction; this is not a linear propagation. The rumor in school spreads through one kind of event: one person tells three-to-four people who are in his clique. He repeats this pattern three times. Agents are collected into groups of three–four, they split up and soon disperse the rumor to other groups. The movement in the spread of rumor is from agent to mid-level group. This grouping is well situated in the context of cliques, which provide the narrative frame.

The bolded text "*and so on and so forth*" denotes two meanings: the generality of the propagation mechanism, but also the pushing forth in time, repeating many times in sequence, rather than in parallel, until the whole class is cognizant of the teacher's antics during vacation time. We cannot see explicit parallel events in this description. Possibly, the parallel spread of the rumor at increasing rates (in the first stage) is condensed into the mid level: Instead of four students each telling one student, one student tells four students, who form a group.

"*They **scatter** it to three–four kids*" indicates a mix of levels, in which a group process (scattering) is inserted into an agent-to-small-group event. We note that the previous scenario in the interview was "Scatter," so that some echoes of this scenario are resounding here. This hints at Tom's attempt to bridge the clearly causal at the agent-to-mid-level, to a global spread of the rumor throughout the whole group.

The number of kids in each clique is stated as "three–four." For Tom, the small groups are part of the core mechanism in propagating a rumor. Removing the clique from his description would cause it to fall apart. These small groups are both target and source for the propagating rumor in a semblance of parallel action, and they serve to transmit the rumor throughout the system.

Scatter I: Clustering while spreading. Throughout this description of the students scattering at PE class, Rachel describes both spreading and clustering. In the first part of the interview, she explains that a social agenda drives some of the scattering students' actions: they want to stick together and talk.

> *There's a bunch of friends talking, and another bunch . . .*

However, a few minutes later, the socializing scenario turns into a "physics" story of collisions:

> *. . . and then they'd start moving in separate directions so you know they won't be grouped up anymore. And people will probably most likely bump into each other . . . I mean you run and you look for an empty place. . . . And like even if two people would see the same place, you know, they'd end up, some, one person would end up going in different directions.*

In the latter part of the interview, she takes a birds' eye view. From this perspective, she sees the students spreading out, although some are still clustered in trios:

> *Most of the people will be spread apart but you'll see some groups still together. Like these three will still be together and these three will still be together. . . .*

She then summarizes, with a statement that disconnects between the local events and group spread:

> *Collisions have nothing to do with scattering, but eventually they'll be scattered you know.*

She does not bridge the individuals' behaviors and the group scattering. These are separate descriptions. The clusters emerge in the process of scattering, but disperse by the time the system has settled down. The clusters form through stochastic collisions, displaying agent-based reasoning in Rachel's simulation of the process. ". . . if two people would see the same place. . . " references the fact that parallel decisions and actions may result in temporary clustering on the background of the group spread.

We can see Rachel forming a mid level from some of the agents, small groups of three. Earlier in the description, this formation is framed in friendly social interactions among the students. Later on, her explanation shifts into the physical domain of stochastic collisions, taking place in the space of the gym. Although she claims that "collisions have nothing to do with scattering," the inclusion of this process in her description points to the pervasiveness of an emergent clustering-while-spreading pattern.

Scatter II: Emerging lines spread out via centralized control. Jessica is describing the scattering class at gym. She portrays how the students move out searching for their own space, making sure they are away from their neighbors, so they can exercise without hurting each other. However, she repeatedly raises a concern. Not only should *she* have her own space, but *her neighbor* should have enough space as well: *"And make sure the other person also has space. You're not taking their space."* As students move, they attend to their neighbors and negotiate with them, guaranteeing they do not move into the same space.

In the following excerpt, we see how these behaviors play into an emergence of lines that further spread out in a safe centralized pattern of scattering.

Jessica: *. . . just look back. And if there's someone behind you, you won't take a step back. And if there's a person in front of you also, maybe you could tell the person on the end, all the way at the end, and they could move a little bit more and everybody could spread out more.*

. . .

Interviewer: *. . . What am I looking for?*

Jessica: *Where is there space.*

. . .

Interviewer: *Then you said something about asking the person at the end . . .*

Jessica: *. . . of the line if he could move a little bit more and everybody could spread out.*

Interviewer: *Now when you say line, are you thinking of this as a line? How do you see this in your mind? Give me an idea. 'Cause you said line, so I'm just wondering.*

Jessica: *Well, see, it's mostly not a line, but there's always someone near you, there don't have to be, but maybe there usually is someone near you, and if you look across that person, he may not be exactly where you're at, but he's next to you, so you consider that kind of a line . . . and maybe there's people in the back, and they're near you, and you consider that back row a line.*

Jessica's mid-level groups are rows of students. They afford the group's spread in both agent-based and aggregate forms.

Initially, she discusses individual students finding their space and negotiating with their neighbors. Finding this mechanism unsatisfactory for sufficient spread, she introduces the idea of a person at the end of a line who is asked to move out and make room for the rest of students. We name this process an "outsides first" pattern. This is an aggregate description of rows stretching, by pulling at their ends. Because people cannot move into spaces where there are other people, the ones that do have room, the ones at the edge of the group, move out into the open space, opening up the spaces for other people to move in. This staggered motion of the individual students ensures their safety. It is regulated by centralized control: *"you can tell the person at the end."* We view this as a centralized description, because instructing the students at the end to move out is based on a global view of the students' location; the group's spread is regulated through a "conductor," who has a birds'-eye perspective of the collective.

However, when she is asked about the nature of these lines, she shifts back to a stochastic agent-based description. After mentioning rows a number of times, when pressed by the interviewer, she retracts slightly: *". . . there don't have to be. . . ."* She turns to probabilistic language *"there usually is someone near you . . . he may not be exactly . . . "* After qualifying her claim to rows, she then returns to explain the fact that rows usually form: "you consider that kind of a line." The

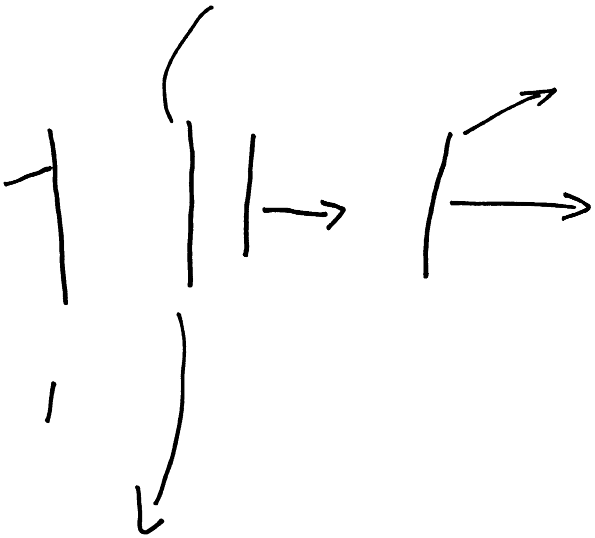

FIGURE 2 Simon's drawing of the scattering class as four (vertical) rows of students. He marks arrows and non-vertical lines by the rows to signify the rows' motion through space.

lines result from the fact that "there's always someone near you," an agent-based description. Thus, Jessica divides the process by which the class scatters into two parts. In the first part, rows form emergently, an agent-based from of reasoning. In the second part, the rows spread out in a staggered process, via centralized control and local rearrangement.

Scatter III: Subdividing the group into rows and clusters. Simon is describing the "Scatter" scenario. Simon wants to prove a point: The people in the middle of the initial cluster move through a greater total distance than the people on the outside. The students in the middle are more difficult to satisfy and they move a greater distance than those on the edges. This is an aggregate or "group" point-of-view.

The interviewer asks Simon: *"Can you explain that to me somehow?"* Simon asks for some paper and markers. He proceeds to draw four parallel lines (see final drawing in Figure 2).

While he is drawing, the following conversation takes place:

Simon: *There are like four rows.* [While drawing the lines] *One right here, one right here. And one right here. And one right here.*

Interviewer: *Yeah.*

Simon:	[points to the outside line on the right] *This one has lots of space here. They can move on the side or something* [marks arrows moving outward to the right from the target row]. *This one* [points to the central row on the left] *doesn't have lots of space, so they can make in the front or in the back or on the side* [marks the central row's motion with arrows from the end of the line upward and downward]. *And this one* [points to the outside line on the left] *just moves right here* [marks a path along which the row moves out to the left]. *Or, right here.*
Interviewer:	*These are row of kids?*
Simon:	*Yeah.*
Interviewer:	*Now, why are they standing in rows to begin with?*
Simon:	*'Cause* ***it's easier to mix*** *all of them up. Like* ***it's easier to know what I said****. Because if you want to know somebody and you know what they said here . . . so you can just* ***look at them in couples****.*

Simon divides the class into four rows. These are four mid-level groups. In this case, the mid-level groups are broken down from the whole group, from-population-to-mid-level. The individual students in the scattering class are ignored in this representation. To demonstrate that the rows in the center move a greater distance than the rows on the outside, he proceeds to mark their motion through space. The outside row moves out a short distance, as it is displaced as a whole to the right, into open space. The central row can move out mainly through the end of the row (upward and downward), so it needs to move a greater distance. Simon is moving each row as a single entity, although the multiple arrows hint at the students in each row. The rows move in sequence, and the states by which the system evolves are not depicted, although the rows' actions are marked with arrows. This use of a single drawing, rather than a series of states, limits his simulation, in that he cannot see that once the outside row moves out, the inside row can move similarly into the vacated space.

We were fortunate to be able to listen in on Simon's motivations in creating this representation. Simon provides three motivations for using rows to depict the class, none of which related to copying from reality. One, "*it's easier to mix all of them up*": the process of modeling the actions of a whole class of students is reduced to the mixing of only four components, thus facilitating his *own* thinking through the process. Two, *"it's easier to know what I said"*: this representation is also meant for *communication*, explaining his conclusion to the interviewer. Three, *"so you can just look at them in couples"*: Simon is aware that interactions between the components of the system are difficult to simulate. His representation serves to reduce the interactions to *"couples,"* two components at a time. Not only do the rows make it easier to mix the students in the class, but also the interactions are simplified and can be considered two-by-two. Thus, dividing the class of students into rows is not a replication of reality, but a way to model the process,

FIGURE 3 Simon models the process by which the class scatters in gym class with coins. He covers groups of coins with each hand (left) and moves them outwards (right).

which affords reasoning through the components' actions and interactions, as well as communicating his understanding of the system. Further strengthening this claim is the following event, in which he employs a completely different form of mid-level to reason through the "Scatter" scenario with coins.

After Simon has drawn four lines to describe groups of student, the interviewer suggests that Simon model the process once more, this time with coins:

Interviewer:	*Let me bring you these pennies that might help you to explain. . . I'm a bit confused.*
Simon:	*These* [shows coins] *will be all the people. This one here* [gestures to the space of the table] *will be all the room. So they can some people can move right here, some can move right here, some can move right here, some can move right here, some can stay in the middle.*

While speaking, Simon moves the coins. He pulls the initially clumped coins apart into small groups, covering them with his hand: one group to the right, one group to the left, one above, and one below (see Figure 3). He ends up with five groups.

Simon does not notice that within each of the five groups, the coins are close together. Later, when asked about this issue, he spreads the individual coins within the groups. When he tries to re-iterate the simulation, the same stages can be seen. Five groups are formed to cover the whole space. After forming five clusters, with no prompt, Simon spreads them out. These are two separate steps in scattering the group. The first step ends with the mid-level groups spread apart. The second step results with the individuals distanced away from each other. The dynamics of the spread from the small clusters to individual students is similar to that for the whole group into mid-level groups: starting from the center of the cluster, and heading out. This two-stage spread allows Simon to ignore interactions among the students: the probability for "collisions" between the scattering students as they concurrently move away from each other is reduced.

Both with the drawings and coin modeling Simon splits the group into four (drawing) or five (coins) sub-groups. Mid-level formation splits the class: from-population-to-mid-level. He ignores the individuality of agents in service of simplifying the parallel sum-spread of students away from each other. He does not describe agent rules in any explicit way, nor does he describe behaviors of individual students. However, his description of the aggregate process is relatively rich: he notes the students' mobility and its relation to their initial location. It seems that he is working backward from his envisioned final state, spreading the group out by moving the mid-level groups away from the center, a direct straight-line path between initial and final states. In essence, the small groups are the agents, each moving as a single entity. This sub-grouping is essential to his explanation of the spread and bridges from his aggregate description to the individual elements.

To summarize these examples, we have seen the following:

1. Mid-level construction shows up in a variety of contexts: scattering in PE for calisthenics, rumors spreading in school, as well as disease propagation in a population. It takes place from the agent level (e.g., Tom in Rumor and Rachel in Scatter I), as well as from the group level (see Simon in Scatter III and Jessica in the second part of Scatter II).
2. Both in moving from agent to mid-level, as well as from group to mid-level, we have three examples with explicit numbers, ranging from three to five. Four or five groups of agents in the Scatter III example, three in the Scatter I example, three–four agents in a group in the Rumor example.
3. The construction of mid-level groupings is usually central in explaining the mechanism of change. Omitting it from the students' explanations causes the whole explanation to fall apart.
4. The construction of mid-level groups was usually accompanied by a "cover story," such as friends sticking together. We have seen a wide diversity in the kinds of stories the students invent.

This ends our qualitative illustration of the students' mid-level construction. We now shift to the quantitative aspects of this construction.

Mid-Level Construction: Quantitative Description

We return to the interviews, and focus on the quantitative aspects of the students' description of the Scatter scenario.

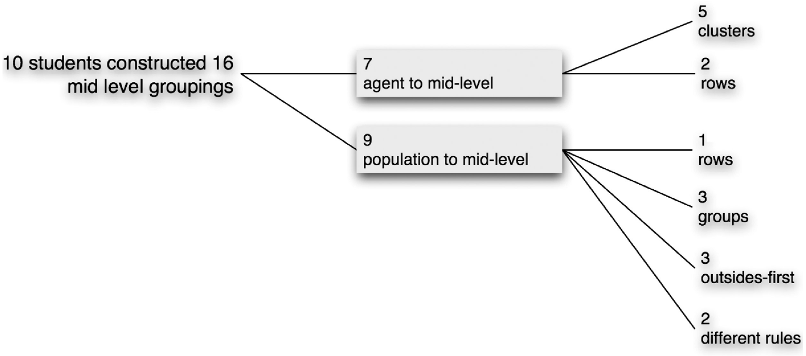

FIGURE 4 Forms of mid-level construction in the interviewees' "Scatter" explanations, categorized by trajectories and their specific manifestations.

Frequency. All the students constructed mid-level groups: *100% of the cases*. Half the students provided more than one kind of mid level: the mean number of distinct descriptions is between one and two ($M = 1.6$, $SD = 0.7$).

Trajectory. We first look at the 16 descriptions (see Figure 4). Nine of these involve breaking down the group into sub-groups, and working with these homogenous entities. Seven out of the 16 show the opposite trajectory: local interactions among agents result in their gathering into small groups or rows.

In Table 3, we can see that four students formed mid-level groups only from the agents, five students only from the level of the population, and one student expressed both trajectories.

Number of entities in a group. We spotlight the number of elements in a group: the number of small groups in the class for the population-to-mid-level

TABLE 3
Mean Complexity Scores of Students Forming Mid-Level Groups with Different Trajectories

Trajectory	*N*	*Complexity Score*[a]
Agent to mid level	4	4.25 (0.5)
Population to mid level	5	2.2 (1.5)
Both	1	Too few
All	10	3.0 (1.5)

[a] The score is a count of the number of expressed complexity principles. Mean scores are based on a 5-point scale; standard deviations are in parentheses.

trajectory; the number of individuals in a small group for the agent-to-mid-level trajectory. Eight out of the ten students demonstrated such numbers. The average number of smaller units in the larger units is slightly more than three ($M = 3.3$, $SD = 1.6$) and the range is 2–5.

Core or peripheral. The instances of mid-level construction were sorted into those that were core to the student's reasoning, and those that were peripheral. Of the 16 descriptions, 12 were core to the process of scattering, while 4 were peripheral and fleeting.

Specific manifestation of mid-level construction. This dimension classifies the mid-level groups at a higher resolution. Students constructed mid-level groups in a variety of ways. The specific forms are classified and described.

The 10 interviewees provided 16 distinct mid-level descriptions. Five students described one form of mid-level groups, four demonstrated two forms of mid-level groups, and one student displayed three forms. In Figure 4, we see their classification:

Clusters (5 students): While the class is scattering, local huddles of students are formed. This is usually described as friends wanting to be together and talk (see Rachel in Scatter I).

Rows (2 + 1 students): Students are standing in rows. This pattern takes form in diverging ways: two girls saw the row pattern emerging in a decentralized manner from the individuals' local behaviors, as a final state of the system (see Jessica in the first part of Scatter II). One boy used the rows as small groups that are moved as single entities (see Simon in the first part of Scatter III), split apart from the larger group.

Groups (3 students): Groups move out of the center at the same time (see Simon in the second part of Scatter III). When the class scatters in gym, a number of groups detach from an initial cluster and head out in parallel.

Outsides first (3 students): In scattering, the students who start out standing on the perimeter of the group move out first. This way, they create open spaces, into which the students on the inside can move (see Jessica in the second part of Scatter II). The students are segregated by their initial location and their first step is staggered in time.

Different rules for different groups (2 students): Different groups operate according to different rules. For example, one boy explained that the bigger students go in the back, farther away (he's framed the problem as preparing for a volleyball game) and the smaller ones stay in the front, because they can't throw as well: "*Spread out first the big people who can hit properly on the back side, the small people that can't hit properly near the net, because they can't throw far.*"

We summarize the quantitative dimensions of mid-level construction as follows:

1. All the students constructed mid-level groups. Among the 10 students, 5 constructed more than one form of a mid-level grouping within the short interview time.
2. The trajectory by which the mid-level groups are formed is consistent for most students, and splits almost equally between creating them from the individuals, and breaking them down from the whole group.
3. The number of units in a group falls into a narrow range, averaging at slightly more than three.
4. In most cases, mid-level construction was central to the students' reasoning processes.
5. The students demonstrated a wide variety of forms in sub-dividing the system. Moreover, a single student may use more than one form of mid-level groups.

Relating "Mid-Level Construction" to "Complex Systems" Thinking

Research Question 3: How does the students' construction of mid-level groups relate to their overall reasoning about emergent phenomena in terms of "complex systems"?

Mid-level construction has been described in a variety of ways. However, it is embedded in a whole process of reasoning about the scattering class, that includes agent rules and behaviors and the changes to the system. We pursue further understanding of how mid-level construction is related to the rest of the students' reasoning about EP. We focus on the students' trajectory in forming mid-level groups and relate it to the total score regarding component beliefs regarding systems and their ideas regarding locus of control in the system.

In Table 3, we see a clear relationship between the overall score regarding reasoning in terms of complex systems principles and the trajectory by which mid-level groups are formed. Forming these groups bottom-up from the individuals is associated with a high score in understanding the scattering of students as a complex system. The Spearman rank correlation coefficient between the trajectory through which mid-level groups are formed and the complex systems score is $r_s = .808$, $p < .05$.

Regarding the locus of control in the system, we have seen that most of the students viewed the process as decentralized. Two types of expressions of decentralized control were observed. One type *implicitly* conveys the distributed nature of the decisions being made, with the individuals navigating locally to find a free space. The second type includes an *explicit* articulation of the lack of centralized control, asserting that the agents control themselves—that no one tells them where to go or what to do. Out of eight students who attributed decentralized control to the system, four students did so explicitly. Every single one of these four also formed mid-level groups emergently from the agent level. The Spearman rank correlation coefficient between the trajectory through which mid-level groups are formed and whether or not explicit reference is made to decentralized control is $r_s = .756$, $p < .05$.

To summarize:

1. Forming mid-level groups from the agents is associated with a high score in reasoning in terms of complex systems and with explicit references to decentralized control.
2. Forming mid-level groups from the population is associated with a low score in reasoning in terms of complex systems and with implicit references to decentralized control.

DISCUSSION

We opened this article by considering familiar expressions, such as "birds of a feather flock together" or "the crowd erupted in spontaneous applause." These expressions describe phenomena that can be construed as complex systems. We posed questions regarding our intuitive grasp of such processes, and the possible strengths students may already possess in interpreting ordinary EP.

We have portrayed sixth-grade students' reasoning about EP, such as the scattering of a class in a gym lesson, which position them as experienced rather than novices. These are everyday events in which they often participate. We supported the students' careful thinking about the system's unfolding over time. We seek their strengths so they may be tapped onto in planning educational environments and activities, as well as in helping teachers develop a fine-tuned ear for students' ideas about EP, ideas that may be drawn into the class' learning. If we can demonstrate that students can bring to bear strong resources for making sense of these EP, it will add weight to the argument that the difficulties are not intrinsic to the nature of EP, but are a matter of helping students recruit existing yet nascent strengths.

Various facets of the students' understanding of "complex systems" were studied. We have found a pervasive construct that the students employ when reasoning through the process of change, which we have named "mid-level construction": the formation of mid-level aggregations of the system, in which either small groups are treated as homogenous entities within the larger system, or a small number of individuals are described as interacting within small groups. We have also shown that the specific characteristics of these mid-level groups are related to the students' understanding of complex systems ideas.

Previous research has reported on students' difficulties in reasoning about complex systems and EP (Hmelo-Silver & Pfeffer, 2004; Jacobson, 2001;

Wilensky & Resnick, 1999). Several researchers (Chi, 2000, 2005; Jacobson, 2001; Wilensky & Resnick, 1999) have described these difficulties as having prevented students from understanding important scientific principles and explanations. Some researchers suggest that this difficulty lies in the intrinsic nature of EP (Chi, 2005; Hmelo-Silver & Pfeffer, 2004; Jacobson, 2001). Other researchers (e.g., Charles & D'Apollonia, 2004; Lehrer & Schauble, 2006; Penner, 2000; Resnick & Wilensky, 1993, 1998; Wilensky, 1997b, 1999a; Wilensky & Reisman, 2006; Wilensky & Stroup, 2003) argue that students can come to understand these scientific EP through recruiting intuitions about individuals and individual behavior. They advocate agent-based modeling as a method for enlisting these intuitions derived from body movement and gestures, which can be mapped onto agent rules and behaviors. Other researchers (e.g., Colella, 2000; Wilensky & Stroup, 1999a) suggest that placing a group of students inside such scientific complex systems as agents enables them to develop intuitions about these systems and to gain shared experiences that can be reasoned about collectively.

Based on our results, we make the following claims:

1. In contrast to previous literature, under appropriate conditions, some of the students spontaneously employ bottom-up processes to reason about EP, even though they have not been trained to do so.
2. In the process of reasoning about EP, students frequently restructure the system by constructing mid-level groups.
3. Forming mid-level groups takes place in two distinct modes: emergently or bottom-up from the individual agents; or top-down by breaking down the system into smaller groups.
4. The mode by which an individual constructs mid-level groups is related to her form of reasoning about complex systems: Bottom-up construction of mid-level groups is associated with a tendency to think in terms of agent-based reasoning about complex systems; Top-down construction of mid-level groups is associated with less predilection toward agent-based reasoning, and may be related to aggregate reasoning in terms of averages and flows.
5. These results lend support to the strong constructivist claim and to the developmental approach within which students' reasoning evolves.

In the following discussion, we elaborate on these claims, and relate our findings to previous research on the topic.

Reasoning about Emergent Phenomena in Terms of "Complex Systems"

One of the questions we have explored in this study regards the nature of students' reasoning about ordinary EP. We have found that when interpreting familiar social systems, some of the students made use of bottom-up processes to explain the system's unfolding over time and described emergent patterns. Half the students proposed that scattering in gym results in small groups clustering and dispersing on the background of the class spread. Many of the students argued that an agent's route is unpredictable. They claimed that this trail depends on its local interactions with other agents (e.g., "*the number of spaces around them*"), and that these local environments change over time and are different for different individuals. Two students predicted a decentralized formation of rows.

Most of the students employed distinct descriptions for the agent and the group level. These levels were clearly separate entities. Individual students act out rules in their local environments, thinking, deciding, and taking action. Yet, a bird sees different things: clustering and group spread, the student actions but not their decisions, and the overall flows of the class. These two views draw on different aspects of their social interactions: as participants or as observers. As participants, they empathize with the individuals, identifying their own sensations, decisions, and actions with those of the agents in the system. As observers, they may look around or stand aside and detect spatial and temporal patterns related to the population. The majority either implicitly or explicitly illustrated a decentralized system with distributed control. The teacher may initiate the process of scattering but does not dictate who will move where and how much. Some of the students acknowledged the variety and unpredictability of the individuals' movement and fewer included equilibration processes in their descriptions. Only one student illustrated a large system-wide effect cascading from a small local perturbation.

Across the ten students we have interviewed, the picture is uneven. We have seen a bimodal distribution in the number of complex systems principles that the students make use of when portraying the scattering class.

Even though these students had not been trained in the sciences of complexity, they displayed an impressive array of ideas from this field. In this respect we raise questions for previous research on the topic, most of which points out various biases, which divert people from attending to bottom-up processes of emergence.

We have proposed that a confounding factor in some of these studies may be the fact that many of the tasks relate to phenomena that are unfamiliar or that the mechanisms underlying their operation are invisible. In contradistinction, we have asked students to work through a problem in a domain with which they are highly experienced. This scenario affords an opportunity to capture students' nascent strengths in reasoning about EP. In this study, we found that in speaking of scattering in gym or spreading rumors, the students did not display some of the described biases. This finding suggests that, in some situations, students can recruit good complex-systems thinking. Given the nature of the task, it is not surprising that students view the scattering class in agent-based terms. We find it interesting to contrast this with the more scientific contexts, in which biases have been found to crop up more frequently.

Mid-Level Construction

While explaining how a class spreads out in gym, rumors travel through school, or disease spreads among deer, the students constructed mid-level groups. The interviewers did not prompt for this description level. The questions about the system involved only two levels: its individual elements and the whole group. However, the students invented an intermediate grouping level, a strategy we call *"mid-level construction."* These intermediate groups assumed a variety of forms: rows, clusters, concentric rings, and allocation of different rules to different groups. Half the students constructed mid levels in more than one such form within the short interview.[5] Mid-level construction was usually central to the students' reasoning process, forming the backbone of their sense-making. For the particular scenario we have investigated, scattering in gym, *all* the students constructed "mid levels."

The notion of a mid level in science has been described by natural and social scientists (e.g., Klein & Kozlowski, 2000; Kulikowich & Young, 2001; Mohan, 1996). Lemke (2001) has reviewed the scientific discussion of "mid levels": he described such levels as emerging between every two levels, particularly for social-ecological systems. He suggested that looking "up and down" the levels provides understanding of this mid level in terms of its components' affordances (lower level) and stable enabling conditions (upper level). He views the mid level as the critical entry level to describing the system of relevance. In this article, we have detected these intermediate levels in an empirical study of students' thinking. We have also demonstrated their centrality in reasoning about EP.

Bamberger (1996) called our attention to the "mid level" in musical perception, which describes the smallest elements that are perceived as entities. Rather than notes in a musical line, this element is larger, a meaningful and contextualized structural chunk, such as figures and phrases. People spontaneously point to the boundaries between such elements, and segment a larger musical piece into such entities when learning to play it "by ear." Only after listening repeatedly to such

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[5] In the term "invention" we do not preclude that mid-level groups, such as cliques, may be part of the students' repertoire of experiences. However, the variety of forms by which such groupings are manifested and the fact that half the interviewees provided more than one form points to a more general strategy in reasoning about systems.

a segment, do they break it down to its constituent notes. Similar to Lemke, Bamberger describes "moving up and down the structural ladder," with the critical entry level as the mid level.

One can relate this finding to a pervasive construct employed in a variety of domains to explain and investigate different phenomena: a meso-level description of systems. Meso-level descriptions involve an intermediate structure between micro- and macro-levels. This term is used in two main forms. It is used to describe either *emergent small-scale structures* or *nested multi-level organizational structures*. Meso-level emergent structures are described in mesophysics and mesochemistry: the study of material structures that are larger than atoms, but small enough so that their properties differ radically from those of larger pieces of matter (e.g., nanotubes or micelles). Meso-levels, which are part of nested organizational structures, are used in Bronfenbrenner's (1979) work in developmental psychology, which extends the view of an individual child to include social ecologies at different scales of magnitude; in economics to describe "populations of rules" as a trajectory to describe change in the system (Dopfer, Foster, & Potts, 2004); and in cultural studies (Erez & Gati, 2004) to encompass both bottom-up and top-down reciprocal effects.

There are two distinct ways in which one can think of a meso-level. One can think of it as a real separate entity, often with clear physical boundaries. Or one can view it as an invented construct that affords a deeper understanding of the connections between individual elements and the larger system. In our scenario of the scattering class, we can take either view. Emergent clusters and rows can be seen as real entities that may form in the process of change. Whereas, sub-dividing the group into smaller groups or assigning distinctive rules to different groups are perhaps more easily seen as invented objects.

Analyzing processes within and among these levels offers a deeper understanding of the systemic nature of the complex phenomenon at hand. In many of these configurations, the crucial lever to a deeper understanding of the relationship between individual elements' behaviors and the system's global patterns lies in the meso-level of the system. This level provides a construct where the interactions between the individual elements can be analyzed, and shifts the description from individuals to groups, which can in turn interact at the macro-level. We have found that our interviewees invented a mid level, when prodded to elaborate on the development of a complex system. It would seem that this construct is not specific to the context, but serves to explicate complex systems among scientists in a variety of domains.

Reaching Up and Down the Levels

We have observed our interviewees as they clustered individuals into groups of three or moved five groups of coins across the table. Why do they do that?

We suggest that constructing mid-level groups reduces the amount of information in the system; by decreasing the number of objects one needs to animate and manipulate mentally, a more specific and causal relationship between individual behaviors and system-wide patterns can be articulated. The mid-level groups retain the dynamic nature of the system and afford its simulation within cognitive constraints. Simon (Scatter III) has told us that he subdivides the class into four rows so he can communicate his ideas about the students' variable mobility as determined by their initial states. However, even more important, he says that it is easier to mix the students in the process when *"you can just look at them in couples*." Reducing the number of entities in the system affords his control of the multiple interactions, making it amenable to modeling and reasoning through the process by which the class spreads out.

Our findings show that when students introduce an intermediate level, the number of entities in the lower level ranges from two to five, averaging at slightly more than three. This number, and especially its narrow range, hints at a possible relation with information processing limitations (Miller, 1956; Simon, 1974). Quantitative and precise mental simulation is restricted in how many items and steps, actors, actions, and interactions can be reasoned through.

How do mid-level groups help bridge the agent- and population-levels in the system? We turn to discuss how constructing mid-level groups relates to agent-based and aggregate forms of reasoning.

An important observation that gives a clue to the utility of mid levels is that we have seen that students reason between the agent and group levels in two distinct modes: *bottom-up*, emergently from the individual elements to the mid-level groups; and *top-down*, by breaking down the system into smaller groups. How can these two ways of operating from the mid level lend themselves to a greater understanding of the system's evolution?

We propose that the mid-level groups serve either as a "large" agent or as a "small" population, depending on the mode of operation. In forming these groups, the process may be generalized beyond the mid level: either up or down the levels. The process by which small-group patterns are formed from the agents' actions and interactions may be extended upward to the population level; conversely, the process by which small-groups move and interact may reach downward to assist in discerning the interactions among agents.

We turn to discuss the two modes in forming mid-level groups: how might they facilitate the bridging of agent-based and aggregate descriptions of the system?

Agent-Based Construction of Mid-Levels

In explicating how clusters form and disperse, one may gain a handle on the connection between the individuals' behaviors and the group's overall evolution. At the first stage, the small group may stand in for the population level, operating as a “small population.” Specification of the particular interactions among the agents as they decide, act, and interact concurrently is made possible when the numbers are small. When these interactions result in a particular pattern within a local environment, this pattern may facilitate generalization of these interactions and patterns at the level of the whole group. In this case, the mid-level groups are a test-tube experiment, which can generate conclusions regarding the larger system-wide patterns.

For example, clustering-while-spreading magnifies the parallel nature of the system’s evolution. Two or more neighboring agents may decide to move at the same time into a near-by “open space.” This move results in the agents being too close. In the next step, they will try to move away from each other. One can ignore the whole group and focus on these local events to elucidate the parallel decisions and actions, and how they interact in the local environment, in turn changing this very environment.

The formation of such clusters results in an uneven density topography. The density gradients trigger further motion, or flow out of these local maxima. Note that this is an aggregate description of flows and rates. This aggregate description of the mid level may in turn be generalized to the whole group. For example, one can surmise that greater mobility will take place in the center of a high-density cluster. Thus, reasoning about a few agents interacting within a boundary can be seen as a small-scale thought experiment.

These two descriptions of group formation meet at the cluster, a local density maximum. Focusing on the cluster level provides a bridge between local events and global changes. It may be easier to envision the formation of a cluster of a few agents, and how this closeness prompts further motion of the individuals. In “zooming out” from the agents’ behaviors through clusters to an aggregate description of the uneven densities, it is perhaps easier to see the complementarity between the agent and aggregate forms of reasoning. Thus, mid-level clustering provides a powerful entry level to understanding both the emergence of group patterns and a more detailed grasp of the group dynamics.

Aggregate Construction of Mid-Levels

We have described how agent-based reasoning could lead the way to an aggregate description of the system. We will now examine the possibility of the reverse trajectory. Can splitting the group into groups provide a gate to understanding the agent level as well? When carving small groups out of the whole, mid levels pose a way of restructuring the system so that its dynamics can be reasoned through while retaining a broad view of the system. However, our data suggest that although this process is useful for setting the system in motion, it cannot provide insight into the specific interactions that the first trajectory affords.

In reasoning about the global pattern, outbound flow from an initial crowding of students moves the system between two states, from high to low density. The rate of change is related to these densities and the available space.

Splitting the system into small groups offers a semblance of moving into the agent level by sustaining the system's multiple and dynamic character. The mid-level group operates as a single entity, serving as a "large agent." However, such a mental simulation does not lend itself easily to an understanding of the individual agent behaviors. As we have see in the Scatter III Simon vignette, some students moved the groups out of the center in parallel. Although this simulation may hint at the parallelism underlying the agents' actions, it does not clarify their mutual interactions and the stochastic nature of their motions in space, as the groups grow only farther apart. Some students stagger the individuals' motion according to their initial location: outsiders move out first, making room for the insiders. Although this relates to the importance of distances among the individuals and some of their interactions, it does not help uncover the stochastic and parallel nature of the students' motion: they are all moving outward along the radius, never colliding or negotiating their next action. The distances between the groups become larger, never smaller.

Thus, the mid level preserves the overall group-level properties of averages and flows. However, several critical properties of the agents are not encountered. These descriptions replicate the group pattern and do not afford an understanding of the agent level.

Bridging between Agent-Based and Aggregate Descriptions through a Mid-Level

Almost all the students used exclusively one trajectory in forming the mid-level groups. However, we have seen how one girl, Jessica (Scatter II), made a full transition from agent to mid level, and from that mid level to the whole group. The mid level links these two forms of reasoning. She envisioned the agents as forming into rows with no central control. She then takes one row and describes a centralized pattern of spreading, where the students at the end are called to move out and make spaces for the ones on the inside. Thus, Jessica has employed both forms of reasoning to bridge from the agent to the whole group, by tying them together at the mid level.

We have seen the students use the mid level as a substitute for either the agents or for the whole group. Some of the students well described the emergent formation of clusters and rows, using detailed agent-based descriptions. Some split the whole group into smaller groups, to describe and explain the overall spread. However, the aggregate descriptions were brief and not as rich as those at the agent level. Describing how the whole system unfolds was challenging for our sixth-grade interviewees.

Relating Mid-Level Construction to the Understanding of Emergent Phenomena in Terms of Complex Systems

How does the process by which students form mid-level groups relate to the larger picture of their reasoning about complex systems?

We have studied the students' expressed ideas in terms of central concepts related to "complex systems" and found a bimodal distribution. Most of the students exhibited one of two trajectories in constructing mid-level groups. In relating the two findings, we have found that students who formed mid-level groups from agents also expressed a larger number of "complex systems" beliefs in their explanation. Students who split the whole group into smaller groups articulated a smaller number of "complex systems" ideas. We may conclude that while all the students constructed mid-level groups in their attempts to relate micro- and macro-description levels, the way by which they formed them is strongly impacted by the ways in which they make sense of complex systems. Along similar lines, Charles and d'Apollonia (2004) have found that students who referred to local interactions among agents when exploring various models of EP had a better understanding of the systems as complex.

The two ideas, which separated the low scores from the high scores, are those relating to the stochastic nature of the agents' behaviors and to equilibration processes. The distinction between the two modes of forming mid-level groups lies in a greater flexibility to shift between specific causal actions and interactions and local group patterns, among those forming the mid-level groups from agents, rather than breaking them down from the population. Understanding the indeterminacy of the agents' behaviors, their dependence on the constantly changing local environment, is grounded in AA, or agent-aggregate complementarity (Wilensky & Stroup, 2003). Although the aggregate patterns are consistent, the agent behaviors are unpredictable. Encompassing both ideas involves reasoning about the system through both agent-based and aggregate forms. The high-scorers described equilibration processes in ways that included both local interactions and the global system, providing a clear example of agent-aggregate complementarity.

Educational Implications: Agent-Based and Aggregate Forms of Reasoning

The questions in this study are set within an arena that involves the interaction between agent-based and aggregate forms of reasoning. Several theorists have approached the challenge of exploring the relationship between these two forms of reasoning and proposed four distinct frameworks for conceptualizing the levels of description of EP. Lemke (1999) has provided a scale-driven framework for organizing these levels. Chi (2000, 2005) has argued for the incommensurability of agent-based reasoning and aggregate reasoning, as they belong to distinct ontological categories of reasoning about processes of change. Wilensky (1993, 1997b, 1999a, 2006; Wilensky & Papert, 2006; Wilensky et al., 2005) has articulated a developmental approach, arguing that agent-based reasoning is developmentally prior to aggregate forms as it is embodied and leverages children's intuitions about individual bodies and their own bodies. Wilensky and Stroup (2003) have argued for the complementarity of the two perspectives and forms of reasoning.

These data provide evidence for and against the described four views. We see this study as supporting Wilensky and colleagues' developmental view as well as Wilensky and Stroup's (2003) argument for complementary relations between agent-based and aggregate forms of reasoning.

They do not lend support for the scale-driven framework, as students clearly described distinct behaviors, metrics, and characteristics at the micro- and macro-level. It would seem that this dissimilarity is crucial in creating an understanding of how patterns at the population level emerge out of locally dependent behaviors of the agents. As such, they clearly show different processes at work, not scale-ups of the same process.

Neither do they provide support for the incommensurability view. Although we have seen evidence for Chi's (2000, 2005) described difficulties in bridging between these two forms of reasoning, we have decidedly not found the two forms to be unbridgeable. Some of the students did connect the two forms of reasoning. Doing so through mid-level construction is important for their sense making of complex systems.

The data do, however, give support for the complementarity view and the greatest support for the developmental view. As students construct mid levels they build up resources that enable them to adopt a complementarity view. Extrapolating from the data we would conjecture that a mature understanding of complex systems does entail employing both agent-based and aggregate forms of reasoning and fluidly transitioning between them as needed. However, the students who formed mid levels in an agent-based emergent form made this transition to complementarity better than the students who formed mid levels from the aggregate. This difference would seem to suggest that although complementarity is a desired end, the path to it is better achieved by starting with agent-based reasoning and then moving to complementarity. This idea endorses the developmental view as the pedagogically preferred progression.

Future Research

In exploring the phenomenon that students invent mid levels to reason between the levels when making sense of an EP, we have described only one task for a small number of students. We wish to continue this study to larger numbers of students, but especially to explore the following questions:

Generality:	Does mid-level construction take place in other contexts, or solely in the domain of social systems?
Developmental trends:	Is this a general strategy, or is it a step in a developmental path to a mature understanding of EP? Does it happen only with younger children, or can we see it for older and younger students as well? Do experts use it?
Design:	Can we support students' understanding better if we include various "mid levels" in the learning environment?

In this article we have shown that in reasoning about EP, our students frequently constructed mid-level groups. We are engaged in further research to confirm this finding. If it is confirmed, we believe that there are clear implications for the design of learning environments that can support a more sophisticated understanding of EP.

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