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Threads of local continuity between centralized and decentralized causality: Transitional explanations for the behavior of a complex system

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Abstract One line of research on student understanding of complex systems has tended to emphasize discontinuities between common misconceptions and relatively more sophisticated understandings. Other work has focused on instruction while acknowledging the existence of other ways of understanding complex systems, but less emphasis has been on examining the knowledge structures within these intermediate ways of understanding. This study takes a microgenetic approach to examining student's explanations for the behavior of complex systems. Using the Knowledge-in-Pieces epistemological perspective, the analysis documents a continuity of reasoning patterns across less prototypically centralized and more prototypically decentralized (a more sophisticated causality) explanations while explaining the movement of sand dunes. The first analysis examines 31 interviews and shows that many reflected a general reasoning pattern that encompassing some combination of an initial centralized explanation, a final decentralized explanation, and transitional explanations. A second analysis examines a single student's reasoning pattern and finds that the activation of relevant intuitive knowledge pieces (p-prims) and transitional explanations function as threads of continuity across the continuum of reasoning patterns. These findings suggest that students are able to exhibit a continuity of reasoning patterns across centralized to decentralized causality and are able to access productive intuitive knowledge about complex systems that are applicable to both the macro and micro levels of sand dune movement. Implications suggest that future research investigate these transitional explanations along with the mechanisms of shifting explanations that can account for this robust continuum.

Keywords Complex systems · Conceptual change · Explanations · Learning mechanisms

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Introduction

Existing research on student's learning about complex systems and emergence has documented student's difficulties (e.g. Chi 1992, 2005; Hmelo-Silver and Azevedo 2006; Resnick 1994, 1996; Slotta and Chi 2006; Wilensky and Resnick 1999), and that work has tended to emphasize discontinuities between common misconceptions and relatively more sophisticated understandings. Furthermore, these discontinuities have been widely used in analyses of student understanding of complex systems in a variety of content areas and settings (e.g. Eilam 2012; Jacobson 2001; Levy and Wilensky 2008; Raia 2008; Sengupta and Wilensky 2009). For example, in a hypermedia learning environment Jacobson et al. (2011) analyzed student learning about complex systems according to two ontological categories, the complexity ontology, which is associated with a relatively normative understanding and the clockwork ontology, which is associated with student difficulties. Other work has focused on instruction to support a shift in understanding (e.g. Sengupta and Wilensky 2009) and some have acknowledged the existence of intermediate ways of understanding (e.g. Grotzer e al. 2017a; Levy and Wilensky 2008), but less work has examined the knowledge structures involved in these intermediate ways of understanding. The current article contributes to a growing recognition that this discontinuity in explanations overlooks a continuum of reasoning patterns across the common misconceptions and relatively more sophisticated understandings. Using a theoretical framework from conceptual change, Knowledge-in-Pieces (diSessa 1993), the analysis illustrates that moment-by-moment changes in understanding can occur through the dynamic process of intuitive knowledge pieces becoming relevant and irrelevant as student's explanations reflect this continuum. Overall, this study finds that the activation of relevant intuitive knowledge pieces (p-prims) and transitional explanations function as threads of continuity across reasoning patterns. These transitional explanations highlight that there is a range of reasoning patterns between the common misconceptions and the relatively more sophisticated understandings. Certain previously documented difficulties reasoning about complex systems might be a productive first step given a wide-range of reasoning patterns, and future research may further investigate these transitional explanations along with the mechanisms of shifting explanations that can account for this robust continuum.

Complex systems

Many pressing issues in our 21st century society can be analyzed through the lens of complex systems and emergent behaviors, including climate change, stock market behavior, and supply and demand economics. In addition, many phenomena that exhibit behaviors related to complex systems play a role in the K-12 science curriculum. In the Next Generation Science Standards, systems are one of the core crosscutting concepts and many of the disciplinary core ideas exhibit complex or emergent behaviors including evolution, ecosystems, and earth systems (Achieve 2013).

In recent decades, there has been a blossoming of exploration in the overlapping fields of complex systems, chaotic systems, decentralized systems, self-organizing systems, and dynamical systems theory among others, supported by recent advancements in applicable methodologies and frameworks. Complex systems contain a characteristic behavior in which the large patterns emerge from simple patterns or rules, which are based on interactions at the micro level. For example, one relatively straight-forward complex system is the formation of a traffic jam. The jam arises from localized interactions between many individual cars that speed up or slow down depending on the behaviors of surrounding cars. The interactions of these individual cars result in the overall formation of a traffic jam. In complex systems the relationship between the macro and micro level, specifically how the macro level pattern or behavior emerges from the micro level phenomena, are of great importance.

Learning about complex systems

From numerous research perspectives, there is general agreement that students have difficulties when learning about complex systems and their emergent behaviors (Chi 1992, 2005; Hmelo-Silver and Azevedo 2006; Resnick 1994, 1996; Slotta and Chi 2005; Wilensky and Resnick 1999). Various lines of research have proposed reasons for these difficulties. For instance, one line of work focuses on the form and function of these systems, and found that experts and novices differ in their understanding of the behaviors and functions, but not structures, of these systems (Hmelo-Silver et al. 2007).

Another line of research, from the conceptual change perspective, argues that student's difficulties are due to their miscategorization of a process across ontological categories, that is basic categories in the world, such as objects and events (Chi 1992, 2005; Chi et al. 2012; Slotta and Chi 2006; Slotta et al. 1995). Building on the idea of distinct ontological categories in the world, Jacobson (2001), found differences between expert and novices understanding of complex systems. Jacobson et al. (2011) hypothesized that a deep understanding requires an ontological commitment to the complexity ontology, and inversely, students had difficulties if they have an ontological commitment to the clockwork ontology; furthermore, they argued that ontological shifts are necessary for learning about complex systems.

From another perspective, Resnick (1994, 1996) observed a deep-seated resistance to decentralized ways of thinking and that students have a strong preference to presume centralized control where none exists. Centralized causality involves a central cause directing or orchestrating the behavior of all individual agents. While working with students in constructing computer programs for the behavior of complex systems, Resnick found that over time they came to recognize the role of decentralized causality embedded within the systems. Decentralized causality involves a distributed cause or self-organizational behavior.

Building off that initial work, Wilensky and Resnick (1999) found that student's difficulties with learning about complex systems are due to trouble connecting the microscopic and macroscopic levels; they refer to this as "levels confusion" and they discussed students' "slippage" between levels. In follow up work, Levy and Wilensky (2008) observed a strategy called "mid-level construction" for making progress by aggregating individuals or subdividing the whole group in order to bridge the micro and macro levels. Additional follow-up research found challenges in bridging the subatomic, macro, mathematical, and experiential levels in chemistry (Levy and Wilensky 2009a, b). Many agree on the importance of the relationship between the micro level and the macro level (e.g. Sengupta and Wilensky 2009; Penner 2000; Wilensky and Resnick 1999; Eylon and Ganiel 1990) and the current article continues in that direction.

Across these perspectives, researchers provide diverse reasons for student difficulties as evident throughout the ontological category theory of conceptual change (Chi 2005; Chi et al. 2012), the complexity ontologies perspective (Jacobson 2001; Jacobson et al. 2011), and the centralized-decentralized mindsets perspective (Resnick 1996). This body of work has been a productive first step, yet, common to this body of work is a tendency to emphasize a discontinuity in student understanding, thereby overlooking possible transitions. Importantly, others have pointed out that these distinctions are problematic (Hmelo-Silver et al. 2007), because students may utilize other ways of thinking about these systems, such as focusing on their observable structures and functions.

Rather than focusing on discontinuous ways of understanding complex systems, other work has examined changes in understanding, often scaffolded with instruction. In a review article, Grotzer (2003) discussed the long-term development of children's causal understanding along several dimensions of causality, including mechanism, probability, and agency (the last of which incorporates emergent processes as a level of increased complexity). Employing an emergent perspective based curriculum in chemistry (Levy and Wilensky 2009a), an investigation of student learning across several weeks examined learning of the submicroscopic level and bridges to the macro level (Levy and Wilensky 2009b). Another line of research used an analysis approach that is similar to Jacobson (2001) to investigate student's ethical decision making where they participated in a multi-week curriculum that aimed to improve their understanding of the complexities within scientific issues with an ethical dimension and socioscientific issues (Yoon 2008, 2011). Although this work adds to our understanding of possible transitions, it tends to emphasize curriculum that scaffolds the transition. Recent work by Grotzer et al. (2017b) employed a microgenetic analysis of student interviews in which there were initial deterministic reasoning patterns and an occasional shift towards probabilistic causality. Additionally, Grotzer et al. (2017a) documented hybrid reasoning patterns that included aspects of both centralized and decentralized causality. Collectively this work has illuminated that transitions are possible, but less is known about the knowledge structures across the transitions and possible learning mechanisms. Furthermore, when examining this transition, others have documented noticeable flexibility and fluidity as individual's understanding may exhibit characteristics of both categories (Gupta et al. 2010), but less is known about the nature of the transition. That is, what is the source of this transition?

Theoretical framework

To conceptualize a continuity of transitional explanations this research utilizes the Knowledge-in-Pieces (KiP) (diSessa 1993) family of epistemological frameworks. This perspective assumes that students have a complex knowledge system containing many knowledge pieces, what has often been referred to as a conceptual ecology (diSessa 2002; Strike and Posner 1992). This construct is useful when investigating differences between people's knowledge systems or changes in knowledge systems along a developmental pathway. There is an assumption of many knowledge pieces that operate at different levels and can be organized and re-organized in different ways across contexts. Knowledge pieces can become relevant and irrelevant as they are continually applied to reasoning about different contexts, or as in the case of this paper, different explanations for the same phenomena. Based on a momentary *sense of relevance* knowledge pieces can pop up as relevant or be relinquished. That sense of relevance also directs students to make judgments about the applicability of an idea, based in part of whatever knowledge piece are being used at a moment in time. External factors, such as another's question or comment may influence what knowledge pieces are deemed relevant (Sherin et al. 2012.) Also, shifts in context can influence relevance, for instance a knowledge piece could be relevant to the movement of sand particles, but not to the movement of an entire dune. The continual re-organization of knowledge pieces across contexts is taken to be an underlying mechanism for learning. One type of knowledge piece commonly discussed is p-prims; these are small intuitions about how the world works that often are typically self-explanatory and used to help explain how the physical world works.

Practically, when using this framework to examine student learning, it is important for an analysis to focus on characterizing the complex knowledge system in terms of the nature and content of the knowledge. It is important to pay attention to the real-time local processing in order to describe the potential learning mechanisms involved, the relationship among the elements, and how the system evolves. As has been described elsewhere, this generally involves microgenetic process analyses of moment-by-moment changes rather than holistic characterizations of experts and novice's knowledge (diSessa et al. 2016). This approach of focusing on moment-by-moment changes allows the focus on a continuum of reasoning patterns, which in turn illuminates the transitional explanations. Furthermore, taking this approach can allow for a focus on learning and specifically mechanisms for change, which is important in a landscape where empirical accounts of changes over time are limited (diSessa 2014).

Research contribution and focus

This article contributes new insights into student's explanations for a complex system and specifically, the continuity of reasoning involved in the transition between an initial more prototypically centralized explanation and a final more prototypically decentralized explanation. The specific focus is on reasoning patterns in a student's explanations for the movement of sand dunes, the first analysis focuses on common patterns across many student's explanations, and the second analysis focuses on a detailed case of one student's explanations. The analysis addresses the following research question: What is the source of continuity and fluidity between centralized explanations, decentralized explanations, and the transitional explanations connecting them? By using Knowledge-in-Pieces to illuminate a continuity in reasoning exhibited by the transitional explanations along with knowledge pieces within those explanations that together serve as threads of local continuity linking the more centralized and decentralized explanation, the analysis is able to account for moment-by-moment changes and possible learning mechanisms. In this field, where there are well-documented student difficulties, along with more normative ways of understanding these systems, analyses of real-time processing and successful learning pathways are important for illuminating the fluidity of understanding and ways learners can make progress.

Research design

Data collection

The data corpus consists of 31 interviews with students from a variety of academic backgrounds, middle school students (n = 3), high school students (n = 11), undergraduates

“Pretend you live in the desert. Say you have a house in the desert and one day you take a walk a little ways from the house. Maybe you take a walk a mile or half a mile, the exact distance doesn't matter, and you get to some place in the desert where there is a whole bunch of sand dunes. And you notice next to one of the sand dunes there is some type of permanent marker like a flagpole or something permanent in the ground. And so you go home and then you don't come back to this area for a couple months say 5 or 6 months. And then you come back at some point and you notice that the permanent marker, the flag pole, is still in the exact same place where you left it, and you’re sure because of a GPS, or something like that, but there is no longer a sand dune there. And there is a new sand dune that appeared maybe 50 or 100 feet away. How does that happen? How does a sand dune appear to move in the desert?”

Fig. 1 Narrative Sand Dune Story

in physics (n = 5), and graduate students in either physics or education (n = 12). Middle and high school students were recruited through a summer academic program for motivated students. Undergraduates and graduate students were recruited through emails to a department list-serve at a large research university. Each interview took anywhere from 45 to 90 min and was videotaped and then transcribed. During the interviews, there were no computational manipulables although students had the option of drawing. The author served as the interviewer. The interview protocol asked about a series of different phenomena each of which exhibited complex systems behavior (e.g. formation of traffic jams, movement of sand dunes) and the order of interview questions rotated in a counterbalanced sequence. Additional details about the data collection and entire data corpus are available in Barth-Cohen (2012).

Sand dune question

The focus of the current paper is on the 5–20-min discussion of sand dunes. The variation in discussion length is due to the nature of the interview. Generally, a switch in discussion topic occurred when the student implied that they had exhausted the topic or when they generated an explanation that encompassed decentralized causality. The sand dune discussion was introduced through an original narrative story, the goal of which was to present the phenomena as something that was plausible and explainable (Fig. 1). Sand dunes are similar to the formation of talus slopes, one of the emergent situations examined in Penner (2000), however, sand dunes have not been extensively discussed in the learning sciences or science education literatures. Furthermore, sand dunes are a phenomenon where students potentially have experiences at both the macro and micro levels. At the macro level, many students mentioned having seen sand dunes before. At the micro level, students have intuitive knowledge about the behavior of granular materials from everyday experiences, such as playing in sand boxes. In comparison, some of the complex systems that have been studied more extensively, such as evolution or chemical systems involve a micro level where students have limited everyday experiences.

Sand dunes are an example of a system that exhibits emergent and self-organizational behaviors in which there is some self-organized criticality (Kauffman 1996). Research in geomorphology has used cellular automaton models to examine how airflow produces sand dune landscapes (e.g. Baas 2007; Kocurek and Ewing 2005). Recognizing these landforms to be complex nonlinear dynamical systems, these modeling approaches incorporate a large number of non-linear interactions and feedbacks between small elements, sand grains, that involve friction, energy loss during collisions, and nonlinear airflow. That micro level process in turn determines the large-scale system properties, such as the dune angle at which an avalanche occurs, dune transportation, and dune–dune interactions, along with distinctive macro level patterns, such as the spatial organization towards fractals. Additional research has focused on self-organization in response to environmental factors, such as vegetation that introduces additional dynamic feedback loops where the vegetation and sand transportation modify each other (Baas 2002; Nield and Baas 2008).

Interview style

After the initial structured sand dune story, each student was given time to think about the phenomena and then there were open-ended follow-up questions. These questions were unique to each interview and are similar to those kinds of follow-up interview questions used in Ginsburg (1997). More specifically, follow-up questions were based on the student's prior comments about the behavior of sand dunes (for example, see lines 50–51 in Analysis II). These questions might have nudged the student's thinking in the sense that students may go in directions that feel possible and where they feel ownership, resulting in them going down generally easier paths. Comparably, nudges that direct students down harder paths may be rejected with disbelief. This is an example of the context sensitivity of interviews in which some paths are easier or harder and the interviewer questions can help reveal these possibilities.

Many of the follow-up questions are also common discourse and conversational moves (Lee et al. 2008). These questions did not involve explicitly judging the participant's thinking and they generally were not introducing new materials. One kind of question asked the student to unpack in detail something they had already mentioned. For example, at one-point a student mentioned sand sticking to a dune. Later, the interviewer reiterated that idea and asked her for more information about what she meant by the idea of "sticky sand." This resulted in her re-focusing on the issue of how sand particles stick to the dune, after her attention appeared to be diverted elsewhere. This is similar to what Lee et al. (2008) refer to as "selecting and zooming," in which the interviewer selects one aspect of a student's complicated explanation and asks for further explication. Other follow-up questions similarly may have subtly shifted the students thinking, but always involved following their lead. These questions did not introduce new ways of conceptualizing complex systems, for instance, these questions did not introduce new levels or new rules. Thus, as described in the literature on clinical interviewing from a Piagetian tradition, this is a type of social interaction derived from naturally occurring patterns of activity in which the goal is to expose the interviewee's natural ways of thinking about the phenomena (diSessa 2007).

The interview goal was to discover how a student made sense of the phenomena. With that in mind, the initial sand dune story and follow-up questions focused on presenting sand dune movement as a phenomenon that is interesting, worthy of consideration, and something for which one can make sense of. The goal was further enhanced by using a context, sand dunes, which is not commonly covered in the science curriculum and therefore, there was less expectation of a correct or school-style explanation. During the interviews a significant emphasis was placed on viewing the sand dune question as interesting and understandable, but which is outside the bounds of traditional science curricular content. Although this interviewing approach is commonly used in the learning sciences, mathematics education, and science education research that focuses on shifts in understanding with a goal of uncovering learning mechanisms (e.g. Schoenfeld et al. 1993; Wagner 2006), this approach has been less common on research within learning about complex systems. Yet, recent work has shown that in interview settings early elementary students were capable of generating elaborate explanations for the behavior of complex systems when provided with appropriate prompts and scaffolds that supported connections between the macro and micro levels (Danish et al. 2011, 2017).

Laurel's interview

The second analysis was done to help illuminate the reasoning patterns, especially the transitional explanations and shifts between explanations. This analysis involves a detailed case of one student, Laurel, who was at the time a masters credential student in mathematics education. Laurel's interview was chosen for an in-depth data analysis as her explanations and reasoning were notably lucid and her initial and decentralized explanations were closely aligned with existing ways of conceptualizing centralized and decentralized causality. Additionally, she had included several transitional explanations, which collectively suggested that the reasoning seen in her interview is representative of the different reasoning patterns seen throughout the corpus. Laurel's sand dune discussion lasted for 13-min. In the transcript, line breaks are useful analytically in regards to knowledge pieces or kinds of explanations and do not necessarily correspond to conversation turns. Descriptions of gestures were included in the transcript in order to help infer meaning.

Analysis methods

Both analyses of student's explanations (initial, final, transitional) involved looking across all of the transcribed explanation for reasoning patterns that were similar to those identified in existing literature on student's learning about complex systems, such as decentralized, centralized, and mid-levels (e.g. Jacobson 2001; Levy and Wilensky 2008; Penner 2000; Resnick 1994; Sengupta and Wilensky 2009; Wilensky and Resnick 1999). Additionally, other explanations for the formation, growth, and movement of sand dunes that seemed central to student's reasoning were also identified. Thus, this analysis involved a mixture of a bottom up and top down process to identify explanation patterns. After that, I identified common themes across the data and then there was a comprehensive coding of all the data for common explanation patterns, including a variety of transitional explanations.

For the second analysis, there was an additional focus on knowledge pieces using a developing empirical analysis method known as Knowledge Analysis (KA); this method is associated with the Knowledge-in-Pieces family of epistemological perspectives. The aim of this method is to identify specific knowledge pieces used in the moment, to describe the internal structure and essence of those knowledge pieces, and to describe how they are organized within one's conceptual ecology (diSessa et al. 2016). There was an iterative process to identify knowledge pieces across the interview, trace how similar knowledge pieces were applied differently over time, and describe the dynamics of how knowledge pieces were found to be relevant and irrelevant.

The specific analysis process enacted in this study is known as microgenetic learning analysis (Parnafes and diSessa 2013), and it is a specialized form of microgenetic analysis (Siegler 2006) that focuses on learning. Using this approach, there was an iterative and bootstrapping analysis process meant to lead to the adaption and extension of existing theories, specifically regarding student's knowledge about the behavior of complex systems. Microgenetic learning analysis involves a continual interaction between theory and data during the iterative analysis process, similar to the "progressive refinement of hypotheses" approach (Engle et al. 2007). Within this analysis process there were iterative cycles of observation, schematization, and systematization (OSS). That is, first there were observations of the student's explanations and of the potential kinds of knowledge that were activated in those explanations and during this phase there was the development of a preliminary list of knowledge pieces. For example, during this phase I listed various kinds of knowledge that were potentially seen in the data (e.g. p-prims such as force as mover and Ohm's p-prim and experiential knowledge such as having seen sand dunes before or recalling the wind direction at beach sand dunes). Next, that preliminary list of knowledge pieces was improved through generating descriptions and working to improve those descriptions through an iterative analysis process of list making, rough coding, and refinement. During this period, I surveyed the entire data corpus to identify common instances of different kinds of knowledge and used that to refine the categories. Finally, the prior categories were systematized and there was an explicit coding of all the data and bounding of categories. Given the significant time involved with using the OSS cycle to identify and bound knowledge pieces this method has typically been applied to case studies to build theory and examine learning mechanism (e.g. Parnafes 2007). As this methodology is not the focus of this manuscript, see Barth-Cohen (2012) for further details.

Knowledge identified

Based on the prior analysis approach, the following p-prims were identified in the Laurel interview. Many of these p-prims were originally documented in the context of Newtonian mechanics (diSessa 1993) and applied to this sand dune context in terms of the motion of sand dunes at the macro level and sand particles at the micro level.

- The *blocking p-prim*, which was previously described as an object's motion being blocked by another object, such as what a brick does to a striking hand, was seen in the context of a sand dune blocking the path of the wind;
- The *Ohm's p-prim*, which has previously been described as more effort begets more results, such as pushing a heavy object that "resists" motion, was seen in terms of the relative amount of sand particles joining a dune and the result being a change in size of the dune;
- The *force as mover p-prim* which was previously described as an impetus acting on an object resulting in a change of speed or direction, such as pushing an object, was seen as the wind functioning as a force that involves a violent or throwing motion that causes sand to move;
- The *continuous push p-prim* which was previously described as a continuous amplitude being applied to an object, such as an automobile engine cruising, was seen in regards to the wind as a force that continuously pushes sand along;
- The *dynamic balance p-prim* or *the equilibrium p-prim* which was previously described as a pair of forces in conflict balancing out, such as two people pushing equally, was seen in regards to the inverse rates of sand particles joining and leaving a dune resulting in some stability in dune size;

Furthermore, the analysis found intuitive knowledge about variability as applied to the strength and direction of the wind, which does not explicitly match any of the previously documented p-prims. Other kinds of knowledge were captured too. For instance, knowledge based on explicit prior experiences, such as seeing pictures of sand dunes and visiting sand dunes at deserts and beaches. From these experiences students were familiar with how sand dunes look from above and from the side. Students also accessed expectations about sand dunes, sand particles, and the behavior of the wind, such as an expectation that there are many dunes together in the desert and an expectation that the wind is variable and changes directions. None of these p-prims or other knowledge was explicitly centralized or decentralized, instead in a specific instance a knowledge piece might contribute to a student's explanation or developing understanding appearing more or less centralized or decentralized, depending on the context.

Explanations identified

Based on the above analysis process, initial, final, and transitional explanations were identified across the data.

Centralized explanations

These explanations were suggestive of an understanding of the phenomenon that is based on centralized causality often involving a central cause directing or orchestrating the behavior of all individual agents. In these explanations, the same behavior is often exhibited by the macro and micro levels. These explanations often involve merging or confusing the relationship between levels (Wilensky and Resnick 1999). Within the micro level, all of the individual agents typically exhibit the same behavior. For instance, in the case of sand dunes, a more prototypical centralized explanation would conceptualize the phenomena in terms of the wind (or another controlling phenomena) moving the entire dune (all sand particles) in unison such that there is literally the same sand dune comprised of the same sand particles at multiple points in time. Another type of centralized explanation would focus on the wind causing the same behavior in each sand particle, for instance that all sand particles move from the windward (upwind) side of the dune to the leeward (downwind) side of the dune resulting in the dune moving downwind. Furthermore, these explanation shares some similarities with a traditional reductionist approach in which sand dunes are modeled as sums of interactions, which has become less prominent in the geomorphology literature in favor of modeling based on non-linear dynamics (Kocurek and Ewing 2005; Werner 1999).

Decentralized explanations

These explanations were suggestive of an understanding of the phenomenon based on decentralized causality and captured decentralized attributes of the behavior, often accounting for the inherent complexity or emergence. For instance, this would have involved recognizing how behaviors at the micro level collectively contribute to completely different behaviors at the macro level where the new behavior is qualitatively different. A more prototypical decentralized sand dune explanation involved recognizing how the behaviors of many sand particles joining or leaving the dune at varying rates collectively results in the dune getting bigger or smaller. That is, the individual motion of sand particles contributes to a broad outcome of macro level change in dune size. When the rates of sand joining and leaving are equal, the dune remains a constant size. Furthermore, a decentralized explanation involved recognition of the sand particles and dunes moving in different directions or recognition of the variability of the strength of the wind and how that influences the dunes. This decentralized explanation shares core features with how others in the literature have defined emergence, such as Levy and Wilensky (2008, 2011) who focus on how macro level patterns arising from the interactions among micro level individuals. As another example, Grotzer et al. (2017a) takes a broad approach to describing three tiers of distributed causality, aggregate, interactions between agents, and interactions of interactions, some of which align with this decentralized explanation. Chi et al. (2012) define emergence narrowly with a focus inter-level attributes, such as the collective summing of all the interactions at each point in time and interactional features between agents, such as agents interacting uniformly. While these definitions from the literature share many similarities, there are also differences as the decentralized sand dune explanation often includes aggregate outcomes, but synergistic outcomes are less common. Further complicating this issue, sand particles interact differently when moving due to airflow as compared to when they are in a dune and in contact with other sand particles. Yet, as previously discussed, research in geomorphology commonly models sand dunes development and evolution as exhibiting emergent behavior (Baas 2002; Kocurek and Ewing 2005).

Transitional explanations

These explanations were not explicitly based on an understanding of either centralized or decentralized causality, but occasionally had elements of both. Typically, these explanations account for sand dune or sand particle movement based on a causal mechanism that is neither explicitly centralized or decentralized. Often students mentioned the wind, gravity, weather, the local environment, and human interference, among other factors that contributed to changes in sand particles or dune movement. Additionally, many of these explanations also involved other general patterns of behavior that describe the phenomenon, such as oscillation (dunes periodically becoming bigger and smaller due to a restoring force), equilibrium (dunes having a common range of sizes due to a balancing effect), and threshold points (large dunes becoming unstable and tipping over).

Analysis I: common reasoning patterns in sand dune explanations

Across the entire data corpus, student's sand dune explanations reflected a general reasoning pattern, as shown in Table 1, many encompassed some combination of a centralized explanation, a decentralized explanation, and transitional explanations. A few interviews contained all three kinds of explanations, but across the data corpus there were many more interviews that contained one or two of these explanations. There was not a strong pattern of explanations related to academic level, for example, of the three students whose interviews contained all three explanations, two were graduate students and one was a high school student. Of the two students whose interviews contained none of these explanations, one was a graduate student and the other was a high school student. Furthermore, there was a general pattern with centralized explanation often occurring at the beginning of the interview, transitional explanations occurring throughout the interview, and decentralized explanations occurring towards the end. The centralized explanations commonly contained a central cause directing the behavior of all individual agents, such as the wind causing all sand particles to move at once. Typically, the decentralized explanation involved the

Table 1 Tally of interviews that encompassed each reasoning pattern

Number of students whoes interviews encompassed each reasoning pattern				
		Centralized	Transitional	Decentralized
	3	X	X	X
	3	X	X	–
	8	–	X	X
	1	X	–	X
	3	X	–	–
	6	–	X	–
	5	–	–	X
	2	–	–	–
Number of times each reasoning pattern was used		10	20	17
Total number of students	31			

collective behaviors of many sand particles contributing to the macro level change in dune size, such as varying rates of sand particles joining and leaving the dune contributing to the dune getting bigger or smaller.

Transitional explanations neither had a central cause nor the characteristic collective behavior seen in the decentralized explanation, but they did often have elements of one or the other and generally functioned as threads of local continuity that were associated with changes in understanding. For example, one graduate student's transitional explanation focused on the question of whether dunes are spread out parallel or perpendicular to the direction of the wind. He initially explained that dunes would get stretched out parallel to the direction of the wind, but then relinquished that explanation and added an explanation based on dunes spreading out perpendicular to the direction of the wind. This led to a conflict among possibilities that was then resolved by him deciding that the motion of the sand grains might be independent from the motion of the dunes and thus the dune and wind could be moving in opposite directions, which is the decentralized explanation. As another example, one of the high school students generated a transitional explanation in which the wind blows sand onto a dune making it bigger and then there is a threshold point where the side of the dune become very steep and the sand crumbles down the sides. That threshold explanation eventually contributed to a decentralized explanation that focused on the rate of sand particles leaving and joining the dune. To further unpack the types of reasoning seen in the transitional explanations along with the relationship between the centralized, transitional, and decentralized explanations, the next analysis presents a detailed case where we document the continuum along with various knowledge pieces used in each explanation.

Analysis II: a case of laurel's sand dune explanations

The case of Laurel involves a centralized explanation, several transitional explanations, and a decentralized explanation. The analysis characterizes each of these explanations along with relevant knowledge pieces in order to capture differences in her reasoning. During the intermediate period when she generated the transitional explanations, there

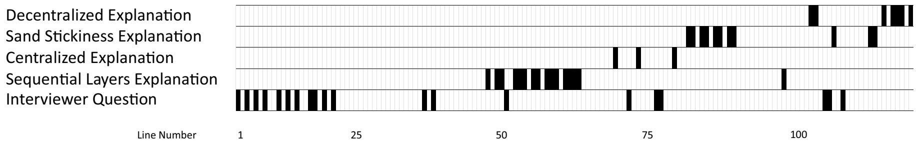

Fig. 2 Explanations apparent from the beginning to the end of Laurel's interview

was a gradual process of her relinquishing prior explanations and putting together new explanations based on changing relevance and irrelevance of knowledge pieces. She generated two transitional explanations that account for how sand dunes move: *sequential layers* and *sand stickiness*. These two transitional explanations function as threads of local continuity that were associated with her changing understanding. As Laurel did not progress linearly, she explored these two transitional explanations many times, often simultaneously, Fig. 2 highlights the distribution of her different explanations across the interview. In the beginning, the interviewer spoke often, this period had involved clarifying the sand dune question, while the interviewer spoke less at later points. Lines of speech that were not coded involved ideas and tangents that were not followed up on and not directly related to the initial, transitional, or decentralized explanations. The patterns seen in Laurel's interview were similar to other students who also went through a process of relinquishing prior explanations while progressing non-linearly through many explanations. To illuminate Laurel's overall reasoning pattern in more depth the following analysis is presented thematically.

Initial centralized explanation

Initially Laurel conceptualized the phenomenon in terms of there being literally the same sand dune comprised of the same sand particles at both points in time as the wind moves the entire dune at once. However, at the beginning of the discussion, Laurel never clearly stated this initial centralized explanation. Instead, at various points during the interview Laurel reflected back on her prior unstated explanation. Across the interview corpus, referring to an unspoken explanation was uncommon, but it did occur elsewhere. When Laurel referred to her prior unstated explanation, she would preface it with a comment that signal her reflecting on her prior understanding and she would speak in the past tense. For instance, mid-way through the discussion Laurel mentioned it being the same dune at two points in time, "I was thinking of it as like the same sand dune. [*Gesture emphasizes direct movement of one sand dune*]" (line 79). At another point, Laurel explained, "I guess I was just assuming that all the things from this sand dune would make the new sand dune" (line 69). In these explanations, Laurel was focusing on the dune and not the individual sand particles. She may have been accessing knowledge that directed her to focus on the entire dune moving as a single unit and she was not taking into account the movement of individual sand grains. This initial sand dune explanation suggested an understanding of the phenomenon rooted in centralized causality because she assumed that the dune was comprised of the same sand particles at multiple points in time. While her centralized explanations might have been consistent with other ways to conceptualize sand dune movement, her explanations were not consistent with decentralized causality.

Transitional explanations

Sequential layers

During the intermediate period Laurel generated an explanation that accounted for sand dunes moving in *sequential layers*. The top layer that was most exposed to the wind moves first, followed by the movement of subsequent layers until the entire dune has moved from one location to another location. Laurel's sequential layers explanation shares some similarities with what has been identified elsewhere as a mid-level construction, that is a productive strategy for making sense of complex phenomena by aggregating individuals within the whole (Levy and Wilensky 2008). Furthermore, this general sequential layer's transitional explanation was seen elsewhere in the interview corpus, but the specifics described below are unique to Laurel.

In the buildup to the *sequential layers* explanation, Laurel first mentioned that the wind would blow all the sand in the same direction, possibly using the force as mover or the continuous push p-prims ("The wind would go in a particular direction, so I guess, which would push the sand in a particular direction [*hands move to mimic wind pushing sand in one direction*]." line 48) Then she mentioned the wind "reformulating" the sand into a new sand dune ("And then it blows it all, kind of in the same area and makes them somehow reformulates [*circular hand movement implies 'reformulation'*] that sand into like a new sand dune. I don't know." Line 50.) Next, the interviewer asked for more information about how that would occur ("How would the wind reformulate the sand into a new sand dune? [*moves hands in cyclical motions similar to Laurel's gesture*]." line 51) Laurel responded by reiterating her prior idea and questioning the scenario, "Well, I guess, I think of it like, like, if there is like a mountain or a sand dune [*draws a sand dune with blue marker*] and then if the wind is blowing this direction [*draws wind going into the side dune with a blue marker*] or well, that doesn't really work anyways. Whatever." (line 52–53) Although the statement about the wind pushing the sand was more centralized (line 48), she found the idea of wind "reformulating" sand into a dune to be relevant (line 50). Reformation likely drew on different knowledge, yet the details are unknown. However, her questioning and expectation that the wind would not blow the entire dune at once, as will be described next, likely contributed to the *sequential layers* explanation.

The *sequential layers* explanation focused on the wind blowing layers of sand sequentially. The top layer of sand was blown first, followed by the next layer, until the entire dune had moved locations in orderly layers.

54. Laurel	So then like, this top layer of sand would kind of get blown first or whatever. Or whatever I don't know
55.	on the first, on the top, it depends on where the wind is coming from.
56.	But some of the, like, outside of the sand dune [*gesture implies outside or top layer of sand dune*] would kind of get blown over here [*draws sand getting blown with a purple marker*]. And then it would kind of end up somewhere [*draws sand particles down wind of the sand dune in a purple marker, see* Fig. 3]. And then now that layer gone so, then, if the wind kept blowing, then it would kind of blow whatever. This, some of the outside again. [*draws outside of sand dune getting blown with a green marker*] And those ones would get blown over here somehow [*draws sand particles down wind of the dune in a green marker*]. And then it would start, I don't know.

Fig. 3 Laurel's drawing of sand moving in *sequential layers*. On the left picture, the entire dune is blue with the top left side being purple and the bottom left side being green. On the right picture, the top sand particles are green and the bottom ones are purple

57. Then it would keep doing that until it all kind of moved over here, to a new sand dune. [*Gesture emphasizes the motion of the sand particles and dune as illustrated on the drawing in* Fig. 3]

Laurel's explanation above accounted for sand dune movement as a multi-step process of the dune moving in continuous layers until it had moved locations. First, the top layer of sand was blown off the dune (line 54 and 55), and then, if the wind continued to blow, the layer of sand that was now on the outside would be blown over (line 56) and, it would continue until the entire dune had moved (line 57). While speaking Laurel drew the picture shown in Fig. 3 with the layers in different colors on the left side of the dune. Within this explanation Laurel was possibly using the *force as mover* or the *continuous push p-prims* to account for sequential movement, the wind pushing one layer of sand, then another layer, and another layer. Thereby, she was using similar knowledge as her prior explanation, but applying it multiple times to sequential layers rather than applying it once to the entire dune. Additionally, in this excerpt she drew on intuitive knowledge about the variability of wind, specifically that the movement of a layer of sand depends on where the wind was coming from (line 55). This piece of knowledge was not crucial here, but became more important in subsequent explanations.

Parallel to how the *sequential layers* explanation was generated after she rejected the more centralized explanation of dunes moving all at once (recall lines 52–53), the *sequential layers* explanation was then rejected because it relied on an assumption that the wind would stay constant which Laurel came to view as also implausible. Laurel found the idea of sand moving in *sequential layers* to be irrelevant because the wind would not be constant. "But then, I know that when it's windy, it's not like the wind is constant, at exactly the same, exactly the same, like, strength it's always blowing in exactly this direction because if it were that would make sense right? Because then the purple would fly over here and the green would fly over here and then whatever. It would go in layers, some kind of layers or a stream like that." (line 58–61) Drawing on possibly the *force as mover p-prim*, she vocalized conflicting assumptions, that she would not expect the wind to be constant in terms of strength or direction, even though it would make sense if it were constant. Continuing her explanation, she next assumed that the wind could be variable in strength and direction ("But sometimes it would be not blowing as hard so then the sand wouldn't go as far, or sometimes it would kind of change directions and then it would blow it into a different direction." line 62) Her idea of variability had been mentioned before (line 55) and here became more important than the prior intuitive knowledge based on force as mover. Yet, Laurel did not explain if or how the varying wind would push the sand into a dune rather than all over the place.

Throughout these excerpts there was a change in Laurel's explanations. She generated the *sequential layers* explanation based on an assumption that the centralized explanation, in which the wind blows the entire dune at once, would not work (recall lines 52–53). As an alternative, she proposed that the wind "reformulates" the sand, and this led into the *sequential layers* explanation. The *sequential layers* explanation was in turn relinquished, despite it making sense, because she did not expect the wind to be constant (recall lines 58–61). Both the centralized explanation and the sequential layers explanation involved the *force as mover* p-prim, and in the former case that p-prim was applied to the entire dune while in the latter case it was applied to layers of sand. When she relinquished the sequential layers explanation she drew on knowledge about variability of the wind in terms of strength and direction. As will be discussed later, knowledge about variation may have contributed to the final decentralized explanation where it was applied to the rate of sand particles joining (accumulation) and leaving the dune.

Sand stickiness

During the intermediate period Laurel generated another transitional explanation that accounted for sand dune movement: *sand stickiness*. This transitional explanation included the idea that sand particles accumulate on the dune because they are "sticky," and sand particles leave a dune because they are no longer stuck to the dune. Despite using that language, Laurel clarified that she meant something more like accumulation rather than stickiness; this is important because accumulation was part of her final decentralized explanation. Interestingly, the sand stickiness transitional explanation was unique to Laurel and not seen elsewhere in the data corpus.

In order for Laurel to generate the *sand stickiness* explanation and focus on the changing size of dunes there was a change in expectations. First, she relinquished the expectation that all the sand in the new and old dune was the same ("I mean, there was other sand. And, I'm guessing, it wasn't just like a random pile of sand in the middle of the desert" lines 70–71.) Laurel used two expectations, first, that there are other sand particles in the desert, which are not a part of the initial dune, and second, that there are many dunes in the desert besides the one in question. This brought the possibility of many dunes into the picture bringing with it the possibility, not yet considered, that the new dune is not the same one that started out. She then mentioned two likely options, the centralized option in which a dune literally moves or a dune disappears and then a new one appears ("So I don't know if it's actually like this sand dune moved over, or if it's like this one just disappeared and then a new one formulated." Line 73–74.) Given these two options, the interviewer then built on her prior ideas and asked a follow-up question that involved mentioning that usually we see "a whole bunch of sand dunes" in the desert (line 77). Laurel then agreed with this idea and mentioned that she was previously thinking about the phenomena as literally the same sand dune at two points in time ("So there is just a lot of them and yeah, you know, [*gesture implies many sand dunes*] okay. I was thinking of it as like the same sand dune [*gesture emphasizes direct movement of one sand dune*.]" Lines 78–79.) Thus, Laurel, with some scaffolding by the follow-up questions, came to see the relevance of many dunes and relinquished an explanation that was based on an isolated dune. This small shift was important because it paved the way for her thinking about the dynamics of how several dunes impact each other's behavior, which was key for the *sand stickiness* explanation and the final more decentralized explanation.

Next, Laurel generated the *sand stickiness* explanation by focusing on sand particles accumulating on the dune because they stuck to the dune and joined it.

81. Laurel I've been to some sand dunes before, so I think I know like, but,
82. I guess, since the sand is like kind of loose [*gestures involves moving hands outwards to imply 'loose'*], right? It's not like it's glued together or compacted or something [*gestures hands together implying 'compact'*]

…

85. Laurel Cause I can imagine if there was a little pile of sand [*holds hands together to imply little pile of sand]* that somehow forms somewhere
86. then the other sand that was being blown would kind of get stuck there, or not stuck, but, like, it would kind of, maybe it could hit the, it could hit the, hills somehow and then it would stop there, right?
87. It would kind of join in, in a way, with that, like, little pile and then it would start getting bigger and bigger, and then more sand would kind of. I don't know if it would be like,
88. you know, it's flying along then hits it, and then it stops there [*gestures implies sand particles flying around and hitting something*] and it then it would be kind of be forming a bigger sand dune [*gesture implies big dune*]

Above Laurel explained how dunes got bigger through the mechanism of *sand stickiness* and accumulation. When sand was not glued together and not compact, then it could fly off the dune (line 82). If a small pile of sand was formed (line 85) it will get bigger as more sand is blown onto it because of accumulation (line 86–88). Notice that this explanation connected the behavior at the micro (sand particle) and macro (dune) levels in order to explain how sand joins the dune as it becomes bigger and how the sand leaves the dune as it becomes smaller.

Within this explanation she accessed several kinds of knowledge. At the beginning (line 81) she mentioned having been to sand dunes previously, potentially accessing some kind of experiential prior knowledge, but the details are unknown. When discussing sand particles that are blown by the wind and then hit the dune and stop (line 86), she was potentially accessing knowledge about the sand particles being in a continuous motion that is interrupted by the dune *blocking* their path. Also, when she mentioned sand particles joining the dune and the dune getting bigger (line 87) she was potentially accessing *Ohm's p-prim* given the implication of more sand particles joining the dune resulting in the dune increasing in size.[1]

In this explanation Laurel explained how a dune increases in size and implicitly how it might decrease in size. Remember, the initial interview question was not about dunes increasing or decreasing in size, it was about dunes moving and her centralized explanation was also about dunes moving. Laurel was never explicitly asked about dunes changing size. Somewhere along the way she relinquished the goal of trying to explain how dunes move

[1] Although Ohm's p-prim typically involves an agent acting through resistance to produce a result, and no resistance was mentioned in line 87, it known that many p-prims have "fuzzy" applicability conditions and Ohm's p-prim has been documented without resistance (diSessa 2017). Another possibility is the applicability of a meta p-prim, which is an abstraction that is common to many p-prims (diSessa 1993).

and found relevant knowledge about there being many dunes in the desert; in turn, she began focusing on dunes changing size, which continued through the decentralized explanation. In summary, to generate this explanation she: (1) relinquished the prior expectations about the composition of dunes being constant, (2) relinquished trying to explain how a single dune moves, (3) added the expectation of many dunes in the desert, and (4) added a focus on how dunes increase and decrease in size. Additionally, she found relevant a variety of knowledge including expectations about many dunes in the desert, prior experiential knowledge of having seen dunes elsewhere, and intuitive knowledge about the dune blocking the path of sand particles and thereby increasing in size.

Final decentralized explanation

Laurel's final decentralized explanation was suggestive of a more normative understanding and related to decentralized causality as it captured the *changing composition* of a sand dune. That is, variation in the rate of sand particles joining and leaving the dune resulting in changes in the size of the dune.

> Maybe it depends on like, cause if things [sand particles] are being, like joining in and some things are being blown away, I'm thinking that if that's happening equally then it's [the dune] just never going to change. Right? But maybe it's more like at some points more is being added than is being taken away, and then at other points, the wind somehow is taking more, more sand away than is joining that little pile. (lines 113–117)

She explained that the dune's size depends on the rates of sand joining and being blown away from the dune. When these rates are equal, the dune stays the same size. She also considered unequal rates resulting in dunes moving. At some point, more sand is being added than is being taken away, and at another point more sand is being taken away than is being added. She also considered how a dune might become bigger in a periodic manner by accounting for some wave-like behavior that resulted in some continuity in dunes repeatedly changing size. "So, maybe it's more of like a wave getting bigger and then getting smaller and then it's getting bigger. Just rotating like that. [*Gestures emphasizing the cone getting bigger and smaller*] possibly." (line 102) These explanations captured the decentralized nature of the process because they connected the behavior of sand particles with the overall behavior of the dune and accounted for the changing rates of sand particles joining and leaving the dune. This general decentralized explanation with a focus on the changing composition of a sand dune was common throughout the data corpus and seen in 17 of the 31 interviews.

Within this explanation Laurel found both the individual sand particles and the entire dune level to be relevant. In addition, she found the relative rates of sand particles joining and leaving the dune to be relevant. Likely the knowledge found relevant here about sand particles joining was similar to the previously accessed knowledge about more sand particles joining the dune resulting in the dune increasing in size (*Ohm's p-prim* from line 87). Interestingly, here she found relevant knowledge of the inverse processes, sand particles leaving the dune. Therefore, potentially this explanation was based on some intuitive knowledge of *balancing*. When the rates of sand joining and leaving the dune are balanced then there is an equilibrium in dune size, and when the rates are unbalanced, then the size of the dune changes. Although this explanation still involved the wind, it is more normative because she was connecting the micro sand particle level behavior with the macro sand dune level behavior; connecting the micro and macro levels is key for an understanding of decentralized causality (Penner 2000; Wilensky and Resnick 1999).

Summary of Laurel's sand dune explanations

Across the explanations Laurel exhibited a variety of reasoning patterns. She generated two transitional explanations, along with an initial explanation that was more prototypically centralized and a final explanation that was more prototypically decentralized. In her centralized explanation, she found relevant knowledge about the wind as a force moving the entire dune (*force as mover*) and this knowledge piece was later applied in the sequential layers explanation to account for sequential movement of layers of sand. In the sand stickiness explanation, she found relevant knowledge about sand particles joining the dune resulting in it increasing in size (*Ohm's p-prim*). Subsequently, in the decentralized explanation the same knowledge piece in order to account for balancing of rates such that the dune's size changes or stays the same. This analysis illustrated that Laurel generated a variety of different explanation with knowledge pieces providing the continuity and fluidity connecting them.

Discussion

Within the literature on learning about complex systems the overall attention has been on discontinuities across two ways of understanding these systems, that associated with either centralized or decentralized causality (e.g. Chi 2005; Jacobson et al. 2011; Resnick 1994; Slotta and Chi 2006; Wilensky and Resnick 1999), along with some work that has examined instruction aiming to support changes in understanding (e.g. Levy and Wilensky 2009a; Yoon 2008, 2011). Evidence suggests that students exhibit notable flexibility in their reasoning about complex systems (Gupta, et al. 2010), but less is known about the nature of the reasoning patterns across the centralized to decentralized continuum. Others in the literature have documented intermediate and hybrid ways of understanding (e.g. Grotzer et al. 2017a; Levy and Wilensky 2008), but this work has less examined the knowledge structures involved in these intermediate ways of understanding and how the shifts occur. The current analysis identified a variety of intermediate transitional explanation and showed that micro level shifts in explanations occur through changing relevance and irrelevance of knowledge pieces that are applied to both the macro and micro level of the relevant complex phenomena. Those micro level shifts connect the initial, transitional, and decentralized explanations while serving as threads of continuity; thereby illustrating a variety of intermediate reasoning patterns that exist along a continuum with centralized and decentralized causality. These results show that there is a range of understandings, including important bridges between centralized and decentralized causality along a continuum. P-prims that were originally discussed in Newtonian Mechanics were documented as applicable to a complex systems phenomenon that involved forces and motion. These knowledge piece may have contributed to Laurel's explanations and developing understanding appearing more or less centralized or decentralized, depending on the context. Future work may benefit from continuing to examine the role of intuitive ideas from Newtonian Mechanics in this area. A challenge in interpreting these results rests on varying definitions of emergence in the literature (Grotzer et al. 2017a), and going forward it may be helpful for there to be a more comprehensive definition that is aligned with the broad scientific literature. Collectively, these findings suggest that contrary to prior assumptions about student difficulties, student's exhibit a variety of reasoning patterns about complex system and it may be beneficial for future research to continue moving beyond this discontinuity to further examine transitional explanations and knowledge used across a continuum of reasoning patterns.

In the conceptual change literature there is an ongoing discussion about the extent to which student's initial ideas are composed of fragmented knowledge pieces or coherent wholes (diSessa 2013; diSessa et al. 2004; Vosniadou 2013). The analysis presented assumed that knowledge systems consist of many knowledge pieces operating at different levels that can be continually reorganized over time. In accordance with this assumption, the analysis identified various p-prims that Laurel found relevant and irrelevant in various explanations for sand dune formation and movement. From the other side of the fence, research using the framework theory of conceptual change focuses on a learner's initial understandings forming a coherent explanatory system. The framework theory perspective recognizes that at points in time learner's understandings may appear fragmented due to instruction and there is a gradual learning process with an enrichment-type learning mechanism in which new scientific information is assimilated with incompatible prior knowledge, sometimes resulting in fragmentation, but overall there is a general search for coherence (Vosniadou 2013; Vosniadou and Skopeliti, 2014). Evidence to support the framework perspective has generally consisted of cross-sectional developmental studies of young children's understanding of topics in school science (e.g. force, matter, energy, day/night cycle) with results showing a range of conceptions, including synthetic conceptions that often are a bridge between an initial conception and the scientific perspective. Comparably, rather than holistically characterizing Laurel's conceptions, this analysis showed that examining micro level shifts in-depth can illuminate changes in conceptions. Additionally, it is important to remember that the formation and movement of sand dunes is an example of a scientific phenomenon generally not covered in traditional science curriculum. Thereby the learning documented here operates at a different grain size and involves a different type of scientific topic than what has previously been addressed.

Mechanisms of shifting explanations

Within Laurel's reasoning patterns there was a changing of relevance and irrelevance of knowledge pieces. The changing relevance of knowledge pieces is one potential mechanism to explain her shift in reasoning. Potentially the application of these knowledge pieces to the macro and micro level may have been key because at those different levels there was further differentiation of what aspects of the explanation made sense and did not make sense. The *force as mover* p-prim was applied to both the centralized and sequential layers' explanation, in the former case that p-prim was applied to the entire dune while in the latter case it was applied to layers of sand. Thereby applying that p-prim to the intermediate level of dune layers might have helped make connections to the micro sand particle level. The mechanism of shifting applicability of knowledge pieces is similar to the mechanisms of incorporation and displacement, as discussed elsewhere (e.g. diSessa 1993; Izsak 2005; Kapon and diSessa 2012; Parnafes 2007). Other potential mechanisms operated at the explanation level. Laurel questioned, rejected, relinquished, and added various explanations that for one reason or another she found problematic or relevant. There were also shifts in her focus and the question being answered. Thus, her explanation moves may have been an additional mechanism for changing reasoning patterns. These potential mechanisms operated at a fine grain size accounting for a series of small shifts in her understanding that collectively resulted in an overall shift from a more centralized explanation to a more decentralized explanation. Other research has focused on a discontinuity in ways of understanding complex systems (e.g. Chi et al. 2012; Slotta and Chi 2006; Jacobson et al., 2011) and then presumed learning mechanisms to be the revision of categorical membership (Chi 2008). The revision of categorical membership is a macro level mechanism that may account for large scale shifts, but is less able to account for all of the micro level shifts Laurel experienced. Furthermore, the revision of categorical membership presumes an adherence to one category at a time and thus is problematized by results demonstrating the flexibility of students' ontological categories (Gupta et al. 2010), similar to Laurel's reasoning patterns. Future work may benefit from a deeper examining of learning mechanism and specifically the interrelationship between shifting applicability of knowledge pieces and explanation moves.

Limitations

Although the first analysis documented that many students exhibit initial, final, and transitional reasoning patterns, similar to Laurel's reasoning patterns, there are still questions about to what extent other students exhibited reasoning that involved changing relevance and irrelevance of knowledge pieces. Furthermore, less work has examined the full corpus of transitional explanations and there are questions about whether certain kinds of transitional explanations are more or less helpful along the continuum and what instruction can do to support these explanations. There is no reason to expect that the nuances of Laurel's shift, and those specific transitional explanations, would be common to others shifts. Instead, we presume that many paths are possible given differences in individual's conceptual ecologies, explanations, questions, and overall emphases, but there might be common mechanisms of changing relevance and irrelevance of knowledge pieces across transitional explanations. Furthermore, given the importance of connecting the micro and macro levels, we might expect that utilizing knowledge pieces to facilitate that connection could be helpful elsewhere. Also, given various definitions of complex systems and emergent behaviors, along with sand particles being homogeneous, we may expect that in other complex systems certain reasoning patterns may be more or less common, raising questions about additional learning challenges.

Using an open-ended clinical interview technique is common across similar interview studies that use microgenetic analysis to examine learning mechanisms, such as Wagner (2006) and Schoenfeld (1993). But, there are known limitations including a limited number of participants, the academic background of participants, and the limited tracking of the interviewer's contributions (diSessa 2007), which have been in part ameliorated by connecting Laurel's reasoning patterns with other interviewees. Future work may examine these shifts with younger students and in classroom settings.

One important dimension of Laurel's shifting explanations was the overall conversation dynamics. She modified the focus of her explanation and asked herself a series of questions about dune movement, thereby there was a notably metacognitive quality of many of her statements. Potentially varying the focus of the explanation and the question to be answered allowed her to activate certain ways of thinking that were then productively used in later explanations. While these questions may appear to be extraneous meanderings, in fact they may be a hallmark of a larger strategy of collecting judgments, reflections, and questions that contributed to the overall shift. Furthermore, Laurel took other actions that may have contributed to her shift, she reflected on her own understanding, made judgments, and used those actions to inform next steps. Similar to the well-documented benefits of explaining to oneself (e.g. Chi et al. 1994), there likely were benefits for Laurel having explained her ideas aloud. Knowing what actions Laurel took to scaffold her own explanations is important as future work may benefit from a closer analysis of student's moves, including self-generated questions and metacognitive statements.

Additionally, the interviewer likely had an important role in the conversation dynamics. The follow-up questions might have nudged Laurel's thinking in various ways, but the essence of those questions was always rooted in her own ideas (e.g. line 51), thus we would expect that the overall conversation dynamics expose the interviewee's natural ways of thinking about the phenomena at hand (diSessa 2007). Furthermore, recent work has shown the importance of appropriate prompts in interview settings for supporting students in generating elaborate explanations for the behavior of complex systems (Danish et al. 2011, 2017).

Instructional implications

In recent years research has been examining various curricular approaches to support student's learning of complex systems (e.g. Tripto et al. 2017; Yoon 2008, 2011). Much of that work has documented instructional approaches that can support student's learning about complex system. Comparably, the current work has highlighted the occurrence of intermediate transitional explanations that can be helpful in a developing understanding of complex systems. Implications of these results may involve instruction that aims to encourage learners to generate transitional explanations that account for general patterns of behavior in complex systems, such as oscillation, equilibrium, and threshold points. Additionally, it may be helpful to focus on the context specific mechanisms of change, for example, in the current data it was sand stickiness and variation in the wind. For other complex systems, there would likely be different content specific mechanisms of change. Furthermore, similar to the documented conversation dynamics in Laurel's interview, it may be important to encourage other scaffolds that help students generate, reflect on, and modify their own explanations across the continuum. Collectively, these instructional implications maybe useful in supporting future students in generating productive transitional explanations.

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