The Role of Prior Knowledge and Problem Contexts in Students’ Explanations of Complex System

By

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A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Science and Mathematics Education in the Graduate Division of the University of California, Berkeley

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Abstract

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The purpose of this dissertation is to study students’ competencies in generating scientific explanations within the domain of complex systems, an interdisciplinary area in which students tend to have difficulties. While considering students’ developing explanations of how complex systems work, I investigate the role of prior knowledge and how students’ explanations systematically vary across seven problem contexts (e.g. the movement of sand dunes, the formation of traffic jams, and diffusion in water).

Using the Knowledge in Pieces epistemological perspective, I build a mini-theory of how students construct explanations about the behavior of complex systems. The mini-theory shows how advanced, “decentralized” explanations evolve from a variety of prior knowledge resources, which depend on specific features of the problem.

A general emphasis on students’ competences is exhibited through three strands of analysis: (1) a focus on moment-to-moment shifts in individuals’ explanations in the direction of a normative understanding; (2) a comparison of explanations across the seven problem contexts in order to highlight variation in kinds of prior knowledge that are used; and (3) a concentration on the diversity within explanations that can be all considered examples of emergent thinking. First, I document cases of students’ shifting explanations as they become less prototypically centralized (a more naïve causality) and then become more prototypically decentralized over short time periods. The analysis illustrates the lines of continuity between these two ways of understanding and how change can occur during the process of students generating a progression of increasingly sophisticated transitional explanations. Second, I find a variety of students’ understandings across the problem contexts, expressing both variation in their prior knowledge and how the nature of a specific domain influences reasoning. Certain problem contexts are easier or harder for students, depending on the kinds of prior knowledge resources activated. For example, in the sand dune problem context, where students are able to access a wide range of intuitive resources that are applicable at multiple levels, coming to explain decentralized causality is relatively straightforward. Third, I find that for these students’ emergent thinking is
not a unified entity. It is diverse in its nature and varies across problem contexts and across the kinds of prior knowledge that students evoke.

This dissertation illustrates the importance of students’ prior knowledge resources in their understanding and developing explanations for how complex systems work. Combined, these results suggest that the fundamental diversity in explanations needs to be respected. Instruction should emphasize the generative process of explaining based on students’ prior knowledge rather than any a priori taxonomy of forms of explanations to be learned.
Dedicated in memory of my maternal grandfather Harold Barth ("Poppy")

You shaped my intellectual life in profound ways.
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CHAPTER 1: INTRODUCTION AND LITERATURE BACKGROUND

Introduction

Learning about complex systems and the emergent processes they give rise to, is an area where students are known to have difficulties learning. In these systems, the macro level pattern or behavior arises from interactions at the micro level. In the Learning Sciences literature a variety of researchers have documented students’ difficulties, and begun to hypothesize why complex systems are so difficult. For example, Chi and colleagues (Chi, 2005; Chi, Roscoe, Slotta, Roy, and Chase, 2012) present a domain general argument for why students’ understandings of behaviors that exhibit emergence are more resistant to instruction than other non-emergent processes. Another example comes from research by Perkins and Grotzer (2005) who argue that students have difficulties with increasingly complex kinds of causality including emergence. Perkins and Grotzer (2005) present results of an intervention to support students’ understanding of complex causal models. Also, there is a body of work by Wilensky, Resnick, Jacobson, and colleagues (e.g. Jacobson 2001; Jacobson, Kapur, So, and Lee, 2011; Levy & Wilensky, 2008; Resnick, 1996; Wilensky & Resnick, 1999) that finds that students’ difficulties are due to their tendency to focus on a centralized cause where none exists and where a distributed cause is more appropriate.

The starting point for this dissertation is data from a short, 13-minute discussion as part of an hour-long, open-ended clinical interview with a masters-credential student in Mathematics Education, Laurel. During the discussion she came to explain the movement of sand dunes as a complex causal process. The discussion began with me, as the interviewer, presenting a narrative story to introduce the phenomena of sand dune movement. The narrative story was about a hypothetical situation in which she lives in the desert, takes a walk away from her house, observes a sand dune at a specific point in time and then goes home. Months later she goes back to the same location and notes that there is no longer a dune at that original location and a new dune has appeared tens of yards away. Laurel’s initial reasoning of how this phenomenon occurred was based on the idea of the entire dune literally moving at once as a single unit. By the end of the discussion, she explained the phenomena in terms of the varying rates of sand particles joining and leaving the dune resulting in the dune getting bigger or smaller. Her initial idea about the entire dune moving at once is suggestive of reasoning about the process through a centralized or direct cause, in which all particles and the entire dune exhibit the same behavior moving together as if there was a wind gust that blew the entire dune at once. Her final explanation about the varying rates of individual sand particles joining or leaving the dune resulting in the dune changing size is suggestive of her reasoning about the process through decentralized causality because she is taking into account the different behaviors of the sand particles and the entire dune and thinking about the relationship between them.

During the intermediate period between the initial and final explanations, Laurel generates a series of transitional explanation and a series of knowledge elements are added and relinquished from her explanation. By focusing on what knowledge is relinquished, including many knowledge elements that supported the centralized explanation, and what knowledge
elements are added, including many that support the final decentralized explanation, I track the lines of continuity in her understanding between her initial and final explanations.

This case of Laurel’s shifting explanations is profound for two reasons. First, the shift was dramatic as it occurred over a short time period and her initial understanding and final explanations centered on vastly different kinds of causality. Second, we can see the intermediate transitional explanations and changing activation of knowledge elements that supported this shift. Thus during this short period she exhibits a surprising amount of competence in understanding and explaining how sand dunes behave as a complex system. From this focal case a series of questions arise that are pursed throughout the dissertation:

1. How does her explanations and understanding of the phenomena of sand dune movement shift from being more prototypically centralized to being more prototypically decentralized? What prior knowledge supports this shift? What other factors support this shift?

Knowing that this shift in explanations can occur, I ask how does it happen? Answers to this question focus on both specific knowledge that support the shift and other factors. In the Laurel analysis I document a series of “moves” that support the shift. This includes major shifts in what question is being explained, dunes moving locations versus dunes changing size. As part of this analysis, I also observe small critical changes in topic that support the shift, for instance her asking the question, how does a dune begin forming? Finally, another “move” that may have supported this shift are the nudges that I as the interviewer.

2. Is the Laurel case of shifting explanations from centralized to decentralized causality idiosyncratic or indicative of a more general phenomena?

Building off the Laurel analysis, I then ask if the case of Laurel’s shifting explanations about sand dune movement is unique or if there are other cases of student’s explanations reflecting a similar shift from more prototypically centralized towards more prototypically decentralized? If there are other cases of this type of shift, in what ways are the particulars similar and different to the Laurel case? Is their one common path between centralized and decentralized explanations or many paths? To begin answering these questions I analyze a second case of a student who also exhibited a similar shift: Keaton. These first two questions about Laurel’s shifting explanations and the Keaton case are pursed in the first piece of analysis, Chapter 4.

3. Knowing that (1) the sand dune problem context was such a productive problem context for Laurel’s reasoning about decentralized causality, and that (2) part of the reason for the problem contexts productiveness had to do with her particular prior knowledge about sand dunes, I then ask: how do other problem contexts influence students’ prior knowledge and productive reasoning about those problem contexts as complex systems?

During the sand dune discussion Laurel activates many transitional explanations and knowledge elements that are particular to sand dunes and were supportive of her shifting explanations. In other problem contexts that are also complex systems, for instance the formation of traffic jams, the spread of forest fires, and the diffusion in water, do students also activate explanations and knowledge elements that are particular to that problem context and supportive of coming to
recognize decentralized causality? In this question I am interested in how the nature of a specific problem context influences students’ reasoning and the variation in students reasoning about these problem contexts in terms of decentralized causality. This third research question about the variation in students’ developing explanations that are supportive for them coming to recognize decentralized causality across problem contexts is pursued in the second analysis chapter, Chapter 5.

4. Is there variation within students prototypically decentralized explanations or are they all similar? Do students’ explanations that capture the decentralized nature of the phenomena vary across problem context and the specific knowledge resources?

In the Laurel and Keaton cases their final, more prototypically decentralized explanations shared some key characteristics about the relative rate of sand particles joining and leaving the dune. For this data set, these two cases are representative instances of emergent thinking and they share some similarities with a classic illustration of emergent thinking in which cars move forwards on a highway while traffic jams move backwards (Resnick, 1994; 1996). Hence, a natural question arises about other students’ prototypically decentralized explanations, do they share the key characteristics about the relative rate of individuals, sand particles or cars, or are they capturing other decentralized attributes of the complex system? In other words, what is the span of decentralized explanations in this data set and what prior knowledge is associated with these explanations across problem contexts? This fourth research question is pursued in the third and final analysis chapter, Chapter 6.

These four questions are thus pursued in this dissertation and the Laurel case is the starting point from which several different lines of intellectual inquiry arise. Naturally the chapter that focuses on the Laurel analysis is the first analysis chapter. As the Laurel chapter is about individuals moment-by-moment shifting explanations, the second analysis chapter takes on a different emphasis and focuses on the similarities and differences across many students’ explanations across all seven problem contexts. This second analysis chapter can be considered the heart of the dissertation as it builds on the initial Laurel case and focuses on the variation across many students’ explanations across all seven problem contexts. The third analysis chapter is an extension both the first and the second chapters in that it focuses on a wider range of emergent thinking than is presented in the first chapter and it focuses on multiple problem contexts similar to the focus in the second chapter. But, differently from the second chapter, which focuses on students’ developing explanations that are supportive for them coming to recognize decentralized causality, the third chapter is about the span of students emergent thinking. Thus together these three analysis address different dimensions of students’ understanding and developing explanations about complex systems across the seven problem contexts.

Overview of the Dissertation

Chapter 1: In the remaining parts of this chapter I present the relevant literature background. I begin with the literature on students’ scientific explanations. I first discuss the importance of explanations in science, and then I discuss the current science education literature, which has tended to focus on pre-determined “forms of explanations,” for instance mechanistic explanations or probabilistic explanations. One of my critiques of this literature is that there is a de-emphasis on the role of prior knowledge within students’ explanations I then transition to
discussing the conceptual change literature, and specifically, Knowledge in Pieces (KiP) (diSessa, 1993), which is the theoretical framework that is used in this dissertation to conceptualize students’ prior knowledge. Within that discussion I focus on the structure, organization, and dynamics of students’ prior knowledge. Then I discuss the existing literature on students’ learning of complex systems. There is a body of work that has focused on documenting students’ difficulties with complex systems. I discuss several hypotheses for the underlying cause of this difficulty and research documenting cases of how students can learn about complex systems. Finally at the end of this chapter I outline several points of departure of this dissertation from the prior literature.

Chapter 2: In the second chapter I present my mini-theory of how students construct explanations about complex systems and this theory is based on their prior knowledge with an emphasis on explanations that capture the emergent nature of the complex phenomena. This mini-theory was developed from the KiP family of theoretical perspectives in order to conceptualize students’ prior knowledge about complex systems and how that prior knowledge supports them in generating explanations.

This mini-theory contains a sketch of three kinds of epistemological resources that were commonly seen in my data. By using the phrase “epistemological resources” I am referring to not only knowledge elements, but also a wide-range of potential resources students could activate with regards to any epistemological activity (Hammer & Elby, 2003). However, this mini-theory focuses on three kinds of epistemological resources. First, there is a catalogue of the four kinds of prior knowledge students activate in their explanations: pragmatic knowledge, experiential knowledge that is or is not cued, p-prims, and agent knowledge. Second, I discuss three characterizations of that knowledge: performances of knowledge, boundaries of knowledge, and the process of creating knowledge. Third, this theory also includes a list of features of the problem context that often influences students’ understanding of emergence, often by focusing them on the underlying mechanism: whether the phenomena occurs again and again or only once, the arrangement of agents, and the relationship between agents and humans.

This analysis of students’ prior knowledge was done in conjunction with an analysis of the students’ generated explanatory patterns that students use to explain and understand the particular problem contexts. These student generated explanatory pattern are ways of focusing one’s attention that students often use within their explanations, and these are similar to dynamic mental constructs (Sherin, Krakowski, & Lee, 2012). For example, an explanation could focus on sand dunes as an equilibrating process, over time dune gets bigger or small but eventually they converge to an intermediate size. Or, perhaps one might notice that the absolute number of sand particles in a dune could be constant but equal rates of sand particles are constantly joining and leaving a dune. Or, one could explain that the dune moves in sequential intermediate layers, first the top layer of sand that is most exposed to the wind moves, followed by the next layer until the entire dune has moved. Each one of these explanations incorporates different underlying pattern. The first sand dune explanation that I mentioned focuses on a pattern that I refer to as, convergence to a limit. The second sand dune explanation focuses on a pattern that I refer to as, changing composition. Finally, the third sand dune explanation that I mentioned focuses on a pattern that I refer to as, mid-levels. While there are many potential explanatory patterns, I focus on ones that may be particularly helpful in supporting students in understanding and generating explanations that are associated with decentralized causality: mid-levels, changing composition, periodic motion, convergence to a limit, steady state, and threshold.
Chapter 3: In the third chapter I present an overview of the methodology used in this study with regards to the data collection and data analysis, at the end of the chapter I discuss my methodology as compared with other researchers methodology. I begin this chapter with a short overview of the science behind each of the seven behaviors that are associated with complex systems: the movement of sand dunes, the formation of traffic jams, fish swimming in schools, the spread of a virus, the spread of a forest fire, birds in flight, and the diffusion in water. Then I discuss my clinical interview with regards to the general open-ended approach, the process of planning for the interviews, the recruitment of participants, the overall chronology of the problem contexts, and the follow up questions. Next I discuss the data analysis with regards to two the central analysis approaches and the associated coding schemes, in particular the knowledge analysis of the specific knowledge elements and the indicators analysis, which is based on a coding scheme for centralized and decentralized causality. Finally I conclude this chapter with a discussion about the similarities and differences between my methodology and other researchers methodologies, and the discussion focuses on learning about complex systems in terms of the process of change, the emphasis on specific prior knowledge, and the focus on comparisons across problem contexts.

Chapter 4: In Chapter 4 I investigate the moment-by-moment shifts taken by individual students as their explanations became less and less prototypically centralized and then became more and more prototypically decentralized. The first two-thirds of the chapter focus on the case of Laurel. To understand how her explanations and understanding shift, I identify two intermediate explanations, which I call: sand-stickiness and sequential layers. I trace lines of continuity in her understanding as she relinquished various pieces of these two explanations, which were more centralized, and she added various pieces, which are more decentralized. I also do an analysis of the moves by both her and me that supported these shifts; specifically, I focus on the interviewee initiated moves supporting her shifting understanding that includes major shifts in what phenomenon is being explained and small critical changes in topic. These are all examples of different kinds of discursive moves by both her and me that contributed to her shifting explanations about sand dune movement.

For comparison purposes, the remaining one-third of this chapter focuses on the case of Keaton. Similar to the case of Laurel, in the case of Keaton there was a general shift in his explanations as they became less and less prototypically centralized and then became more and more prototypically decentralized. However, his intermediate explanations were different. In the analysis, I trace a line of continuity as he wrestled the relative direction of the wind motion as compared to the direction of the sand grain movement and to the direction of dune movement. The analysis illustrates that although these two students traverse similar paths, given a common shift in their explanations, their intermediate explanations are quite different. Thus, this different in their intermediate explanations suggests that there may be at least two paths that can be associated with the general common shift. Both students were able to revise their explanations based on their prior knowledge resources, and their final explanations are aligned with decentralized causality—these results are different from the Chi, Roscoe, Slotta, Roy, and Chase (2012) hypothesis about misconceived causal explanations not necessarily pertaining to a lack of knowledge. Also, this analysis illustrates the lines of continuity between these two ways of understanding and illustrates how change can occur. This result is different from some of the prior work on students’ learning about complex systems (e.g. Chi, 2005; Jacobson, 2001; Perkins & Grotzer, 2005) that has tended to emphasize the divisions between centralized and decentralized explanations and understandings.
Chapter 5: In Chapter 5 I investigate similarities and differences across many students’ explanations and understanding in terms of their prior knowledge. My goal in this chapter is to investigate how the nature of a specific domain influences students’ reasoning about phenomena whose behavior is associated with complex systems. Using the theoretical machinery introduced previously, I focus on variation across many students’ explanations of the seven problem contexts within their student generated explanatory patterns. For each explanatory pattern, I investigate its use across all seven-problem contexts, and I use the mini-theory of knowledge that was introduced in Chapter 2 to capture how students’ prior knowledge influence their explanations. I also focus on explanatory patterns that are potentially helpful for students along the process of coming to generate decentralized explanations.

For example, I find that one explanatory pattern, convergence to a limit, is often mentioned when students’ prior knowledge supports them in focusing on an underlying mechanism, for instance an unstructured group of birds converging to a V-shape as they prefer to fly in formation because it minimizes wind resistance. However, with other problem contexts, for instance, diffusion, students suggested that the mixing of water and juice results is a natural state of the phenomena with no explicit mechanism needed.

The results illustrate variety of students’ understandings across the seven problem contexts in terms of prior knowledge. Specifically, these results call into question a general trend of de-emphasizing domain differences in students’ understandings of emergence because students’ understanding varies widely across the seven problem contexts. Also, these result call into question the general trend of de-emphasizing the multitude of prior knowledge resources that influence students’ understandings of emergence. I find that a factor distinguishing certain problem contexts as being easier or harder for students involves the kinds of prior knowledge resources activated. In sand dunes many students generated decentralized explanations and they were able to access a wide range of intuitive knowledge elements. In comparison to the sand dune problem context, with other problem contexts for instance the diffusion problem context, there were few students who generated decentralized explanations. Of those explanations, they were generally based on prior academic experiences (instruction) not intuitive knowledge elements.

Chapter 6: In Chapter 6 I document the span of emergent thinking and the associated prior knowledge within this data set. Unlike the prior chapter in which I focused on explanations that are potentially helpful in coming to generate emergent explanations, in this chapter I focus on explanations that are emergent. The prior literature uses many indicators as rough gauges to capture underlying emergent thinking (e.g. Jacobson, 2001; Jacobson, Kapur, So & Lee, 2011; Levy & Wilesnky, 2008; Wilensky & Resnick, 1999). In this chapter, I take two indicators of decentralized causality from the existing literature, small perturbations leading to large effects and different behaviors at different level, and I investigate the diversity of students’ thinking that would be encompassed by each indicator. This prior literature has tended to use each indicator as a label within their coding scheme. In comparison one can view the analysis in this chapter as opening up these indicators, and looking at what kinds of prior knowledge and specifics about the problem context contribute to this label. Thus, this chapter is about investigating the underlying pieces that contribute to individuals emergent thinking.

The core of this chapter is the analysis of students’ generated explanations that incorporate one of these two indicators. For each indicator I present two cases of a students’ explanation incorporating that indicator in order to illustrate some variability. Hence the analysis consists of a total of four cases.
In the first half of the chapter I discuss two examples of students’ generated explanations incorporating the indicator of *small perturbations leading to large effects*. The first case is about how one bird’s random perturbation can either lead to the flock breaking apart because all of the other birds get confused or can lead to nothing changing because all the birds compensate. The second case is about one car switching lanes leading to a snowball effect of lots of other cars needing to slow down to accommodate the car switching lanes, given a desire to avoid accidents. For both cases I discuss the specific prior knowledge that influence the students’ explanations, and I discuss some variation across the cases in terms of the, initial behaviors, number of possible outcomes, and overall effects.

In the second half of the chapter I discuss two examples of students’ generated explanations incorporating *different behaviors at different levels*; one of these explanations is about forest fires and the other explanation is about diffusion. For forest fires the student explains that at the micro level there is conservation of energy, but at the macro level conservation of fire is not very applicable as a fire spread from one tree to another tree without influencing the first tree’s amount of fire. The second explanation focuses on three competing processes influencing different aspects of the diffusion in water: 1) diffusion acting on individual molecules behavior resulting in random motion, 2) gravity dealing with the molecules weight resulting in the water molecules moving towards the bottom of the cup, and 3) swirling resulting in mixing. Although both the forest fire and diffusion cases incorporate a common indicator based on fairly abstract principles, they are quite different in terms of the specific prior knowledge that influences the explanations and the specific relevant principles.

The prior literature has tended to emphasize emergent thinking as a unified entity, which is illustrated by its tendency to use a top down approach to code the data and to identifying emergent thinking, for example the complex system mental model (Jacobson, 2001). This chapter concludes that for these students emergent thinking is not a single unified entity—it is diverse and varies across problem contexts and across kinds of prior knowledge.

**Chapter 7:** Finally in Chapter 7, I discuss each of the three analysis chapters, Chapters 4, 5, and 6. For each analysis chapter I summarize the chapter, reiterate the main conclusions, and then discuss some limitations of the analysis. I conclude with a discussion of future research and instructional implications as pertaining to students’ understanding and developing explanations of how complex systems work.

**Literature Review**

In this section I present the relevant background literature. I begin by discussing students’ competencies with scientific explanations. I discuss why scientific explanations are important in students’ learning of science, and then I discuss several existing perspectives that tend to focus on pre-determined “forms of explanations,” for instance mechanistic explanations or probabilistic explanations. In describing these perspectives I refer to them as “forms of explanations” although other researchers use other language. Many of these perspectives tend to de-emphasis students’ prior knowledge and de-emphasis differences in explanations across problem contexts, emphasizing instead domain general forms of explanations.

As I am interested in the role of prior knowledge in students’ explanations, I then turn to the conceptual change literature. There are many perspectives on conceptual change. For example Carey (1999) discusses conceptual change that involves cases of a students’ theory at one point in time being incommensurable with their theory at another point in time. From a different perspective, Vosniadou (1994) discusses a difficult form of conceptual change that
involves revisions of the fundamental presuppositions of the framework theory, which act as constraints on individuals interpretations of their observations and information from the physical world. For an overview of the history of conceptual change research with a focus on the theoretical threads and fault lines see diSessa (2006), and in the introduction to a recent handbook on conceptual change Vosniadou (2008) provides an overview of conceptual change research.

In this dissertation conceptual change is operationalized in terms of changes in the activation of particular pieces of knowledge within explanations over short time periods. In this section I identify several framing questions within conceptual change; these questions are centered on issues of students’ prior knowledge, how knowledge changes, and why conceptual change is so hard. I then address possible answers to these questions in terms of the Knowledge-in-Pieces family of theoretical perspectives, which is used in the analysis.

Then I turn to discussing the relevant background about the content area that is the focus of this dissertation: complex systems. I summarize the literature documenting students’ difficulties with reasoning about the emergent behaviors within complex systems, and then I discuss a series of hypotheses for why students have difficulties learning about complex systems. Given students’ difficulties there are a handful of studies that focus on how students can learn about these systems.

Finally, I conclude this chapter with a discussion of several points of departure between this prior work on students’ learning about complex systems and the current dissertation. Primarily, the existing literature on students’ learning and concerning the development of explanations has tended to focus on students’ difficulties, in contrast, I emphasize competencies. I am motivated both by the competencies Laurel exhibited and by the KiP perspectives emphasis on competencies.

**Scientific Explanations**

Explaining is often considered to be a core competency in science. Generating scientific explanations that describe the behavior of scientific phenomena is often considered to be at the center of the professional scientific enterprise, and this is reflected by the importance of scientific explanations in the science education standards. Over the last two decades science education standards have consistently highlighted the importance of explanations in K-12 science education. The 1996 National Research Council (NRC) national science education standards discuss the importance of explanations when focusing on inquiry. These standards focus on explanation in two ways, thinking critically about the relationship between evidence and explanations and constructing and analyzing alternative explanations. Also in the 1996 NCR report evidence, models, and explanation are also considered one of the unifying concept and process standards across grade levels. The 2007 National Research Council report “Taking Science to School” defines four strands of proficiency in science education, one of which involves interpreting scientific explanations. Another one of the strands in the 2007 report involves generating and evaluating evidence and explanations. Most recently, in the new science education standards—the 2012 Framework for K-12 Science Education—the construction of explanations is highlighted as one of the core scientific practices that is essential to student learning in grades K-12. In these recent standards developing explanations in science and generating solutions in engineering is together one of the three spheres of activity for scientists and engineers. Also, these recent standards discuss the importance of engaging students in scientific practices, including explanations at younger grades. Although the specific details have
shifted, there is a common theme across these standards pinpointing the importance of explanations in the K-12 classroom because it is important to professional scientific practices. Given the importance of scientific explanations in science education it becomes necessary to be clear about what we mean by a scientific explanation. In this section I problematize this issues and I discuss different perspectives on the question of “what counts as a scientific explanation?” If one is observing a lesson or activity, it is not always obvious when students are generating explanations versus generating descriptions or engaging in other activities, and in order to separate these related activities one needs to be able to clearly articulate what counts as a scientific explanation.

There are a variety of approaches in the literature trying to specify what counts as an explanation from different intellectual perspectives. Within the philosophy of science literature there is a tendency to focus on the relationship between the explanation and the thing it explains, see Woodward (2003) for a summary and history of perspectives on scientific explanations in the philosophy of science literature. In the developmental psychology literature some researchers, for instance, Wellman (2011), define explanations as answers to how or why questions. When trying to identify children’s causal explanations within everyday conversations Hickling and Wellman (2001) using key words such as “because,” “so,” and “therefore” as a heuristic to identify the causal explanations.

In science education research one approach is to focus on scientific explanations containing important scientific components. This approach of focusing on important scientific components of explanations is used by McNeill and Krajcik (2008) who focus on teachers’ instructional practices around scientific explanations. They define a scientific explanation as containing these three components: claims, evidence, and reasoning. Operationalizing explanations in terms of these three components involved an adaption of Toulmin’s (1958) model of argumentation, and there is currently a debate in the literature about the relationship between argumentation and explanation (Osborne & Patterson, 2011; 2012; Berland & McNeill, 2011).

Another approach to tackle this issue of what counts as a scientific explanation is to focus on specific pre-determined kinds of explanation. I refer to these as “forms of explanations.” These are types or kinds of scientific explanations that are deemed to be important in professional science and thus relevant to students’ explanations, for example mechanistic, probabilistic, formal, and teleological or functional explanations. I view forms of explanations as structures that can contain, limit, or guide an explanation. For example, a mechanistic explanation incorporates a causal mechanism that underlies the natural phenomena (Russ, Scherr, Hammer, and Mikeska, 2008). In this section I describe the existing literature that focuses on these forms of explanations. Then I contrast this existing literature with the different and novel approach that is used in this dissertation. The current approach focuses on student generated explanations rather than focusing on pre-determined forms of explanation or focusing on explanations containing the three components that are adapted from Toulmin’s model of argumentation. Thus the difference is that the current approach focuses on capturing the kinds of explanations that just happen to materialize as opposed to the prior research that has tended to focus on a set of pre-determined forms of explanations.

In this section I argue that across this literature on forms of explanations there are the following three characteristics: 1) These forms are often considered to be domain-general, many of them are applicable to explanations in biology, physics, chemistry, among other domains. 2) Sometimes these forms are treated as an autonomously learnable and thus considered to be an
instructional focus. A common assumption across this literature is that it is possible to teach and learn about these forms of explanation and the result of this will be that students will be able to apply these forms of explanations in new contexts appropriately. In viewing these explanation forms as autonomously learnable many researchers are de-emphasizing the process of generating explanations and de-emphasizing the role of students’ prior knowledge in these forms. 3) Finally there is also a trend of viewing these forms of explanations as reflecting underlying cognitive structures. In that case the literature has sometimes focused on a limited number of domains of knowledge and those domains of knowledge corresponding to a limited number of kinds of explanations.

There are many overlapping and divergent trends within the research that focuses on forms of explanations. One way to organize this literature is about the relationship between knowledge and explanation form. This focus on prior knowledge is especially important as I focus on students’ generating explanations, as opposed to their evaluation of explanations. An assumption is that the process of generating relies on students’ prior knowledge, more so than their evaluation of explanations. In order to illustrate this relationship between explanations and prior knowledge I draw on literature from diverse perspectives including research in developmental psychology, research in conceptual change, and research on students’ alternative conceptions.

A nice framing for this discussion is presented in Keil and Wilson (2000) who discuss the relationship between explanation form and domains of knowledge. They focus on this relationship as a spectrum with regards to the level of dependence between explanations forms and knowledge. At one end of the spectrum are many distinct and diverse contexts. Each of the contexts has its own explanation form, and there would be many ways the explanation and knowledge can be related. At the other end of the spectrum all contexts may be interdependent and not very diverse, and hence then there would be a limited number of explanations forms in the world. Keil and Wilson (2000) sit on this latter side of the spectrum, along with other researchers, to be discussed below, who focus on there being a limited number of autonomously learnable explanation forms. On this side of the spectrum researchers tends to assume that explanation forms are independent and can be directly taught. The most extreme points along this spectrum are not realistic or plausible, for instance, viewing every single explanation as completely unique or viewing all explanations as identical. This spectrum is informative in order to delineate trends in investigating the role of context specific knowledge in explanations. Below I discuss a series of researchers who focus on the side of this spectrum in which there are a limited number of explanations.

Although Keil and Wilson (2000) discuss a spectrum of relationships between explanation types and knowledge, Keil (2006) focuses on a limited number of kinds of explanations that are linked to particular domains early in development, and he discusses the relationship between these explanations and cognition. Building off work in the philosophy of science on scientific explanations, Keil (2006) focuses on different kinds of explanations in terms of the kinds of causality the explanations evoke and the domain being explained. He discusses the central role of causality in explanations and distinct kinds of causality, for instance common cause, common effect, linear causal chains, and causal homeostasis. Also Keil and Wilson (2000) discuss three distinct kinds of explanations, principle based, narrative based, and goal based.

Similar to Keil, another perspective that focuses on the limited number of explanations forms and is rooted in the development psychology literature comes from the work of Susan
Carey. Carey (1985) argues that there are two intuitive domains of knowledge, and these domains are associated with two modes or forms of explanations. One of these intuitive domains of knowledge is based on an intuitive psychology that contains at its core intentional causality. This intentional causality is central to children’s concept of animal and person. A second intuitive domain of knowledge is based on a physical mechanics that contains at its core contact causality, and this is central to children’s concepts of material objects. The assumption is that these two intuitive domains, psychology and physical mechanics, may account for two distinct modes of explanation form based on the respected two domains of knowledge, psychology and physics. Carey is arguing that these two distinct domains involve two unique explanation schema, thus she views her work as domain specific. However, I take a different perspective as I would view all of intuitive physics as involving many different kinds of explanations that would be based on various kinds of causality. This difference might be rooted in our respective empirical emphases; she focuses on young children while I focus on older students and adults.

From the perspective of focusing on students’ alternative conceptions in physics, Andersson (1986) argues that there is a common causal core to student’s explanations and that this common core applies to different areas in science. “We shall attempt to demonstrate that there is a common core to the pupils' explanations and predictions in such widely differing areas as temperature and heat, electricity, optics and mechanics. We will call this core the experiential gestalt of causation.” (Andersson, 1986, p. 156, emphasis included in the original.) By experiential gestalt of causation Andersson is referring to different components (agent, instrument, and object) that come together to establish a whole that is greater than the parts. This research is based on Lakoff and Johnson (1980) theory of causation. As an example, they discuss a causal chain in which a child (agent) throws a snowball (instrument) in order to knock a hat (object) off a friend’s head. Andersson applies this experiential gestalt of causation to a variety of topics including, melting snow, expansion of gasses, electric circuit, vision, and mechanics. Overall Andersson is focusing on one method to capture all explanations, a common core that is based on the components of the experiential gestalt of causation and is applied widely to many topics in science.

Building off the conceptual change research and with a focus on encouraging conceptual change through instruction, Tina Grozter and colleagues have built a taxonomy of causal models (e.g. Basca & Grotzer, 2001; Grotzer & Perkins, 2000; Metcalf, Tutwiler, Kamarainen, Grotzer, & Dede, 2011; Perkins & Grotzer, 2005). This taxonomy is meant to account for the increasing complex types of causality that students need to address in science. The taxonomy has four dimensions to characterize causality: underlying causality, relational causality, probabilistic causality and emergent causality. Within each dimension there are categories of increasing complexity, which might correspond with increasingly sophisticated causal explanations. The authors used data from students’ learning about disparate areas in science including electricity (Perkins & Grotzer, 2005), density (Perkins & Grotzer, 2005), pressure (Basca & Grotzer, 2001), and ecosystems (Grotzer & Basca, 2001; Metcalf et al., 2011). Grotzer and Perkins (2000) tested the effectiveness of instruction that was built to support students’ understanding of the nature of causality through the taxonomy of causal models. More recently, Metcalf et al., (2011) present preliminary findings about the impact of students working with an ecosystems curriculum on their understanding of the causal models. The instrument used to evaluate students’ causal understanding included a series of statements that are assertions based on different kinds of causality. The students were asked if they agree or disagree with the assertions and why. Across this collection of papers students are generally not generating explanations or causal assertions
themselves, they are instead responding to researchers’ prompts about causality. Also, across these papers there is little emphasis on knowledge-based factors or other factors, such as the scientific domain, that might influence students’ understanding of causality.

The final perspective I will discuss on a limited number of explanations forms comes from Michelene Chi and colleague’s research on ontological categories perspective on conceptual change (Chi, 1992; Chi, 2005; Chi, Roscoe, Slotta, Roy, & Chase, 2012; Chi, Slotta, & De Leeuw, 1994; Slotta & Chi, 2006; Slotta, Chi, & Joram, 1995). Within this perspective the fundamental claim is that concepts differ in ontological ways, and whether or not someone assigns the correct ontological category to a specific concept influences their misconceptions and the possibility of conceptual change. For example, in Chi (2005) there is a discussion of certain processes, such as the diffusion in dye, being an emergent process while other processes, such as the flow of blood in the human circulatory system, are direct processes. The authors claim that misconceptions for direct processes are not robust because students have misinterpretations of them within the correct ontology. In comparison, misconceptions for emergent processes are often robust because students are misinterpreting the emergent process as a direct process. Correcting this misinterpretation requires a shift across ontological categories, which is difficult. As this is a domain general argument for students’ misconceptions, the authors claim that it has implications in terms of teaching the specific underlying causal structures that can allow students to recognize emergent processes. Although this body of work has tended to focus on the diffusion in dye as an example of an emergent process, Slotta & Chi, (2006) discuss electrical current and recently Chi et al., (2012) discusses the diffusion in dye and natural selection. This body of research has emphasized only a few emergent processes, and there is a thread of a domain-general argument based on the distinct and limited number of ontological categories throughout this body of work. There is an assumption that these ontological categories are aligned with cognitive structures, and these categories influence students’ explanations (Chi, 2005; Chi, 1992; Slotta & Chi, 2005).

Recently, Chi et al., (2012) focus on what is a misconceived explanation, why they are so resistant to instruction, and how they can be overcome. Similar to their prior research, in this paper the researchers focus on the direct-causal schema and the emergent schema, the former is similar to the direct processes ontology and the latter is similar to the emergent processes ontology. Based on their ontological categories theory of conceptual change they suggest that in order for students to overcome their misconceptions they need to be taught about the general emergent-scheme, and they suggest doing this with students who have no prior knowledge about the schema. In summarizing their hypothesis, the authors claim that learning more about relevant conditions or using simulations is not sufficient to impact “misconceived causal explanations” because they do not pertain to a lack of knowledge.

“In short, our hypothesis for what a misconception is implies that (a) learning more about the structure, behavior, and function of each level of a process, or (b) learning more about the conditions and how they affect the behavior of each level, or (c) making each level more visible through simulations, will not impact (improve or remove) misconceived causal explanations, because misconceived causal explanations do not pertain to a lack of knowledge about any single level nor are they caused by invisibility of either the pattern or the agents. Rather, misconceived explanations result from an appeal to inappropriate inter-level relationships between the interactions at the agents’ level and the pattern.”
To summarize and place in context, Chi et al., (2012) are saying that none of the following will be sufficient in helping students misconceived causal explanation: learning more about the structure, behavior, and function of each level, which is suggested in Hmelo-Silver, Marathe, and Liu (2007), or learning more about the conditions that will affect the behavior at each level, or making levels more visible through simulations, which is discussed in Jacobson and Wilensky (2006). Chi et. al (2012) rationalize this by claiming that “misconceived causal explanations do not pertain to a lack of knowledge about any single level nor are they caused by invisibility of either the pattern or the agents.” For example, they are saying that incorrect explanations about the diffusion in dye are not due to a lack of knowledge about the molecular movement of water or the invisibility of the molecular level, but instead are due to inappropriate inter-level relationships between the macro and micro levels. In other words, the incorrect explanation would be due to an inappropriate schema or what they have elsewhere called an ontological category.

I am dwelling on this point about the role of knowledge because it becomes important when discussing the results of the Laurel case. Remember in the introduction, in the Laurel case her explanation shift because of the specific prior knowledge cued about sand dunes. As will be discussed extensively in Chapter 4, where the Laurel analysis is presented, the results of the Laurel analysis are different from Chi and colleagues hypothesis. Her explanations shifted from one that is prototypically centralized to one that is prototypically decentralized. There are many reasons for this shift, but of the those reasons connects with the claim made in Chi et al., (2012); she cued some knowledge resources about the relationship between the macro and micro levels.

In summary in this section I presented a series of perspectives on the relationship between explanation form and knowledge from research on instructional approaches in science education, research on students’ alternative conceptions, and research from developmental psychology on explanations. I described these researchers through a series of trends including: 1) Viewing these forms of explanation as domain-general. 2) Treating these forms as an autonomously learnable and thus an instructional focus while thus de-emphasize the process of generating explanations and de-emphasizing the role of students’ prior knowledge in these forms. Many of these researchers do acknowledge the importance of students’ prior knowledge. For instance, Michelen Chi and colleagues approach to addressing students’ misconceived causal explanations focuses on directly teaching students about the specific schema via texts and simulations that have been designed for this purpose. 3) Viewing these forms of explanations as directly reflecting underlying cognitive structures. Some researchers have focused on a limited number of domains of knowledge and those domains producing a limited number of kinds of explanations. Although this literature is varied in scope and emphasis across diverse fields, I have aimed to draw out some commonalities based on these three trends because this prior works view on explanation forms and how it construes the role of knowledge serves as one of the starting point of this dissertation.

Knowledge in Pieces

Referring back to the previous question about the relationship between explanation forms and domains of knowledge, the Knowledge-in-Pieces family of theoretical perspectives would likely fall on the side of the spectrum in which there are many distinct contexts each with its own explanation form and many ways that explanations and knowledge can be related.

To better understand the relationship between explanation and knowledge within this perspective, I begin with an existing argument about the relationship between new knowledge
and prior conceptions. Smith, diSessa, and Roschelle (1993/1994) question prior misconceptions research, which has focused on students flawed understandings in math and science. In this section I use their argument about the misconceptions research in order to conceptualize the prior research on students’ scientific explanations. Smith, diSessa, and Roschelle (1993/1994) point out that much of the prior misconceptions research (e.g. McCloskey, 1983) focuses on students’ ideas as being flawed incorrect conceptions that need to be confronted and replaced. They also discuss that the existing viewpoint promoted by the misconceptions research conflicts with the basic premise of constructivism, that students build new knowledge from prior knowledge and that there exists continuity between students and experts conceptions. Derived from this argument is the implication that one should focus on the lines of continuity between novices and experts, and one should focus on how old conceptions are resources for growth and learning.

Although this paper is almost 20 years old, the argument is still timely and it is inspiring the argument presented in this dissertation.

Next I draw parallels between Smith, diSessa, and Roschelle’s argument and the current argument about the relationship between existing explanations and generating new explanations. In the prior section I discussed that researchers, in different domains and with regards to different science content, focus on the existence of a limited number of explanation forms that need to be taught to students. They are not often emphasizing the explanatory resources students have at their disposal nor are they emphasizing on the lines of continuity between students and experts scientific explanations. Many of these researchers (e.g. Perkins & Grotzer, 2005) would not likely deny the role of explanatory resources and the lines of continuity between students and experts, but I argue they are not putting enough emphasis on students’ prior knowledge. If one were to take a view of explanation, similar to what was outlined in Smith, diSessa, and Roschelle (1993/1994) one would focus on students building new explanations from old explanations. One would assume that novice students are able to access many resources about explanations that they can use to generate new explanations, these resources could be called “meta-explanatory knowledge.” This is in agreement with Kapon and diSessa’s (2012) work on intuitive explanatory primitives. Also, this position is supported by developmental psychology research that documents that young children can produce scientific explanations (e.g. Brewer, Chinn, & Samarapungavan, 1998). In parallel to the argument presented in Smith, diSessa, and Roschelle (1993/1994), a constructivist view of explanations would also focus on lines of continuity between explanations generated by people with varying levels of expertise. In this dissertation I use that perspective when I address prior knowledge, but I also expand it in order to conceptualize student generated explanations. I focus on the lines of continuity between explanations, and I look at how knowledge elements within the initial explanations serve as resources for the final more expert-like explanations.

Knowledge in Pieces (diSessa, 1993) is a family of theories that focuses on the structure, organization, and dynamics of students’ knowledge. I discuss these three threads within KiP in the service of answering central questions about knowledge and in service of the goal of investigating the relationship between explanations and knowledge.

One theory within this family of theories is about phenomenological primitives (p-prims), which are a type of knowledge that functions as a small intuitive causal structure. A meta-focus of this theory is the idea of a ‘sense of mechanism.’ This is a sense of how things work in the physical world. This sense of mechanism allows us to assess the likelihood of events that we expect to happen or not happen, make predictions, and provide causal explanations and descriptions (diSessa, 1993). This sense of mechanism influences our ability to interact with the
world in a variety of ways, including physical muscular control, it also influences our ability to solve problems and learning science, the latter of which is of primary interest. In KiP a primary intellectual aim is to chart the structure, organization, and dynamics of knowledge associated with this sense of mechanism. As KiP is a theory about knowledge, thus fundamental questions to be answered in this theory are centered on the following:

1. What is the structure of prior knowledge? How are the knowledge elements organized?
2. What changes over time? How does it change? Why is change so hard?

The first question addresses the structure and organization of that knowledge and the second group of questions focuses on the dynamics. This formulation of KiP into the structure, organization and dynamics of knowledge originated in diSessa (1993) and more recently is discussed in Campbell (2011). Answers to each of these sets of questions are discussed sequentially below.

**Structure:** The structure of knowledge consists of many kinds of knowledge elements that exist at different levels and function in different ways. By using the phrase “knowledge elements” I am referring to piece of a knowledge system that can exist at various grain sizes, that can be organized in various ways, and importantly, that can be identified within someone’s knowledge system. One kinds of knowledge element discussed in detail in diSessa (1993) and centrally important to this analysis are p-prims. P-prims are a small intuitive causal structure and they often entail behavior which allows them to serve a central role in explaining physical phenomena. They are thought to involve “nearly superficial interpretations” of one’s experiences in a situation, when one is activated no further justification is needed, that is just the way things are. P-prims are a knowledge element that is discussed extensively within KiP, but other potential knowledge structures may exist too, include schemas and explicit propositional knowledge. P-prims and other kinds of prior knowledge are discussed extensively in Chapter 2 where I present a sketch of the epistemological resources relevant to students’ explanations about complex systems in this data set.

**Organization:** P-prims, among other kinds of knowledge elements, are organized in a large and complex knowledge system known as a conceptual ecology. In educational literature the term conceptual ecology originates with work by Strike and Posner (1992), but others have also focused on the complex structure of students’ knowledge system. diSessa (2002) discusses the idea of a conceptual ecology within KiP. The main idea is that a students’ knowledge system contains many knowledge elements, p-prims among other kinds of knowledge elements, and these elements are activated at different times depending on the context. Using this approach we can look at the differences between experts and novices knowledge system, and we can ask questions about a developmental pathway.

The conceptual ecology perspective can be used to characterize the difference between experts and novices in terms of the organization of the cognitive structure. We expect both novices and experts to have a complex structure of knowledge elements, but the difference lies in the systematicity of the structure. Novices conceptual ecology is not systematically organized, thus the activation of knowledge elements only occurs in a localized area. In comparison, an expert-like knowledge system is more systematically integrated as the knowledge elements are organized in a systematic manner. In this case, the activation of knowledge elements would occur across a wide area.
Thus from these differences between experts and novices we would expect a developmental path to involve increased systematicity in the organization of knowledge elements. Along a developmental path the relatively unstructured collection of knowledge elements becomes more structured as the priority of certain elements may shift, for instance new elements may be added or the function of an element may change. First the priority of certain knowledge elements increases or decreases depending on learning. For example, a given knowledge elements range of applicability might increase or decrease beyond the initial range of applicability, depending on how it is used in the developing knowledge system. Consider the behavior of traffic jams, which is a phenomenon that I expect people to have lots of prior experiences with. A novice, someone who has minimal experiences with traffic jams, might find that a knowledge elements range of applicability is increased as they come to see city-street and interstate highway traffic jams as similar in nature. Second new knowledge elements might be generated. These new elements are often added based on experiences within different contexts. For example if one experiences a traffic jam of lap swimmers in a deep pool, where one can avoid the jam by swimming underwater, this experience might add new knowledge elements to ones knowledge system. Third, a given knowledge element might have its function changed. A specific knowledge element that might have been self-explanatory in a more unstructured knowledge system might be subsumed into a large knowledge system. The overall effect of this process is that some knowledge elements may come to have weaker or stronger roles in an experts knowledge system. The fundamental idea is that over time the knowledge elements within a conceptual ecology are re-organized many times in increasingly systematic ways; the organization of the system is dynamic.

Dynamics: Having already discussed the dynamics of the changing organization of the conceptual ecology, it is now important to discussing the mechanism by which individual knowledge element are activated—the micro level dynamics. This mechanism is referred to as cueing. The underlying process for cueing a knowledge element is hypothesized to be recognition by the student. Based on a particular context in which some existing knowledge elements have already been cued, a new knowledge can be activated. Knowledge elements are activated in relationship to other already activated knowledge elements. This process of activating knowledge elements occurs in layers, the top layers are complicated ideas and concepts that are composed of many lower elements.

Depending on the level of structure within a conceptual ecology, we would expect the cueing priority to shift. In an unstructured conceptual ecology the cueing priority may only be reliable in a local area. The following is a rather simplistic example, but it illustrates the localized nature of a novices conceptual ecology: In the context of discussing traffic jams on busy city streets a novice might cue one knowledge element about how it feels to be stuck in a traffic jam in cities. However, if the student is learning to drive and has little experience driving on inter-state highways they might not cue that knowledge element when discussing traffic jams on interstate highways because that knowledge element is context bound to city streets. When a particular knowledge element is cued depends directly on one’s experiences. The knowledge element’s range applicability might be limited to localized areas in a novice’s conceptual ecology, but it may change over time. For someone who has a more structured conceptual ecology, the cueing priority may be reliable across a wider area. For example an expert who has a long history of driving in many situations, when discussing traffic jams might cue the same knowledge elements, despite varied circumstances.
Given that within this perspective conceptual change involves both a developmental path with an increased systematicity in the organization of knowledge elements and the shifting cueing priority of knowledge elements, why is conceptual change hard? Remember that knowledge elements are context bound. There are many knowledge elements, each one being bound to a context. Change involves trial and error for each individual knowledge element. Over time there is trial and error in terms of cueing a knowledge element in a new context, based on the surrounding knowledge element. It takes time to strengthen the “right” connections and weaken the “wrong” connections. The result of this process is an increased systematicity in the organization and cuing priority of knowledge elements. Due to the timescales and number of individual strengthening and weakening connections there is no simple one step fix to support conceptual change.

Over time we expect an increased systematicity in the organization of knowledge elements and increasing strengthened connections between knowledge elements and particular contexts. This is the perspective being advocated by Smith, diSessa, and Roschelle (1993/1994) when they discuss students building new knowledge from old knowledge and the continuity between novices and experts. This perspective on competence serves as a starting point for this dissertation, which investigates the relationship between explanation forms and prior knowledge within students’ explanations.

**Complex Systems**

Complex systems, and the emergent processes they give rise to, are processes that are composed of individual elements each of which has a particular pattern of behavior. Each individual element following its rule or pattern of behavior results in a macro-level behavior that is different from the micro-level behaviors. One characteristic of these systems is their self-organizational nature; over time patterns arise out of the individual interactions. There are different rules or possibly different principles governing the behavior at the micro and macro level, and the relationship between the two levels is complicated, often described in a probabilistic manner. Complex systems exist in many domains across various academic fields, for instance computer science, physics, biology, geology, economics, and astronomy.

An example of a complex system that is relevant to this dissertation is the formation of traffic jams. Traffic jams are composed of individual cars, each of which has their own behavior. Each car follows its own pattern of behavior, speeding up or slowing down, depending on the behavior of all of the surrounding cars, and each cars individual behavior is going to be different from other cars behavior. The behavior of the entire traffic jam is different from the behavior of individual cars. For example individual cars move forward while the entire jam moves backwards as cars leave the jam from the front and join from the back. Within a jam that is getting worse (slower average speed) an individual car may be increasing or decreasing in speed, even though the average speed of individual cars is decreasing. The relationship between each of the individual cars behavior and the entire jams behavior is complicated as there are different rules governing the behavior at the macro and micro levels, and the relationship between those levels can be probabilistic.

A traffic jam is just one example of a complex system. Complex systems are a broad family of research areas and they exist across many domains. One stance on complex comes from researchers who may identify with the perspectives advocated by the New England Complex Systems Institute\(^1\) and the Santa Fe Institute\(^2\), and explicitly uses the term complex

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1. [http://necsi.edu/](http://necsi.edu/)
systems. This perspective tends to focus on parts of systems, and the relationships between those parts in various domains, such as economics, human behavior, physics, and biology. For an overview of this perspective see Bar-Yam (1997) and Kauffman (1995). A slightly different perspective comes from Dynamical Systems theory, which focuses on mathematical descriptions of how states change over time. I think that underlying these points of view are families of related modeling and computational tools that are used to understand many types of complex emergent systems.

**Students’ Learning about Complex Systems**

From various perspectives there is general agreement that students have difficulties when learning about complex systems and the emergent process they give rise to (Resnick, 1994; 1996; Chi, 2005; Chi, 1992; Slotta & Chi, 2005; Wilensky & Resnick, 1999; Hmelo-Silver & Azevedo, 2006). Two of the most prominent lines of research on students’ difficulties with complex systems are derived from Resnick’s work on the centralized-decentralized mindset and Chi’s work on ontological categories.

In the context of working with students while constructing computer programs of complex systems, Resnick (1994; 1996) observed a deep-seated resistance to decentralized ways of thinking. He observed students having a strong preference or attachment to presume centralized control where none exists. Resnick names these two ways of thinking, “mindsets.” He noted that the centralized mindset is not only a bias seen with his students but it has been seen throughout the history of science. While working with students in constructing computer programs of complex systems, he found that over time they came to recognize the role of decentralized causality embedded within the systems.

From the conceptual change perspective, as mentioned previously, Chi and colleagues (Chi, 1992; Chi, 2005; Chi, Roscoe, Slotta, Roy, & Chase, 2012; Slotta & Chi, 2006; Slotta, Chi, & Joram, 1995) have also observed students’ difficulties with emergence processes as compared to direct processes. They present a hypothesis for students’ difficulties based on ontological category. They argue that there are distinct ontological categories, such as substances and processes (Slotta & Chi, 2006; Slotta, Chi & Joram, 1995) or direct and indirect processes (Chi et al., 2012). Although the names for these categories have shifted over time, the central idea is common: students’ difficulties are due to their miscategorization of a process. Whether or not someone assigns the correct ontological category to a specific concept, for instance, diffusion, influences whether or not a student exhibits a certain misconception. Therefore a main difficulty with emergent processes is that they are misinterpreted to be direct processes.

Given the wide-spread agreement that students exhibit difficulties with reasoning about complex systems there are a series of hypotheses for the underlying cause of this difficulty. As mentioned previously, Chi’s hypothesis is based around the categorization of a specific process, she and colleagues claim that incorrect explanations about emergent processes, such as diffusion, are due to students viewing those processes in terms of inappropriate schema or ontological categories, and an inappropriate inter-level relationship between the agent level and the macro level pattern. Wilensky and Resnick (1999) find that students’ difficulties are due to them having trouble connecting the micro and macro levels, in other words there is levels confusion or “slippage” between levels. Similarly Penner (2000) also argues that students have trouble connecting across levels. The importance of connecting the macro and micro levels is documented by many including: Eylon and Ganiel (1990), Frederiksen, White, and Gutwill

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2 http://www.santafe.edu/
Jacobson and Wilensky (2006) also discuss that students find these systems difficult because they have an underlying preference for centralized causality and decentralized causality is counter-intuitive.

Given the agreement that students have difficulties with these systems and the various points of view about the underlying cause of these difficulties, a natural question arises about student learning. How can students learn about these systems? There are a handful of studies that have demonstrated student learning of the emergent behavior of complex systems. Central questions include: How does this happen? What methods do the researchers use to capture students’ learning of these systems?

Knowing that students have difficulties with these systems Hmelo-Silver and colleagues (Hemlo-Silver & Pfeffer, 2004; Hmelo-Silver, Marathe, & Liu, 2007) focus on supporting students’ learning by helping students conceptualize these systems as an interrelated web of behaviors, functions, and structures. They have built a coding scheme that focuses on the structure, behavior, and function of these systems, and they apply it to understand how novices and experts differ in their ways of understanding complex systems in biology, the human respiratory system, and an aquarium ecosystem.

Research by Wilensky, Resnick, and colleagues have documented several different ways that students can learn about these systems. Resnick and Wilensky (1998) argue for the importance of role-playing activities in the science and mathematics classroom. They present descriptions and analysis of students’ role playing about the behavior of complex systems. They discuss that these activities helped students develop better intuitions for how the behavior of a complex phenomena arises from simple rules. For example, by having students act out the behavior of ants within an ant colony they gained insights into the relationship between individual interactions and the larger pattern of behavior.

Similarity, from this perspective there is also a body of research that looks at students’ learning with computer modeling activities. Wilensky and Resnick (1999) consider students model building within the StarLogo modeling language. They present a series of cases of students developing an understanding of different levels within modeling environments of slime mold, gas particles in a box, and the predatory-pre ecosystems. They present data on how students’ experiences in the modeling environment and their understanding of the different levels supports their reasoning about the scientific phenomena that they were investigating.

Another example of students’ learning comes from Levy and Wilensky (2008) who observed a widespread strategy, called the “mid-level construction” in which small mid-level groups are formed by aggregating individuals or by subdividing the whole. For example students mentioned “cliques” of students or packs of deer forming by individuals being aggregated into a small group. Students also mentioned an entire classroom of students being subdivided into several rows, which is a version subdividing of the whole. The authors find that the strategy of subdividing the whole is explicitly related to reasoning about the phenomena using decentralized control. This is similar to the aggregate models discussed in Frederiksen, White, and Gutwill (1999) that are presented to students in order to help them derive the emergent behavior at the macro level from the micro level.

One methodology used by Wilensky, Resnick, and colleagues to capture students’ learning of complex systems is a coding scheme that operationalizes students’ understanding of underlying principles associated with complex systems. Resnick (1994; 1996) identified a series of guiding heuristics that students used for making sense of decentralized phenomena. He did not intend for them to serve as a coding scheme, but they have influenced other’s coding
schemes. The five guiding heuristics of students successful reasoning about complex emergent systems include: positive feedback can be constructive, randomness can help create order, don’t confuse levels, the composition of macro objects is always changing, and don’t underestimate the role of the environment. Penner (2000) used a simplified version with only three indicators that also overlaps with Resnick’s original list of guiding heuristics. Jacobson (2001) built an explicit coding scheme to identify when students are using beliefs associated with a mental model based on centralized control or beliefs associated with an emergent mental model; this coding scheme has eight indicators, several of which loosely overlap with Resnick’s list of indicators. When discussing the mental models Jacobson (2001) cites Vosniadou and Brewer (1992; 1994), which suggests that he views these mental models as coherent and integrated, different from the assumptions of students’ knowledge within KiP. Recently, Charles and d’Apollonia (2004), Jacobson et. al (2011), and Levy & Wilensky (2008) have all used modified versions of the coding scheme presented in Jacobson (2001). This coding scheme will be discussed further in Chapter 3, as it influences the methodology used in this dissertation.

At this point, I have reviewed the existing literature on students’ learning of complex systems. I first described what complex systems are and their ubiquity across many fields. I then described students’ difficulties when learning about these systems and a variety of perspectives on the underlying cause for these difficulties. Finally, I discussed some instructional approaches to support student’s learning and a methodology that some researchers have used to capture student’s learning of complex systems. I now transition to the focus of this dissertation—students’ competencies with learning and explaining how complex systems behave.

This Dissertation

This dissertation extends existing literature by investigating the role of prior knowledge in students’ explanations and by emphasizing students’ competences in generating explanations. Scientific explanations are important in students’ learning of science, and many existing perspectives tend to focus on pre-determined “forms of explanations” while de-emphasizing students’ prior knowledge and de-emphasizing differences in explanations across problem contexts. Using the knowledge-in-pieces theoretical perspective I investigate the role of prior knowledge in students’ explanations for how complex systems behave, and I specifically focus on problem context variability across many students’ explanations. In other words, a central point of distinction is that the current study focuses on students’ competencies in generating explanations while much of the prior literature focuses on students’ difficulties.

A central point of departure for this dissertation is the Laurel case, which was briefly discussed earlier in this chapter and will be discussed extensively in Chapter 4. During a short interview sequence, Laurel’s understanding of sand dunes shifted dramatically from presuming that a single dune literally shifted locations, to assuming that the relative rates of sand particles joining and leaving the dune contributes to the appearance of a shift. Her initial explanation was more prototypically centralized while her final explanation was more prototypically decentralized. In this case it becomes clear that despite whatever difficulty Laurel had in the beginning by the end of the short discussion she demonstrated quite a bit of competency with understand the behavior of sand dunes. Therefore I take as a starting point the fact that she does have some competency with reasoning about complex systems and she exhibits this competency by her ability to explain and generate an explanation that is prototypically decentralized.

From the Laurel case and the existing work on students’ difficulties with complex systems, the central questions of this dissertation become:
1. How does her explanations and understanding of the phenomena of sand dune movement shift from being more prototypically centralized to being more prototypically decentralized? What prior knowledge supports this shift? What other factors support this shift? These questions are answered in the analysis in Chapter 4, which focuses on the lines of continuity between these two ways of understanding and illustrates how change can occur. This analysis is different from the prior literature that has tended to emphasize divisions between centralized and decentralized causality. For Laurel, her choice in what to explain was both different from what I as the researcher intended to be explained and turned out to be a key feature in her shifting understanding. This methodological result suggests that allowing students some flexibility in deciding what to explain is a potentially important in their reasoning and shifting explanations.

2. Is the Laurel case of shifting explanations from centralized to decentralized causality idiosyncratic or indicative of a more general phenomena? These questions are also addressed in Chapter 4, which includes a second case of another student shifting explanations, Keaton. I show that his explanations exhibited a similar shift becoming less and less prototypically centralized and then becoming more and more prototypically decentralized. However, his transitional explanations are different from Laurels, thus there are at least two paths of shifting explanations. Also, a commonality across both students is that they revised their explanations based on their existing knowledge resources, which is different from the previously discussed hypothesis in Chi, et al., (2012) about misconceived causal explanations not pertaining to a lack of knowledge and instead them pertaining to an inappropriate inter-level relationship between the micro level and the macro level that requires an ontological level shift.

3. Knowing that (1) the sand dune problem context was such a productive problem context for Laurel’s reasoning about decentralized causality, and that (2) part of the reason for the problem contexts productiveness had to do with her particular prior knowledge about sand dunes, I then ask: how do other problem contexts influence students’ prior knowledge and productive reasoning about those problem contexts as complex systems? These questions are answered in the analysis in Chapter 5. In this chapter I focus on explanatory patterns that are potentially helpful for students along the process of coming to generate decentralized explanations. Primarily this chapter finds that there exists a great deal of variation across the kinds of explanations students generate for the behavior of these seven problem contexts. I find that this variation exists in terms of both the kinds of explanations student generate about these complex systems problem contexts and in the kinds of prior knowledge students activate in those explanations. Secondly, I discuss the existence of the many different kinds of prior knowledge in students’ understanding and developing explanations. This calls into question the general trend of de-emphasizing the multitude of prior knowledge resources that influence students’ understandings of emergence. I find that a factor distinguishing certain problem contexts as easier or harder for students has to do with the kinds of prior knowledge resources activated. From one perspective are sand dunes, where students are able to access a wide range of intuitive resources that are applicable at multiple levels, coming to see the decentralized nature of the phenomena is not an enormous challenge. From the other perspective are other problem contexts, for example, diffusion, where students encounter many challenges, such as a lack of intuitive knowledge about the molecular level of water.
4. Is there variation within students prototypically decentralized explanations or are they all similar? Do students’ explanations that capture the decentralized nature of the phenomena vary across problem context and the specific knowledge resources? These questions are addressed in Chapter 6, which focuses on the diversity of students’ emergent thinking. The prior literature has tended to emphasize emergent thinking as a unified entity, which is illustrated by its tendency to use a top down approach to code the data and to emphasize identifying emergent thinking through codes, such as was used by Jacobson (2001) when using a complex system mental model coding scheme to look at differences between experts and novices problem solving of complex systems.

5. In the analysis in this chapter I open up two of the pre-existing “codes” for decentralized thinking and I find that for these students decentralized thinking is not a single unified entity—it is diverse and varies across problem contexts and across kinds of prior knowledge.
CHAPTER 2: THE CONSTRUCTION OF STUDENTS’ EXPLANATIONS ABOUT COMPLEX SYSTEMS

Introduction

In this Chapter I present a mini-theory about the different kinds of prior knowledge that are relevant to students’ reasoning about emergence, how that prior knowledge is cued within student explanations, and how these explanations support students’ emergent thinking. By emergent thinking I am referring to students’ reasoning about the problem contexts, which exhibit emergent behavior, in ways that capture the decentralized nature of the processes. The central claim is that when students’ generate explanations that capture the decentralized nature of these complex systems their explanations are based on a variety of kinds of prior knowledge resources and specific features of the problem context that influence their understanding of emergence.

There are many explanations that could be generated when one is explaining problem contexts, such as traffic jams. Traffic jams are a complicated decentralized process, and their behavior can be conceived of in many different ways. For example, an explanation could focus on traffic jams as an equilibrating process in which, over time, the average speed of traffic converges to an average speed. Or, one could explain traffic jams as exhibiting some periodic behavior in which individual cars speed up and slow down multiple times. Or, perhaps one might explain that the absolute number of cars in a jam could be constant, but equal rates of cars are constantly joining and leaving a jam. Each one of these explanations incorporates a different pattern. The first one uses what I refer to as the pattern of convergence to a limit, the second one uses some periodic or cyclical behavior, and the third one uses a dynamic equilibrium, which I refer to as changing composition. I refer to these behaviors as patterns, similar to how patterns of change and control is discussed by diSessa (2007b).

In this dissertation I focus on cases of explanations that are a special subset of explanations that exhibit a core concern for particular patterns. I predominately focus on cases in which students’ generate explanations for traffic jams and other complex-system problem contexts that incorporate one of these patterns in the description of the behavior being exhibited. I explicitly focus on cases in which students generate the explanations, not cases in which the explanations were forced or instructed. I refer to these student-generated explanations, which incorporate one or more of these patterns as a central feature of the behavior of the complex system as student-generated explanatory patterns. I only focus on student-generated explanations that encapsulate the problem context as exhibiting one of these specific patterns within the behavior, threshold, mid-levels, periodic motion, steady state, changing composition, or convergence to a limit. Thus I am not referring to general forms of explanations, for example, mechanistic explanations or teleological explanations. I am referring to explanations that incorporate these particular patterns of change and control, like oscillation or equilibrium. The reason I focus on these particular patterns is because initial analyses suggest that reasoning about these problem contexts, for instance, traffic jams and sand dunes, through these specific patterns.
might help students in understanding these problem contexts as decentralized processes that exhibit emergent behaviors.

This chapter is building on the prior discussion, in Chapter 1, of the intellectual terrain of this dissertation, specifically prior work from the Knowledge-in-Pieces perspective and prior work on scientific explanations. In this Chapter I use the existing family of Knowledge in Pieces (KiP) theories in order to present a specific mini-theory. I first discuss some relevant background, then I present the domain specific mini-theory about the kinds of prior knowledge relevant to students’ understanding of complex systems. Finally I discuss how that prior knowledge contributes to the student generated explanatory patterns.

Background
The theory presented in this chapter is a mini-theory about how students construct explanations about complex systems based on their prior knowledge, with an emphasis on explanations that capture the emergent behavior of the complex phenomena. Primarily, this is a mini-theory about the dynamics of students’ knowledge during a clinical interview. Secondarily, this is a mini-theory of how the knowledge pieces are connected within the dynamics of generating an explanation. This is also a mini-theory about the relationship between students’ epistemologies and their reasoning about complex systems.

This mini-theory focuses on the how and why of students’ knowledge in terms of developing explanations of complex systems. This is not a broad theory that is widely applicable, nor is it untested speculation. It is a narrowly focused (“local”) theory. This mini-theory focuses on how students’ generate explanations that reflect an understanding of emergence and how these explanations vary across problem contexts. Within that arena the mini-theory focuses on what knowledge is relevant to these explanations, how those knowledge pieces are cued, and the relationship between the knowledge pieces and the explanations. For a more detailed discussion of the development and importance of mini-theories see diSessa (1991).

This mini-theory emphasizes students’ competences rather than their difficulties. In developing this mini-theory an emphasis has been on students’ competencies within complex systems. This emphasis on competencies has resulted in an analysis of the productive prior knowledge student’s use when explaining how complex systems work, and analyzing how that knowledge supports their understand of the emergent nature of the phenomena. As was discussed in Chapter 1, many studies have focused on students’ difficulties. In contrast, this study focuses on students’ competences. I do not neglect students’ difficulties with understanding complex systems and cases of students’ difficulties are discussed in Chapter 4. However, the emphasis of this dissertation is on students’ competences as this emphasis sheds new light on issues of learning and instruction. For a detailed discussion of a constructivist argument in favor of focusing on students’ competence as opposed to their misconceptions see Smith, diSessa, and Roschelle (1993/1994).

This mini-theory is limited; it is a theory of the knowledge resources that relate to students’ explanations about complex systems in this data. This is not a theory of all resources students might cue as related to complex systems. Nor is this a theory of all resources students cued within this data. The contribution of this theory is rooted in its emphasis on students’ understanding and developing explanations of complex systems, with a focus on students’ prior knowledge. As this is a theory of competences in an area where incompetence is the norm, this theory adds a unique contribution to our understanding of students’ competencies with regards to learning and their developing explanations.

As this mini-theory is applicable to all three analysis, chapters I present it here with
sufficient details and examples such that the analyses presented in subsequent chapters will be clear. In Chapter 4 I use this mini-theory in two cases of shifting explanations over short time periods, I trace various knowledge pieces that were relinquished and then other knowledge pieces that were added to explanations. In Chapter 5 I focus on variation across students’ understanding and explanations of the seven problem contexts within six explanatory patterns that have the potential to support students developing decentralized explanations, including: threshold, periodic motion, and convergence to a limit. I explicitly focus on differences in the specific knowledge pieces activated with the explanatory patterns across the seven problem contexts. In Chapter 6 I focus on the diversity of emergent thinking with regards to variability across kinds of prior knowledge and with regards to explanations that focus on common student generated explanatory patterns. Finally in Chapter 7 I argue that this theory, with its emphasis on competence, offers unique instructional and theoretical insights into students’ learning about complex systems. Before the presentation of the details of the theory, I discuss the relationship between this specific theory and Knowledge in Pieces.

Knowledge in Pieces
Within Knowledge in Pieces (KiP) there are a family of related theories focusing on different dimensions of students’ prior knowledge as related to their learning. In this sub-section I briefly describe how the current mini-theory is related to various other existing theories within this family. I focus on the specificity of several sub-theories within this family and on the size of the conceptual piece as a way to delineate differences. The purpose of this discussion is to situate the current mini-theory in terms of the existing KiP theories. This family of related theories originated with work on individual knowledge elements within students’ conceptual ecology, such as facets (Hunt & Minstrell, 1994) and p-prims (diSessa, 1982; diSessa, 1993). P-prims are small intuitive knowledge elements that are cued in the moment based on the specific context and then are used within students’ reasoning. In this mini-theory I focus on p-prims along with three other kinds of knowledge pieces: experiential knowledge that is or is not cued, pragmatic knowledge, and agent knowledge. Prior research on p-prims has focused on specific and intuitive knowledge elements, mostly in the context of naïve students’ early learning of physics. Another line of research emphasizes an expert-like model of a concept in physics that is known as a coordination class (diSessa & Sherin, 1998; diSessa & Wagner, 2005; Levrini & diSessa, 2008; Parnafes, 2007; Thaden-Koch, Dufresne, & Mestre, 2006; Wagner, 2006). Despite the difference emphases, individual knowledge pieces versus concepts, the former being small and the latter being larger, a commonality in these two perspectives is that both are individually specific. For example, coordination class theory is only applicable to a specific kind of concept. Quantities such as force are a prototypical example of a coordination class (diSessa & Sherin, 1998). Within the KiP family, there are other perspectives that are less specific in how they operationalize knowledge. One example of these more general theories is known as Resource theory, which focuses on context-sensitive epistemological resources that are productive for learning in physics (Hammer, 2000; Hammer & Elby, 2003). A central difference between Resource theory and the more specific theories, like p-prims and coordination class theory, is that the former focuses on general kinds of resources and there is less emphasis on the structure of the particular elements than the latter. There is a third theoretical approach within this KiP family of theories that is between these two perspectives with regards to the level of specificity, the mode-node framework. This third theoretical approach focuses on more specificity than Resources theory, but less specificity than p-prims. One of the main differences among these theories is their level of specificity, not with regards to the number of situations that the
conceptual piece applies to, but instead with regards to the level of precision of the theoretical machinery. Some of the differences between these three perspectives are illustrated in figure A. This third theoretical approach is the main starting place for the theoretical machinery developed in this dissertation.

![Figure A](image)

Figure A: Graphical illustration of some differences among various theoretical perspectives within the KiP family along the dimension of the size of the specific conceptual piece versus the level of specificity of the theory.

The mode-node framework focuses on a set of knowledge elements, called nodes, which produce a temporary explanatory structure, which is called a Dynamic Mental Construct (DMC) (Sherin, Krakowski, & Lee, 2012). The nodes are individual knowledge elements, of many kinds including p-prims and propositional knowledge, which form interconnected sets of knowledge structures, known as modes. The modal reasoning process produces DMCs, which are temporary explanations that correspond to temporary mental states. Within this theory, temporary usually refers to a short time scale as relative to the length of the interview. Thus these explanations often only last for a few minutes or less. Sherin et al., (2012) use their framework to illustrate a series of cases where students search through available nodes which are assembled into explanations about the seasons during clinical interviews. They discuss a series of common DMCs. For example they present a case of a student reasoning about the seasons using the correct explanation that is based on the Tilt-Based DMC. Within that explanation there is evidence that the student uses nodes including, the earth orbits the sun, the earth is tilted, and the sun is the source of heat (Sherin, Krakowski, & Lee, 2012, p. 177-178). Another explanation they discuss is one in which students justify the seasons by explaining that different sides of the earth experience summer and winter at different times, this is based on the Side-Based DMC. This DMC is consistent with the node that specifies different seasons in different locations (Sherin, Krakowski, & Lee, 2012, p. 178). Also, the authors discuss cases in which students’ DMCs shift during the interview. Sometimes students completely abandon a DMC, and sometimes they shift DMCs in such a manner where some of the nodes in the old DMC are weaved into the new DMC.
The mode-node framework is an obvious starting place for the current theory. There are several overlapping emphases with regards to a focus on specific knowledge elements and the moment-to-moment shifts in students thinking in the context of clinical interview. Both the current theory and the mode-node framework emphasize specific knowledge elements in student-generated explanations during clinical interviews, and both focus on moment-to-moment changes in students’ thinking. However, one main difference centers on the current theory being explicitly about students’ reasoning about complex systems. The knowledge pieces, nodes, are general. In this mini-theory I focus on specific kinds of knowledge and characterizations of that knowledge that were seen in this data set. In the second half of this chapter there is a discussion of the student generated explanatory patterns, which are similar to DMCs.

**Sketch of Epistemological Resources**

In this chapter I present the developing mini-theory, and in this section I focus on the specific kinds of knowledge and the characterizations of that knowledge, which I refer to as a “sketch of epistemological resources.” By using the word “sketch” I am implying this this should be thought of as a preliminary version that could be refined and modified in future work. I present three kinds of epistemological resources, the first two focus on knowledge and the third focuses on features of the problem context. First, I present a catalogue of kinds of knowledge, and then second I present a list of characterizations of knowledge. Third, I present a list of features of the problem context that often influences students’ understanding of emergence. An overview of this entire sketch is presented in Table A. As will be discussed latter, there is a relationship between these two lists. I focus on student generated explanatory patterns that are based on both their prior knowledge and based on characterizations of that knowledge, and these explanatory patterns depend on features of the problem context.

<table>
<thead>
<tr>
<th>Kinds of Epistemological Resources</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kind of Prior Knowledge</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiential knowledge that is or is not cued</td>
<td>Knowledge about peoples’ experiences with events includes perspectives on that event and not on other events, which influences what they find relevant or not relevant.</td>
<td>Students have lots of experiences sitting in cars in traffic jams and no experiences sitting on sand particles.</td>
</tr>
<tr>
<td>P-prim</td>
<td>Small intuitive causal knowledge pieces that are cued in a particular context based on surroundings.</td>
<td>A sand dune blocking the wind.</td>
</tr>
<tr>
<td>Pragmatic Knowledge</td>
<td>Knowledge about the underlying pragmatics about the situation based on encounters with the situation.</td>
<td>In traffic jams, knowledge about wanting to avoid accidents and be safe.</td>
</tr>
<tr>
<td>Agent Knowledge</td>
<td>Knowledge about the behaviors, characteristics, and nature of the agents.</td>
<td>Knowledge about birds and fish behaving in ways that shares some characteristics of humans.</td>
</tr>
<tr>
<td><strong>Characterization of Knowledge</strong></td>
<td>Performance of</td>
<td>An action by which knowledge is coordinated or aligned by</td>
</tr>
<tr>
<td></td>
<td>Spreading of viruses as similar to spreading of forest fires</td>
<td>Spreading of viruses as similar to spreading of forest fires</td>
</tr>
<tr>
<td>Knowledge</td>
<td>linkages or a common abstraction.</td>
<td>because both are spread by physical contact.</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Boundaries of Knowledge</td>
<td>Things that are not seen or not construed as relevant</td>
<td>Macro level of trees on fire was usually within the boundary of students’ knowledge about forest fires but often the micro, plasma, or electron level was not relevant.</td>
</tr>
<tr>
<td>Process of Creating Knowledge</td>
<td>Readouts of a situation that are relevant to particular situation or problem, visible to the student, and immediately apparent as important.</td>
<td>Car speed readout as important in traffic jams.</td>
</tr>
</tbody>
</table>

**Features of the Problem Context**

<table>
<thead>
<tr>
<th>Features of the Problem Context</th>
<th>Occurs again and again or only once.</th>
<th>For various problem contexts, the behavior may or may not plausibly occur again and again.</th>
<th>Sand dunes can plausibly move back and forth. The same fire cannot occur again and again, a tree cannot be unburnt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrangement of agents</td>
<td>Relative arrangement of the individual agents.</td>
<td>Sand particles are arranged in natural layers on a dune, which divides the macro system into layers.</td>
<td></td>
</tr>
<tr>
<td>Relationship between agents and humans</td>
<td>A close or distant relationship between the agents and humans influences whether students have a tendency to personify the agents or readout information about social issues.</td>
<td>It’s easier to personify fish and birds because they are closer to humans than sand particles or water molecules.</td>
<td></td>
</tr>
</tbody>
</table>

Table A: Overview of the Sketch of Epistemic Resources

**Catalogue of Kinds of Prior Knowledge and Characterizations of that Knowledge**

In this section I present a catalogue of the four kinds of prior knowledge I find in my data set and the three characterizations of that knowledge. The four kinds of prior knowledge that I focus on include: pragmatic knowledge, experiential knowledge that is or is not cued, p-prims, and agent knowledge. The three characterizations of that knowledge include: performances of that knowledge, boundaries of knowledge, and the process of creating knowledge. For each kind of prior knowledge, I provide a description, I discuss its relationship to existing constructs in the literature, and I present a series of examples. This catalogue is not meant to be exhaustive. It is a list of the most common kinds of prior knowledge and characterization of that knowledge that I find in this data set. As will be discussed in Chapter 3, the development of this catalogue was done in a bottom-up manner and drew on existing KiP theories. A key assumption of this catalogue is that each kind of prior knowledge could potentially equally apply to any of the seven problem contexts, although I do find that some are more common in certain problem contexts.

**Pragmatic Knowledge**

The first kind prior knowledge in this catalogue is students’ knowledge about the underlying pragmatics about the situation. I refer to this as pragmatic knowledge. This knowledge is based on their encounters with the situation. This knowledge is based on a focus on preferential...
aspects of the situation that they should pay attention to and actions that should be taken, both of which subsequently influence their explanations, for example, in traffic jams knowledge about a desire to avoid accidents. In the data set I find that pragmatic knowledge was most applicable to issues of safety and health of humans and animals, within the traffic jam, virus, bird, and fish problem contexts, but it could have been applied to other contexts.

In traffic jams many students cued underlying pragmatic knowledge of wanting to avoid accidents or crashes along with a general desire to be safe. For example Antonio said, “when it's more crowded, people tend to go slower just because they feel safer, there is nothing like moving 70 mph with a whole bunch of people right next to you, seems kind of scary.” In this excerpt Antonio is explaining that people have a desire to be safe and that desire influences their driving.

Similar to traffic jams, when considering viruses, students sometimes cued pragmatic knowledge about wanting to avoid getting sick. Also, students cued pragmatic knowledge about being sick and wanting to minimize the spread of the illness. In addition, some students cued pragmatic knowledge about their hopes for a speedy recovery. For example, Jared cued some knowledge about wanting to minimize the spread of the illness. He said: “if people are prepared about it, if people know about it. Then they would make an effort, a conscious effort not to make so much contact with people, to wash their hands more or I don't know if that will work for viruses. But, you know, just to try and try and avoid situations where they could get infected. And then that would make it less easy for them, for them to spread.” Jared is explaining that if people make a conscious effort to minimize the spread of the illness by washing their hands or avoiding situations where they could get infected, then that would make it harder for the illness to spread.

For birds and fish students sometimes cued pragmatic knowledge about avoiding predators and needing food and sleep. For example, when discussing fish, Cara cues some knowledge about the pragmatics of fish wanting food. She said: “if someone put fish food in the tank, they all go to get the fish food. Because they all want to be first to get food or like, if they like, don't want to be last or else there would be no food left for them.” In this excerpt Cara is cueing some knowledge about fishes desire for food, which she used as a mechanism that could control their behavior. Similarly, when discussing the bird problem context Cara cues some prior knowledge about the pragmatics of birds wanting to avoid threats. She says, “if they were like, heard like gunshots and they like left because they didn't want to get killed. // Lauren: Sure // Or there was something that scared them, and they just wanted to leave because they didn't want to go over there.” In this excerpt she is cueing prior knowledge about birds wanting to avoid being harmed. She infers that when birds hear gunshots, something that has the potential to do harm, they will flee.

For some problem contexts students’ pragmatic knowledge plays an important role in whether emergence can be seen or not. Pragmatic knowledge can focus students on human encounters with particular aspects of a situation and the course of action that one should take. This knowledge can thus direct students to focus on underlying mechanisms of a situation, for instance, birds fleeing because of fear, which in turn can influence recognition of emergence. In the traffic jam example, Antonio’s pragmatic knowledge led him to focus on an individuals desire to avoid accidents and how scary it is when there are people moving fast near by which results in the people slowing down, thus this knowledge influences his reasoning for why traffic jam forms.
Experiential Knowledge That Is Or Is Not Cued

A second kind of prior knowledge that influences students’ explanations and understanding is experiential knowledge that is or is not cued. This can refer to academic prior experiences or everyday experiences. Peoples’ experiences with certain kinds of events includes perspectives on that event and not on other events. These experiences influence what they find relevant and what they will not find relevant. For example, students have lots of prior experiences sitting in cars in traffic jams but no prior experiences sitting on sand particles in sand dunes. Their experiences with forest fire are likely from seeing photos of fire or imagining the spread of a fire. I would expect the students to imagine the spread of a fire from either the ground level or from the perspective of sitting on a hill watching a fire in a valley below, which was stated in the interview question. However, imagining a fire might be different from the act of sitting in a car in a traffic jam. Below I discuss two examples about students’ different prior experiences in traffic jams and diffusion that in turn cue different certain resources or not. For traffic jams I discuss students’ experiences with the agent level, with diffusion I discuss students’ experiences with the particle level, these levels are similar micro-level perspectives.

In traffic jams, students have lots of prior experiences riding in cars, as both drivers and passengers and this experiential knowledge was often cued when discussing the movement and formation of traffic jams. Associated with these experiences students are aware of how they feel in jams. They also have experiential knowledge about how they believe they behave in jams and how they expect others to behave. Students also have a have experiential knowledge from being in a car during rush hour and experiencing what happens when many cars are all trying to go to the same location. All of these experiences are from the perspective of the car level. Students likely have limited experiences with knowledge about how traffic jam look from above. Students’ experiences are from being in a jam, not watching a jam from above, and knowledge based on these experiences influences students’ reasoning about traffic jams. For example, one can claim that a bad driver or an inattentive driver slows everyone else down and causes a jam. Or, one can claim that a jam is caused by everyone trying to get off the highway at a popular exit. For example, Antonio said, “a big event, say everyone is getting off the freeway over at a baseball stadium on a game night // Lauren: Right // Something like that. Or coming off, away from the game. Or everyone is coming out of the parking lot and they are all trying to exit one driveway and they are all coming together.” In this excerpt, Antonio is cuing some experiential knowledge about attending baseball games and being in a car while a large number of cars all have the same destination. This experiential knowledge comes from the perspective of a human observer or participant, not a helicopter view and it incorporates a centralized mechanism for why jams form.

With diffusion students also have lots of experiential knowledge, but the nature of the experiences are different from traffic jams. With diffusion students’ experiences are based on watching the process from the outside as they pour together two liquids and watch the color change, for example, pouring milk into coffee or for the specific problem used in this study, pouring juice and water together. From these and similar everyday prior experiences, students have experiential knowledge that reflect the nature of their experiences. Notice that the connection between this experiential knowledge and the microscopic level is not obvious. From academic (instructional) prior experiences, students might have experiential knowledge about the molecular level. However, certain experiential knowledge will likely not be cued because students have minimal intuitive experiences with the particle level. Students’ experiences with the micro level are most likely going to be based on science class explanations of the random motion of particles. Unlike traffic jams, where students are accustomed to the agent level as they
sit inside cars, students are not tacitly accustomed to the molecular level in diffusion. Students do not have many experiences with hypothetically what water molecules “see” or “feel” during diffusion. Therefore based on students’ experiential knowledge we expect a different set of resources to be cued about the molecular level in diffusion than the agent level in traffic jams. This experiential knowledge or lack of it can influence what underlying mechanisms students see as relevant. If students have minimal experiences with the molecular level of diffusion, it would be unlikely for them to mention mechanisms that operate at this level. In comparison, for traffic jams students have experiential knowledge from sitting in cars and how cars appear to behave in traffic jams. This experiential knowledge may help them in reasoning about the underlying mechanisms.

**P-Prims**

A third kind of prior knowledge addressed in this catalogue is phenomenological primitives, p-prims for short. P-prims are small intuitive causal knowledge pieces that act by being recognized. They are cued in a particular context based on the surroundings. Once cued p-prims can be used in conjunction with other knowledge pieces or they may subsequently cue different knowledge pieces. Most of the p-prim cued in this data are behavioral in nature. These p-prims were originally documented in diSessa (1993) in the context of Newtonian mechanics, but in this data corpus they were cued while explaining how complex systems work. P-prims originate from minimal abstractions, they are some of the smallest behavioral elements within the conceptual ecology.

One p-prim discussed in diSessa (1993) and seen in this data corpus is **blocking**. The canonical example of blocking is the behavior exhibited by a stationary brick when a hand strikes it. The brick blocks the hand. An important aspect of the p-prim nature of this knowledge element is that when a student cues it no further explanation is necessary. As p-prims are intuitive and originate from minimal abstractions, one does not need to explain why a brick blocks the hand. It just does. In this corpus the blocking p-prim was occasionally seen in the sand dune problem context in terms of a dune blocking the path of the wind. Another version of this same p-prim is when there are two dunes such that the upwind dune blocks the wind from hitting the downwind dune. For example, when discussing the behavior of sand dunes Morgan says, “wind is trying to go through the dune, it can't really work so it just runs in to it, and then it releases sand and then it just like makes the sand dune get bigger.” She might be using **blocking** saying that the dune blocks the wind and this results in the wind releasing the sand and the dune getting bigger. As expected, in this and other cases, students do not justify why the dune blocks the wind, it just does.

Other p-prims including cancelling, Ohm’s p-prim, and dying away were seen in this data corpus. For example, when discussing how a dune could be the same size at two points in time, one student explained that the wind could blow with equal strengths from two opposite directions cancelling itself out. Another example of a p-prim being applied to sand dunes is when a student explained that for larger dunes there is more surface area leading to the wind taking away more sand from the dune. In that case the student was using the intuition of more is more, which is potentially a version of Ohm’s p-prim. Ohm’s p-prim involves an agent and an impetus acting against some resistance that produces a result, commonly this p-prim is cued in terms of involving circumstances such as more effort implies more result or more resistance implies less results. Another version of the same p-prim was seen in the traffic jam context when a student explained that for more cars on the road it is more likely that a traffic jam will form. In the forest fire problem context there is a case of a student using the dying away p-prim when explaining
the dissipation of fire. Many of these examples, along with other cases of p-prims being used in this data corpus, are discussed in Chapter 5.

The analysis of p-prims being cued in these problem contexts is important for two reasons. First, many of these p-prims were originally documented in Newtonian mechanics and this analysis illustrates cases of them being applicable to complex systems. Second, this analysis is important as p-prims were not found evenly in all six problem contexts. Specifically, I do not find any p-prims in diffusion. The lack of any p-prims is potentially noteworthy given that these are intuitive causal knowledge elements and without them intuitive causality might be more challenging. When p-prims are noted is important because as they are abstractions of underlying causality and that causality could be helpful in focusing on the mechanisms that influence the behavior.

Agent Knowledge
A fourth kind of knowledge that influences students’ explanations in this data corpus is knowledge about the behaviors and nature of the agents. This is knowledge about the characteristics of the agents or individuals in the system. For example, this includes knowledge about birds and fish behaving in ways that shares some characteristics of humans. This also includes knowledge about the motion of agents, such as water molecules having a probabilistic behavior. In forest fires, this includes knowledge about the behavior of sparks of fire, for instance their tendency to jump from tree to tree. This is important because cueing knowledge about the specific agents and their behaviors might influences ones understanding of the behavior of the phenomena at the macro level, the relationship between the levels, and the underlying mechanism.

Process of Creating Knowledge
Now that I have discussed four kinds of knowledge, I switch to discussing three characterizations of that knowledge, which includes performances of knowledge, boundaries of knowledge, and the process of creating knowledge. By “characterizations of knowledge” I am referring to depictions of how that knowledge is used including the limits of that knowledge and how knowledge is used to create new knowledge. These are only a few of the many potential characterizations of knowledge.

One kind of characterization of knowledge is the process of creating knowledge. By the process of creating knowledge I mean things that are relevant to particular situations or problems, visible to the student, or immediately apparent to them as important are readout as relevant. This is similar to what diSessa and Sherin (1998) and Wagner (2006) refer to as readouts. Those papers focus on the readout strategies, which are things students do to readout information from a situation, which is associated with the readout process of creating new knowledge. For example, for almost all of the students in the sand dune problem context viewed the wind as having an important role in the formation and movement of sand dunes. This knowledge was immediately readout and important to many subsequent explanations. As another example, in traffic jams the cars speed was usually readout as an important piece of knowledge about the individual agents. This is important because reading out information about the relative speeds of cars influenced students’ understandings of the relative rates of cars leaving and joining a jam, which is important in their changing composition decentralized explanations.
Boundaries of Knowledge
The second characterization of knowledge is about the boundaries of students’ knowledge. Sometimes students’ know some kind of thing is relevant and thus it is within the bounds of their knowledge. Other times students simply do not find certain things salient in a situation, even when they look. In both cases this is based on both things that one can conceive of as relevant and things that are relevant to a particular situation. This is primarily about things that are not seen or not construed as relevant. If students are aware of certain aspects of a situation to be relevant, then they find those aspects of the situation to be relevant and within the boundaries of their knowledge. But students are unaware of the relevance then they do not find them within their boundaries of knowledge.

In the forest fires problem context all students found the macro level to be within their boundaries of knowledge. However, few students found the micro level to be in their boundaries of knowledge. This is to be expected given common prior experiences with the macro level of fire, for instance, candles, pilot lights, and campfires. During the interviews the forest fire question was phrased in terms of the macro level, so we would expect students to find that level within the boundaries of their knowledge. For the micro level, the common exception in the data corpus was a few undergraduates and Ph.D. students who mentioned fire in terms of the plasma level of energy. Perhaps from prior academic experiences those who had relevant physics instruction knew to find those levels within their boundaries of knowledge and in those cases some of them connected the two levels together, thus potentially supporting their understanding of the underlying emergent behavior. Other students tended to not see fire in terms of individual agents, either individual leaves on fire or individual excited electrons. Interestingly, across the entire data corpus there were other characteristics of the phenomena that students found relevant. Many students found attributes of the forest, for instance, the individual trees and leaves, the canopy, the bark, and the density of the vegetation to be within their boundaries of knowledge. In addition, students sometimes saw the location of bodies of water (rivers, streams, ponds, lakes, etc.) to be relevant as the location of water can influences the spread of a fire. However, other times students mentioned this but found it irrelevant.

In the sand dune problem context there were many commonalities across students seeing both the dune and grain levels as relevant along with the wind as relevant. This in turn supported them in seeing rate as important, in addition some students’ encountered challenges around whether geological activity was or was not relevant. During the course of the sand dune discussion almost all of the students came to see the wind as relevant and many came to see the rate of sand joining and leaving the dune as relevant. Seeing wind as relevant was relatively common and easy for students. But, seeing rate as relevant depended on one cueing knowledge about the movement of individual sand grains and the changing size of dunes, which some students saw as relevant and some did not see as relevant. This is important because once students saw the relative rates of sand particles leaving and joining the dunes as relevant they often generated explanations that incorporate changing composition, which is emergent. Some students initially saw geological and meteorological activity as relevant, such as earthquakes, water erosion, and flooding. However, after a little while students often stopped seeing the geological activity as relevant, this often occurred once they cued other kinds of prior knowledge that suggested that the geological and meteorological factors are not relevant to the particular situation. In sum, the boundaries of students’ knowledge, what they do and do not find relevant, influences the limits of how they understand the phenomena and in turn whether or not they see emergence.
Performance of Knowledge
The third characterization of knowledge is performances of that knowledge, specifically coordination or alignment of knowledge. This is an action that happens to create new knowledge, possibly by linking similar things, or by providing a common abstraction. This is similar to alignment in which there is knowledge that is sensitive to two or more problem contexts and is aligned together based on some commonalities across the two problem contexts (diSessa & Sherin, 1998; Wagner, 2006). In the data corpus I often found cases in which students coordinate prior knowledge or experiences across two or more problem contexts. Often this occurred in the second half of the interview, after students had the opportunity to discuss several problem contexts. At that point in time students spontaneously commented on some aspect of one problem context being similar to two or more problem contexts. For instance seeing the spreading of fire as similar to the spreading of a virus because both are based on a mechanism involving physical touch. In the analysis I focus on cases in which the piece of knowledge being coordinated across two of more problem context is related to mechanisms of how and why.

An example of a student coordinating across problem contexts is when Blake saw the explanatory pattern changing composition as relevant across traffic jams and viruses. He explains that for both traffic jams and viruses the absolute number of sick people or the absolute size of a jam could be constant, while equal numbers of individuals are getting sick and getting well or equal number of cars are joining and leaving a jam. This might have been a case of him providing a common abstraction across the two problem contexts in which he is creating some new knowledge based on this commonality.

Beyond cases in which students coordinated knowledge across two complex systems problem contexts, there were also cases in which students coordinated knowledge across one complex systems problem context and another non-complex systems problem context that was cued from their prior experiences. For example, a few students spontaneously mentioned traffic jams and water flowing in pipes as similar. In coordinating across these two problem contexts, students also recognized that there are differences in the two problem contexts. For example, when the diameter of the pipe decreases the water flows faster, in comparison when the number of lanes decreases the traffic goes slower. One student mentioned that water flows fastest in the middle of the pipe and traffic moves fastest in the left lanes, while in the right lane the traffic is going slower similar to water going slower at the edges of the pipe where there is friction between the water and pipe material. In recognizing these similarities across problem contexts students might have been finding new features of the complex systems problem context relevant, or they may have been finding new ways to understand the behavior of the complex system problem context, which could subsequently influence their understanding of the emergent behavior.

Catalogue of Specific Features of the Problem Context
In the above section, I present a list of the four kinds of prior knowledge and three characterizations of that knowledge that are found in this data set and that are related to students’ emergent thinking. The four kinds of prior knowledge that I focus on include: pragmatic knowledge, experiential knowledge that is or is not cued, p-prims, and agent knowledge. The three characterizations of that knowledge include: performances of that knowledge, boundaries of knowledge, and the process of creating knowledge. A key assumption of this catalogue is that these kinds of prior knowledge and characterizations of that knowledge could hypothetically apply equally to any of the seven problem contexts. I specifically focus on how this prior
knowledge and characterizations of that knowledge are related to students’ understanding of emergence.

Before I begin, there are a couple comments about the relationship between the prior list of kinds of knowledge and characterizations of that knowledge and the subsequent catalogue of features of the problem context. The mini-theory presented in this chapter is that students’ explanations that incorporate the various patterns are based on their prior knowledge and characterizations of that knowledge along with features of the problem context. Remember at the beginning of this chapter I discussed what hypothetical traffic jam explanations might look like that incorporate traffic jams as exhibiting various patterns. For instance an explanation focusing on the individual cars speeds increasing and decreasing in a periodic manner, thus the explanations would be said to be incorporating the periodic motion pattern.

In this next section I present a list of three specific features of the problem context that have the potential to influence students’ decentralized thinking. This list includes, but is not limited to whether the phenomena occurs again and again or only once, the arrangement of agents, and the relationship between agents and humans. For each of these features of the problem context, I present a series of examples of that feature of the problem contexts and discuss how it influences students’ emergent thinking.

**Occurs Again and Again or Occurs Only Once**

The first specific feature of some problem contexts is about recurrence. I argue that one important distinction among these problem contexts is that some have more recurrent behaviors than others. For some problem contexts, the behavior being recurrent is more or less plausible. For some problem contexts to be recurrent, it would require only a physical modification. For other problem contexts to be recurrent there would need to be a chemical or biological change. In other words, there is a graduated scale of how recurrent a specific phenomenon is perceived to be by the students. This is important because it influences whether or not students use the periodic motion explanatory pattern. Problem contexts where recurrence seems more likely to be an applicable feature are more likely to be explained by periodic motion.

I argue that sand dune can be considered to be recurrent by the student because only a physical change is needed to move a dune back and forth. For a sand dune to move from one location to another location it would require a physical change in the position and arrangement of sand particles. Sand dunes could move back and forth again and again based on this physical change. This is a physical modification of position and arrangement of particles, not a change of molecular structure or chemical change. This nature of sand dunes possibly influences students’ understanding about sand dunes as emergent. It may be easier for students to see sand dune motion as periodic than some other problem contexts where seeing periodicity is possibly more difficult.

Forest fires are different from sand dunes and not as recurrent as there is a chemical change involved with burning wood. During a forest fire the wood undergoes a chemical change when burnt. Once a forest fire has spread and burnt the materials in its path, an impossible molecular change would be needed in order to literally undo the results of the fire. Hence, a single fire cannot be recurrent. As mentioned previously, students’ have prior knowledge about burning materials such as paper or candles and that knowledge supports them in recognition of the finality of combustion. The only way a forest fire can be thought of as recurrent is in terms of different fires burning the same location at different points in time. If this piece of knowledge, about multiple forest fires in the same location at different points in time, were to be cued by students then perhaps they might have seen the phenomena as recurrent, but this did not happen.
Thus because students are likely not cuing knowledge about forest fires being recurrent, they are in turn likely not seeing the behavior of forest fires in terms of periodicity.

Sand dunes and forest fires might be the extremes along this dimension of recurrent and non-recurrent natures of the problem context while other problem contexts might be in the middle. Viruses might be similar to forest fires as there is a biological/chemical change when a virus infects an organism. Diffusion might be similar to sand dunes in some ways and different in other ways. For diffusion there is no way to undo the processes, it would be impossible to separate a dye from water after diffusion. However, the nature of diffusion is about the physical arrangement of molecules, although temperature and energy are important and influence the phenomenon. In some ways traffic jams are similar to sand dunes as the formation of a jam involves the physical arrangement of cars, which is maybe similar to the arrangement of sand particles. However, in traffic jams cars are using up fuel and it would be impossible to undo that activity. Therefore, depending on which attributes of traffic one focuses on, it could be thought of as either recurrent or not.

The central argument is that these different problem contexts require different levels of modification in order to potentially be recurrent. This idea of recurrent or non-recurrent, whether the phenomena occurs again and again or not, varies across the problem contexts. This is important because it influences if students generate periodicity explanations. Students are more likely to explain sand dunes in terms of periodicity because sand dunes moving back and forth sounds plausible. Students are not likely to explain forest fires in terms of periodicity because fire moving back and forth sounds not very plausible. In Chapter 5 I argue that students use the periodic motion explanatory pattern more often in recurrent problem contexts and less often in non-recurrent problem contexts because of the how their prior knowledge and the specific nature of the problem context influences their thinking. This issue is important because as will be argued latter, explaining these problem contexts through periodic motion may help students see the self-organizational nature of the phenomena.

Arrangement of Agents
The second specific feature that illustrates an important distinction among the problem contexts is the physical and geometric arrangement of individuals or agents. While every problem context has a specific arrangement of agents, I argue that for certain problem contests there are some arrangements that are congenial for emergent thinking. For instance, in sand dunes some sand particles are on the surface of the dune and are thus more exposed to the wind than other particles. In that case there are natural layers of sand particles and that divides the macro system into specific layers. Some students use this specific feature of sand dunes to construct an explanation about the sand particles on the top of the dune moving first, then after they move another group of particles that are now exposed to the wind move. In Chapter 5 I argue that the arrangement of sand particles influences students’ reasoning in particular ways, specifically it supports them in using the mid-levels explanatory pattern.

In this section I discuss two ways in which the arrangement of individuals is important. First, I discuss the issue of homogeneity. If students view the individuals as homogeneous, then focusing on individual’s unique behavior becomes less central because all of the individuals have the same behavior. If students view the individuals as not homogeneous, then there is more emphasis on individual’s behavior, for example, specific locations influence subsequent behaviors or a sequential ordering of behaviors. Second, I discuss the environment influencing students’ reasoning. If there are constraints imposed on the system by the environment, these
constraints can influence the arrangement of individuals and in turn that can influence students’ reasoning about emergence.

**Homogeneity:** Whether or not the student views all of the individual agents as homogeneous or not has a bearing on whether the specific arrangement of individuals is relevant. By homogeneous, I mean that in some problem contexts all agents are fundamentally homogeneous, they all have the same behavior and properties of the nature of the agents, such as location, are also all the same. For example, in diffusion all molecules behave in identical ways based on the same principles. The molecules individual speeds, positions, and directions vary; but, we generally do not need to describe each individual’s motion. For diffusion it is usually sufficient to describe averages. Because of this emphasis, students generally do not discuss specific mechanism that apply at the individual level and that can influence the larger macro level behavior, which in turn could influence ones understanding of emergence.

In comparison to diffusion, other problem contexts, for instance, birds, fish, and traffic are different because the individuals are treated as heterogeneous. For example, in the bird and fish problem contexts the position of a given bird or fish in the flock or school is important. Some students mentioned the ones in front being the leader. Other students mentioned one bird or fish in the middle doing something random that confuses other birds or fish behind them. Some students mentioned how it is easier to fly in the middle or back because you experience help from the drag of the ones in front. As will be discussed in Chapter 5, these actions of individuals serve an important role in students focusing on the underlying micro-level mechanisms that influence the macro-level phenomena. In traffic jams students often discuss one car going faster or slower than other cars. This variation in relative speeds of individual cars influences the behavior of the entire phenomena. When students focus on distinctions among individuals in terms of location, speed, position, or other characteristics this often has a subsequent bearing on their reasoning.

Many students do not see birds, cars, and fish as homogeneous; they pay attention to variations among the individuals. In comparison, students do not pay attention to the differences among water molecules; students see all of the water molecules as homogeneous. Of course from the scientific perspective, one can view any of these problem contexts as being composed of either homogeneous or heterogeneous individuals. However, for students whether they view the individuals as homogeneous or not can have a subsequent influence on their reasoning because it influences whether or not they focus on mechanism that operate at the individual level.

**Role of the Environment:** Next, I discuss how the environment influences the arrangement of agents and that in turn influences whether or not the students’ reason about the phenomena in an emergent manner. Prior research that was discussed in Chapter 1, by Resnick (1994; 1996) focuses on the role of the external environment in students’ reasoning about complex systems. That research has tended to focus on whether the students view the environment as something to be acted on, or if they view the environment as something to be interacted with. The latter is associated with decentralized causality and the former is associated with centralized causality. For example, in sand dunes the terrain of the desert can influence movement, perhaps by hindering the movement of a dune in a certain direction, thus the dunes are interacting with the environment. As will be discussed in Chapter 3, this distinction about a more centralized or more decentralized view of the environment was not included in the coding scheme or robustly in the analysis because I could not reliably distinguish the two possibilities in the data. Yet, despite this distinction not being explicitly included in this analysis, I do observe that the role of the external environment does have an impact on students’ reasoning.
The argument in this section is that specifics of the external environment influences students’ understanding the physical arrangement of individual agents which then in turn influence students’ reasoning about the differences among the seven problem contexts. These are attributes of the environment that one is likely to readout and have the potential to influence students’ emergent thinking. For example, in traffic jams there are several parallel lanes. This attribute of the environment, lanes, influences students’ understanding of the physical arrangement of individual agents. In the case of traffic, individual cars travel in these lanes due to convention. Another example of the external environment influencing students’ understanding of the physical arrangement of individual can be seen in viruses. A relevant environmental factor in viruses is the existence of population centers and work places. The existence of population centers is something that students often readout of this situation, and the existence of these population centers in turn influence students’ reasoning about the emergent nature of the spread of viruses as these population centers influence there not being a uniform distribution of people’s positions. In both cases, the lanes on the highways and the population centers, are attributes of the environment that are man-made, that influences students’ understanding of where they expect the individuals to be located (e.g. centers of population), and that influence how students expect individuals to move (e.g. within or across lanes of traffic or between centers of population).

The next piece of this argument is that together the specifics of the environment and the physical arrangement of individual agents both have a bearing on distinctions among the seven problem contexts which in turn influence students’ reasoning about the variability of the problem contexts. For example, in traffic jams the existence of lanes and the fact that cars travel in those lanes due to traffic conventions influences students’ thinking about what happens when cars switch lanes. The specifics of the environment and the physical arrangement of cars also influences students’ thinking about variation across lanes, for example cars traveling faster in the left lane. Notice that this idea of lanes and all of the implications mentioned above does not apply to other problem context. No students discussed birds, fish, viruses or fire traveling in established lanes. This is important because it influences student understanding of the differences of the emergent behaviors of traffic versus birds, fish, viruses, and fires.

One more example of the specific external environment influencing students’ understanding of the physical arrangement of individuals can be seen in the role of an external boundary (e.g. a fire break or aquarium wall) illustrating distinctions between the fish, bird, and forest fire problem contexts. In the fish problem context many students mentioned the role of the aquarium wall as it influences fish behavior. Fish turn around and change directions when they are near the wall. However, there is no parallel “wall” in the sky that would cause birds to change directions. This is important because the “wall” was often mentioned by students as a centralized factor controlling the behavior of fish, they all turn around when they hit the wall. There is not parallel environmental controlling factor that influences birds changing direction in a centralized manner. Thus the existence of a wall is potentially negatively influencing students’ understanding of the movement of fish as a decentralized process. Similar to the aquarium wall, in forest fires students mentioned a stream or a road serving as a firebreak. This natural (stream) or artificial (road) boundary served a function similar to the aquarium wall in that it functions as a centralized controlling factor potentially negatively impacting students’ decentralized understanding of forest fires. To summarize, in this section I have provided a series of examples from different problem contexts (traffic jams, viruses, birds, fish, and forest fires) where an
aspect of the external environment influences students’ understanding of the physical arrangement of individuals, illustrating distinctions between the various problem contexts.

To review, in this subsection I discussed a second feature of the problem contexts that highlights important distinctions among the problem contexts, the arrangement of agents. I discussed two versions of this feature of the problem contexts: homogeneity of individuals and environmental constraints. First, I discussed the role of homogeneity of individuals. Whether or not students focused on individuals as homogeneous or not influences whether or not they focus on individual’s behavior and relevant micro-level mechanisms. Remember for sand dunes, the fact that the sand particles form natural layers and some layers are more exposed to the wind supports students in dividing the macro system into intermediate levels. This is important because it influences students use of the mid-levels explanatory pattern, which as will be discussed later can be related to their understanding of emergence. Second, I discuss different ways in which the environmental constraints and associated arrangements of individuals influence students’ reasoning about the phenomena as emergent. The central idea is that the relative arrangement of the individuals is an important feature of the problem context that can influence if or how students’ understand the decentralized behaviors. Remember I discuss that for fish in aquarium tanks students mentioned the walls of tank serving as a controlling factor that influences when fish turn around thus potentially hindering students’ decentralized thinking; there is no parallel controlling environmental factor for the birds problem context. Overall in this section I argued that the arrangement of the agents influences students’ reasoning about the emergent nature of the problem contexts and illuminate some variability in students’ reasoning across the problem contexts.

The Relationship Between Agents and Humans
The third feature of the problem contexts that distinguishes problem contexts from each other and influences student reasoning, is the relationship between agents and humans. Whether or not there is a close or distant relationship between agents and humans influences whether students have a tendency to personify the agents or if they have a tendency to readout information about social issues. This tendency influences students’ understanding of variability across the problem contexts and it influences students’ application of underlying mechanism to explain the behavior. I find that for problem contexts that involve humans or animals close to humans, there is a stronger tendency to invoke knowledge about the agents that involves personification or social issues. For problem contexts that students view as farther from humans, this tendency decreases. This observation is in agreement with Inagaki and Sugiyama (1988) and Inagaki and Hatano (1996), which together found that young children apply personification to animate objects (tulips and rabbits) at varying rates depending on the closeness of that animate object to humans. Applying this result to the current paper would suggest that I might expect to see more personification of fish and birds than of trees on fire. A similar argument about the role of personification is discussed in Wilensky and Reisman (2006). They discuss the role of personification as a building block in students’ reasoning about complex systems through agent-based models. In this analysis I focus on the role of personification in terms of students understanding of emergence, but there is a large literature on the more general role of personification in learning. For example, Legare, Lane, and Evans (in press) investigate how anthropomorphic language influences children’s understanding of evolution and they find that anthropomorphic was least likely to influence a scientifically accurate understanding and that need-based language may provide conceptual scaffolding. Below I present examples in which
this tendency helps students’ focus on the underlying mechanism, which in turn can help
students’ reasoning about emergence.

In the fish and bird problem contexts there are many examples of students personifying
the behavior of birds and fish. For example, after asking Antonio about how two groups of fish
could merge, he explained it through an analogy of two groups of friends meeting up.

Ones all going in one direction, ones all going in another direction. And then sooner or
later they are going to hit, so I guess, it seems likely to me… I don't know how they all
think. [Laughter] I wonder how they all think. Maybe they all just keep [going] with their
group. Are they like people who like have a group of friends, and another group of
friends, that I don't know. And they will kind of walk by each other [gestures implies
'walk by without knowing’] and just keep going in opposite ways. Or do they know each
other and be like, I'm going to go hang out with this guy?

In this excerpt Antonio is using his knowledge of the dynamics of groups of friends in order to
hypothesize how two groups of fish could merge. Notice that this explanation includes a
mechanism for why the groups may or may not merge, namely, wanting to hangout with certain
friends. Similar to this example, there were many instances of this specific kind of knowledge in
the birds and fish problem contexts.

As mentioned previously in the virus and traffic jam problem contexts, which obviously
do involve humans as carriers of viruses or drivers of cars, there was a strong tendency to discuss
hypothetical expectations, social issues, and reasons for others actions. For example, students’
mentioned that people know to stay home when they are sick, but sometimes there is pressure to
go to school or work, thus they inadvertently spread the virus. Stephen said: “[a] person
traveling with the virus, who doesn't know that they are sick yet, or who doesn't know they are
sick and already made plans and has to go anyway. People are selfish like that.” In this excerpt
Stephen is cuing some knowledge about his expectations and reasons for why people travel when
they are sick. Within this explanation there is an underlying mechanism for why people travel
spreading the virus: they are selfish. This mechanism is important because it can potentially
influence his understanding of viruses as emergent. In the traffic jam problem context students
cued knowledge about others actions and reasons for those actions, which also serve as
mechanisms that can influence students’ understanding of traffic jams as emergent. For instance,
mentioning that sometimes people speed because they are running late, but in taking this
speeding action they annoy everyone else on the road.

Finally, the difference across problem contexts in students’ reasoning about the
relationship between agents and humans illustrates some larger variability in their reasoning.
Across the data set students uniformly did not personify sand particles or water molecules.
Given the differences between humans and water molecules or sand particles, this observation is
in agreement with the results from Inagaki & Hatano (1996) and Inagaki and Sugiyama (1988).
This difference about which agents students personify and which ones they did not personify,
illustrates some variability in their reasoning across the problem contexts. For the problem
contexts in which students did personify agents, there was a tight relationship between the agents
and humans, and there is a tendency to focus on underlying mechanism derived from this
personification. These underlying mechanisms are potentially useful in reasoning about that
problem context as emergent.
The Relationship between the Kinds of Knowledge, Characterizations of Knowledge, and Features of the Problem Contexts

So far in this chapter I have presented a sketch of the kinds of epistemological resources relevant to students’ learning about complex systems. This sketch is a part of a larger mini-theory about how students construct explanations about complex systems as based on their prior knowledge, the characterizations of that knowledge, and features of the problem contexts. First, I presented a catalogue around knowledge, it includes both kinds of knowledge and characterizations of knowledge. The four kinds of prior knowledge that I focus on include: pragmatic knowledge, experiential knowledge that is or is not cued, p-prims, and agent knowledge. Then second I presented three characterizations of that knowledge include: performances of that knowledge, boundaries of knowledge, and the process of creating knowledge. Third, I presented a list of features of the problem context that often influences students’ understanding of emergence: whether the phenomena occurs again and again or only once, the arrangement of agents, and the relationship between agents and humans.

There is a relationship between these three lists, often the explanations students generate that are based on an explanatory pattern that depends on their prior knowledge, characterizations of that knowledge, and features of the problem context. Below I discuss examples of how epistemic resources from these three lists could influence a students traffic jam and diffusion explanations.

Many students generated explanations based on ideas about wanting to avoid traffic jams. These explanations often included knowledge from students’ experiences sitting in traffic jams, knowledge about wanting to avoid accidents, and knowledge about the behavior of cars. Characterizations of this knowledge might include reading out specific information about a jam situation as relevant, for instance, cars’ speeds, and not reading out other information. In traffic jams often students’ knowledge was bounded by their experiences watching traffic jams from the perspective of being inside a car. Thus a bird’s eye view of traffic jams was usually not seen as relevant. In these explanations often the arrangement of agents is a feature of the problem context that students find relevant, for example, cars traveling in lanes and the dynamics of switching lanes. Thus by looking at the different knowledge students cue about traffic jams, their characterizations of that knowledge, and the features of the problem context that influenced their explanations, we can see that they come together within their explanations about wanting to avoid traffic jams.

Similar to common traffic jam explanations, many students’ diffusion in water explanations also can be seen in terms of students’ prior knowledge, characterizations of that knowledge, and features of the problem context. In diffusion many students cued prior knowledge about experiences based on watching the diffusion process, such as pouring milk into coffee. Only a handful of students cued knowledge about the motion of water molecules. The molecular level was likely just something that the students did not construed as relevant. Focusing on the macro level, some students’ readout information about the change in color and what they saw happening. One feature of the problem context that was often relevant is the homogeneity of the molecules behavior. Thus as hopefully is clear, there is a relationship between these three list as students’ explanations are often based on the explanatory patterns, and in turn the specific explanatory pattern used depends on both their prior knowledge and the characterization of that knowledge along with features of the problem context.
Discussion of the Sketch of Epistemological Resources

There are several contributions from this sketch in terms of our understanding of students’ knowledge about complex systems. One contribution of this sketch is evidence that p-prims, which previously have been discussed in Newtonian mechanics, also apply to complex systems phenomena. Another contribution is the catalogue of the four kinds of prior knowledge because it is likely relevant to other complex systems problem contexts. This catalogue is more expansive than existing work in the literature that looks at prior knowledge within students learning of complex systems through the KiP family of theories. In a pilot implementation of multi-agent based computational curriculum about electricity, Sengupta and Wilensky (2009) investigate students’ learning of electricity as a complex system and documented several p-prim knowledge elements activated within learners knowledge construction process. The catalogue of four kinds of prior knowledge relevant to students’ explanations about complex systems presented in this analysis is more detailed than the knowledge analysis in Sengupta and Wilensky (2009).

One final discussion point is about the relationship between the current sketch of epistemological resources around complex systems and the view of knowledge presented in the ontological theory of conceptual change (e.g. Chi, 2005). In Chapter 1 I discussed the ontological theory, which hypothesizes that students’ difficulties with emergent systems are due to a miscalcategorization of emergent processes, such as diffusion, as direct processes (Chi, 2005; Chi et al., 2012; Slotta & Chi, 2006). This perspective mainly focuses on ontological knowledge that is general to either emergent or direct processes while not accounting for any knowledge that is specific to a particular emergent process, in their case diffusion. In comparison, the current perspective focuses on specific kinds of prior knowledge and characterizations of that knowledge, which is more than is emphasized in the ontological categories perspective. This is important because it influences the analysis. For the current perspective I document differences across problem contexts in terms of knowledge pieces and characterizations of that knowledge. In comparison within the ontological categories perspective there is not an analysis focus on differences across problem contexts that are all emergent. This is important as I am able to illustrate variations across students’ reasoning of many complex systems problem contexts, while this focus is not easily supported by the ontological categories perspective.

Student Generated Explanatory Patterns

Next, I focus on the patterns, for instance, mid-levels, changing composition, threshold, and periodic motion, that are incorporated into student’s explanations; I refer to these as student generated explanatory patterns. I look at how the students’ knowledge, characterizations of that knowledge, and features of the problem contexts are connected together within the dynamics of generating an explanation. In the data, students generate all kinds of explanatory patterns, but in this section I focus on the ones that are potentially helpful in supporting an understanding of decentralized causality and were relatively common across the data set. Thus I am not referring to patterns of explanations. I am referring to explanations that incorporate these particular patterns of change and control, for instance, threshold and periodic motion. The reason I focus on these particular patterns is because initial analyses suggest that reasoning about these problem contexts, traffic jams, sand dunes, and others through these specific patterns might help students in understanding these problem contexts as decentralized processes. The student generated explanatory patterns that I focus on encapsulate one of the following patterns: threshold, mid-levels, periodic motion, steady state, changing composition, or convergence to a limit. One of
the ways these patterns are helpful is by focusing on the underlying mechanisms because that
focus in turn is potentially helpful in understanding the how or why of the specific behaviors
associated with decentralized causality. One of these patterns, changing composition is emergent.
As will be discussed in Chapter 5, the other explanatory patterns can be altered by the students
into other explanations that are emergent. One contribution of this analysis is an understanding
of how and why certain explanatory patterns can be altered into being emergent based on how
the explanatory patterns were altered as the students generated their explanations.

Before I delve into a discussion of the specifics of each explanatory pattern, there are a
couple notes about how this construct fits within the existing idea of Dynamic Mental Construct
(DMC) (Sherin, Krakowski, & Lee, 2012). DMCs are temporary explanations constructed in the
moment during clinical interviews. These are dynamic explanations and they are thought to
correspond to temporary mental states and they are produced based on a set of knowledge
elements. The student generated explanatory patterns are similar to DMCs as both are temporary
explanations constructed in the moment during a clinical interview. Similar to Sherin et al.,
(2012), my data consists of clinical interviews and the students’ reasoning changes on a moment-
to-moment basis. Therefore it is necessary to use a theoretical framework that accounts for these
small changes in students’ reasoning. Inherently, the focus on explanatory patterns recognizes
that which patterns students use shifts over short time frames. In the analysis, sometimes the
explanatory patterns are distinct and separated in time. However, sometimes students generated
a couple of explanatory patterns within a very short time period, this is similar to what Sherin et

In this section I include an argument for why each specific pattern is potentially helpful
in supporting students to understand emergence. Making this argument involves a complication
in that patterns such as equilibrium and threshold exist in many areas of science, both in complex
systems and non-complex systems. Because of this complication I cannot assume that when a
student discusses, for example, sand dunes sizes as exhibiting a threshold behavior, that it
necessarily is associated with an understanding of decentralized causality. To construct this
argument I focus on reasons for how a specific explanatory pattern might support understanding
decentralized causality. For example, as will be discussed below and is discussed more
extensively in Chapter 5, I find that connecting micro and macro levels or focusing on the
underlying mechanism are both sometimes helpful for understanding decentralized causality.

Thus, in this section below I go through in detail each of the six explanatory patterns:
Threshold, Mid-Levels, Periodic Motion, Convergence to a Limit, Steady State, and Changing
Composition. I discuss these patterns sequentially; for each pattern I focus on the general pattern,
I focus on the relevant literature when applicable, and I summarize the arguments presented in
Chapter 5 for why that specific pattern either is emergent or is potentially helpful in in reasoning
about the phenomena in terms of decentralized causality. In table B, I present an overview of
each pattern with a graphical representation of that pattern.

<table>
<thead>
<tr>
<th>Explanatory Pattern</th>
<th>Description of the Pattern</th>
<th>Graphical Representation of the Pattern</th>
<th>Emergent or not?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Levels</td>
<td>Intermediate level group between the macro and micro level.</td>
<td><img src="image" alt="Graphical Representation" /></td>
<td>Can be altered into being emergent.</td>
</tr>
</tbody>
</table>
Table B: Overview of the Six Explanatory Patterns.

<table>
<thead>
<tr>
<th>Explanatory Pattern</th>
<th>Description</th>
<th>Can be altered into being emergent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td>Initial behavior, change in behavior that is different from the initial behavior</td>
<td></td>
</tr>
<tr>
<td>Changing Composition</td>
<td>The behavior at the macro level is stable but the behavior at the micro level is changing.</td>
<td>Emergent</td>
</tr>
<tr>
<td>Periodic Motion</td>
<td>Cyclical and oscillatory behavior</td>
<td>Can be altered into being emergent.</td>
</tr>
<tr>
<td>Steady State</td>
<td>Nothing is changing at either the macro or micro level.</td>
<td>Can be altered into being emergent.</td>
</tr>
<tr>
<td>Convergence to a limit</td>
<td>The behavior converges at either the macro or micro levels.</td>
<td>Can be altered into being emergent.</td>
</tr>
</tbody>
</table>

Mid-Levels
One explanatory pattern, *mid-levels*, captures an intermediate or mid-level group that is between the macro and micro levels, this pattern is important because it may support making connections between the macro and micro levels which in turn can help seeing emergence. Within explanations based on this pattern students construe the phenomena by reasoning through the intermediate level, as opposed to only the macroscopic level or only the microscopic level. By focusing on the intermediate level students are often connecting the behavior of the macro and micro levels. A variety of researchers have documented the importance of the connection between the macro-micro levels (Eylon & Ganiel, 1990; Frederiksen, White, & Gutwill, 1999; Levy & Wilensky, 2008; White, 1993a; White, 1993b). For Levy and Wilensky (2006) this was important as they were investigating students’ reasoning about complex phenomena and specifically a strategy in which students’ focus on a mid-level, small groups of individuals formed out of the whole. For Frederiksen, White, and Gutwill (1999) this was important as they were developing students’ understanding of electricity and electrical circuits by linking phenomena at the microscopic particle level to an intermediate aggregate level and then to the emergent phenomena (circuit laws) at the macroscopic level. Connecting levels maybe productive in understanding the decentralized nature of complex systems because it may support one in seeing how the macroscopic behavior can arise from interactions at the microscopic level, which is a key part of emergence (Wilensky & Resnick, 1999).

Some of the prior research on the intermediate level focuses on students’ learning of electricity. Eylon and Ganiel (1990) document students’ difficulties with electricity, they found that students had trouble connecting the macro level circuit devices and the micro level electric charge. Similarly, Frederiksen and White (2000) documented cases of students not connecting the electrostatics and electrodynamics levels. White (1993a) advocates an instructional approach that focuses on intermediate causal model via a progression of increasing complexity that
support an understanding among different levels, specifically the macroscopic and microscopic levels, and the iconic and symbolic levels. Finally, Frederiksen, White, and Gutwill (1999) found that making conceptual links between levels, such as the macroscopic and microscopic levels, is productive for students’ learning. One of the differences between some of this prior work and the current study is that the prior work focuses on intermediate levels to improve existing instructional activities, in comparison the current study focuses on spontaneously use of intermediate levels.

Recently, in other complex systems problem contexts Levy & Wilensky (2008) found that the mid-levels strategy can be helpful in understanding the behavior of complex systems because it may support making connections between levels. Levy & Wilensky (2008) documented this strategy in the context of students explaining the emergent behavior of packs of deer and students on the playground. In the data they found two versions of this strategy, subdividing the whole into intermediate levels or aggregating individuals into intermediate levels. For example, in their study participants mentioned an entire classroom of students being subdivided into several rows to perform calisthenics on the playground, which is a version of subdividing the whole. The other version of the strategy involved participants mentioning aggregate individuals, such as sick deer socializing in groups thus spreading disease faster. Based on a coding scheme aimed at capturing when students’ beliefs are associated with a complex system model or a clockwork model the authors found that the strategy of subdividing the whole is related to a high complexity reasoning scores and thus supportive of students’ understanding of “complex systems” principles.

As will be presented in further detail in Chapter 5, students’ generated explanations based on the mid-levels pattern in several problem contexts. In sand dunes they generated explanations based on the top layer of sand moving off the dune first, followed by the next layer down in sequential order until the entire dune moves. These explanations were often based on prior knowledge about the arrangement of sand particles, specifically knowledge about the sand particles on the surface of the dune being most exposed to the wind, thus those particles being most likely to move first. They also generated explanations about intermediate groups, such as groups of birds or fish moving together.

Following the existing hypotheses, in this dissertation I hypothesize that students’ use of the mid-levels explanatory pattern is potentially helpful in reasoning also about decentralized causality. This is potentially helpful for students by supporting them in connecting the macro and micro levels, as is discussed in Wilensky and Resnick (1999). In the analysis presented in Chapter 4, I argue that it may in addition be helpful for students’ reasoning about decentralized causality as it focuses the students on a sequential priority order of behaviors, as mentioned in the sand dune example where the top layer moves first.

**Threshold**

I view threshold as a process in which there is initial behavior, a change in behavior, and then a subsequent behavior that is different from the initial behavior. During the initial behavior the time scale is important. Often there is a gradual build up of a substance or a tension. The change in behavior is often dramatic and related to an underlying mechanism. After the change there is a subsequent behavior that is often different from the initial behavior. For example, in traffic jams students’ explanations capture the idea of an initial process in which cars are going at a high speed, then there is a change perhaps a change in density of cars or a change in the number of cars on the road, the result being a change in behavior, cars slow down. In this example the student would likely be cuing prior knowledge in which the individual car’s speeds and the
density of cars are important relevant features. Potentially this is an example of a common trend in which students cue prior knowledge about the individual agents within the threshold explanatory pattern.

There is a variant of threshold, lag effects, that is similar to threshold but one difference is the heightened importance of the role of time. Lag effects is canonically a period of time before something occurs. With lag effects there is an initial behavior, which takes time and then there is a change in behavior. Although time is an important attribute of threshold, for lag effects the period of time before the change in behavior is a defining feature. For example, in traffic jam students mentioned the period of time it takes for a jam to clear up. It takes time for cars to have enough space between them such that they can resume their previous speed. A key piece of this explanation is that the change in behavior depends on a period of time so that the cars have enough space in between them to be able to increase in speed.

The learning sciences literature on threshold is sparse with a few exceptions. Resnick (1994) discusses the idea of a tipping point as important within a context of students interacting with a series of computational models of complex systems. Also, threshold is considered to be one of the patterns of change and control discussed in diSessa (2007b) that is related to students’ learning of dynamical systems theory and applicable to many problem contexts in physics and elsewhere. However, threshold is not widely discussed in the learning sciences literature.

From the analysis presented in Chapter 5 I have four potential reasons why threshold might be helpful in supporting students’ reasoning about decentralized causality. In that analysis I argue that threshold is possibly productive towards supporting students’ generating explanations associated with decentralized causality because it may also support: 1) students recognition of critical variability in the behavior of the phenomena, 2) students in connecting the micro and macro level behaviors, 3) students in recognition of the underlying mechanisms, and 4) students application of the threshold pattern in conjunction with another explanatory pattern, such as cyclical motion or mid-layers. As threshold is not a widely researched pattern, this list of four possible reasons why it might be helpful in reasoning about decentralized causality should be viewed as a series of initial hypotheses.

Changing Composition

Changing composition is a type of equilibrium behavior in which the behavior at the macroscopic level appears to be stable—but the behavior at the microscopic level is changing. At the microscopic level the motion involves agents, for example, cars or sand grains, joining and leaving at equal rates. This behavior results in the composition of the microscopic phenomena changing over time while the macroscopic phenomena may appear constant. This behavior is sometimes referred to as dynamic equilibrium. This pattern, unlike the other patterns, is emergent. In the sand dune problem context students discuss the size of the dune as constant while equal rates of sand particles are joining and leaving the dune resulting in the composition of the dune changing at the microscopic level. One could also extend this idea to explain the sand dune getting bigger or smaller depending on the relative rate of particles joining and leaving the dune. A sand dune becomes bigger when the rate of sand joining is greater than the rate of sand leaving. A sand dune would get smaller when the rate of sand joining is less than the rate of sand leaving the dune. Generating an explanation based on this pattern requires seeing both the grain and dune levels as salient and also paying attention to the relative rates. When students are using the changing composition explanatory pattern they are pay close attention to rate and applying ideas of relative rate in order to hypothesize how it would influence the changing behavior.
Changing composition is emergent because it highlights the self-organizational nature of the phenomena in terms of the connection between levels. When students generate explanations based on this pattern, their reasoning is capturing the decentralized nature of the specific problem context. In the context of traffic jams, Resnick (1996) noticed that students had trouble connecting the behavior of individual cars with the overall behavior of jams because the behaviors at the macroscopic (jam) and microscopic (car) levels are different. A key part of the decentralized and self-organizational nature of traffic jams is that cars move forwards while jams move backwards as the behaviors at these two levels are different; Resnick observed that students often incorrectly presumed that cars and jams were both moving forwards. Building off that research Wilensky and colleagues (Sengupta & Wilensky, 2009; Wilensky & Resnick, 1999) discuss the importance of understanding the relationship between the behaviors at different levels as it is aligned with a normative understanding of decentralized causality.

Student generated explanations based on changing composition are discussed in detail in Chapters 4 and 5. In Chapter 4 I discuss cases of two students changing explanations over short time periods, and in both cases their final decentralized sand dune explanations incorporate the pattern of changing composition. In Chapter 5 I discuss variations in changing composition across all seven problem contexts, this pattern was used in student generated explanations in the sand dune, traffic jam, and virus problem contexts. As mentioned above, this specific explanatory pattern is important because it is emergent.

Periodic Motion
Another student generated explanatory pattern used when conceptualizing these problem contexts is periodic motion. For the purposes of this analysis, periodic motion includes both cyclical motion and oscillatory behavior. Cyclical and oscillatory behavior may be distinguished by the existence, or not, of a restoring force. A mass on a string oscillates, but the seasons are cyclical as there is no force that pushes or pulls on them, returning them to a neutral position (no restoring force). For the purposes of this analysis, I lump them together and refer to the combined group as periodic motion because it is often difficult to discern the difference in the data. Similar to threshold, periodic motion is considered to be one of the patterns of change and control discussed in diSessa (2007b), and this pattern is relevant to both students’ learning of dynamical systems theory and applicable in a wider arena. There is limited prior research on students’ understanding of oscillation. Parnas (2007) focuses on students’ understanding of frequency and speed of oscillation through the use of external computational representations; in comparison, this work focuses on students generating explanations based on periodic motion.

In Chapter 5 I discuss excerpts in which students generate explanations about sand dunes getting bigger and smaller over time in a cyclical or periodic manner. I also discuss the periodic motion in traffic as cars get closer together and farther apart. Underlying the former example from sand dunes is some knowledge about the size of the dune as a relevant. Underlying the latter is some prior knowledge about reasons why cars would change their speeds. As cars are closer or farther to other cars they pragmatically want to avoid accidents. Whether or not students use this explanatory pattern is likely connected to whether they view a particular problem context as occurring again and again or not. As discussed previously, both sand dunes and traffic jams can be thought of as recurrent more easily than some other problem contexts, for instance, forest fires.

Given that there is limited prior work on students’ understanding of periodic motion, there are not preexisting hypotheses in the learning sciences literature for if or why periodic motion would be helpful for students in coming to recognize decentralized causality within
emergent processes. The analysis in Chapter 6 of students’ reasoning about viruses, traffic jams, and sand dunes through the explanatory pattern of periodic motion concludes with hypotheses for why periodic motion maybe helpful. In that Chapter I argue that it can be helpful in seeing the self-organizational nature of the phenomena and the underlying mechanism that influences the behavior.

**Steady State**

*Steady state* is an explanatory pattern in which the behavior of the system is in a state where nothing is happening at either the macro or micro levels. Notice that this is different from the process of settling into a steady state, which I refer to as convergence to a limit and is subsequently discussed. This is also not dynamic equilibrium. Examples of this include a sand dune that is not moving and no sand particles joining or leaving the dune. Nothing is moving, the entire system is in a steady state.

There is some evidence that steady state motion maybe aligned with centralized causality (Jacobson, 2001), but I find a more nuanced situation. As was mentioned in Chapter 1, Jacobson (2001) presents a coding scheme for when students’ thinking while solving complex systems problems reflects either a clockwork mental model or a complex systems mental model. The clockwork mental model is associated with centralized causality. The complex systems mental model is associated with decentralized causality. One of the component beliefs associated with the clockwork mental model is static structures. Likely this is similar to what I call, steady state, but I do not assume that it is always associated with students difficulties with understanding complex systems and centralized causality. Similar to the argument in Jacobson (2001), one could suggest that steady state is unhelpful in supporting students in recognition of complex systems and the emergent processes they give rise to given that self-organizational behavior is dynamic. However, as discussed in Chapter 5, I find that in some cases, after generating steady state explanations students’ generated explanations that invoke other patterns. Often it is patterns that are emergent, namely changing composition or patterns that are potentially associated with decentralized causality, periodic motion. I argue that sometimes the steady state pattern might highlight certain knowledge pieces that lead to students questioning the relevance of this pattern, which in turn sometimes results in the generation of a new explanation based on a different explanatory pattern. For example, there were cases in which students generated an explanation based on the steady state for sand dunes or traffic jams. But then they realized that some aspect of that explanation was unrealistic and they rejected that explanation in favor of changing composition.

**Convergence to a Limit**

*Convergence to a limit* is a pattern that can be incorporated into a student generated explanation and is based on one of the phenomenon, for instance, traffic jams, exhibiting a behavior in which some aspect of the system, such as speeds of cars, or size of the jams, converges over time. For example, one could imagine a range of speeds of cars such that sometimes the averages speed is greater or lower but over time the average converge to an intermediate speed. As another example, one could imagine a sand dune getting bigger and smaller over time, but eventually the size of the dune settles into an intermediate size. In these examples, students would likely be cuing prior knowledge in which the changing size of dune or changing speeds of cars are relevant. Similar to threshold and periodic motion, convergence to a limit is not widely discussed in the learning sciences literature. However, it is one of the patterns of change and
control discussed in diSessa (2007b) and is relevant to students’ learning of dynamical systems theory.

Similar to the situation with periodic motion and threshold, given limited prior work in the learning sciences, there are not preexisting hypotheses for if or why convergence to a limit would be helpful for students in coming to recognize decentralized causality within these problem contexts. However, from the analysis presented in Chapter 5 of students’ reasoning about birds, sand dunes, and diffusion involving the explanatory pattern of convergence to a limit, I argue that it can be helpful in seeing the decentralized nature of the specific phenomena because it often incorporates an underlying mechanism for why the behavior convergences and these mechanisms often explicitly connect the microscopic and macroscopic levels. For example, in Chapter 5 one student explains that birds’ positions converge to a V-shape because it is easier to fly in formation than out of formation. Thus this student is presenting a hypothesis for an underlying mechanism for birds’ individual behaviors, which may support their understanding of decentralized causality.

Student Generated Explanatory Patterns Final Comments
Before I conclude this chapter it is important to reiterate that these particular explanatory patterns are important because they support students in doing specific moves that have the potential to support this recognition of complex systems and the emergent processes they give rise to. From the prior literature there are some existing hypothesis about what things students can or ideally should do that support this recognition of emergence. As mentioned previously Wilensky and Resnick (1999) discuss the importance of connecting the microscopic and macroscopic levels. Focusing on the mechanistic reasoning is important in scientific reasoning (Koslowski, 1996; Russ et al., 2008; Schauble, 1996), and I argue that specifically focusing on the underlying mechanisms is potentially helpful in understanding the how or why of the specific behaviors associated with decentralized causality. In addition to these two hypotheses, from the analysis presented in Chapter 5, I also have other hypotheses to add to the list. I hypothesize that in many cases students’ explanatory patterns can be altered into being emergent or are altered into the changing composition explanatory pattern which is emergent, sometimes via an emphasis on rate. For each of these six explanatory patterns I have presented specific hypothesis about why each one of them is potentially supportive for students’ reasoning about the decentralized nature of the phenomena.

Conclusion
In this chapter I introduced the specific theoretical machinery that has been developed for the analyses and is based on the Knowledge-in-Pieces family of theoretical perspectives. This mini-theory claims that when students’ generate explanations that capture the decentralized nature of these complex systems their explanations are based on variety of kinds of prior knowledge and specific features of the problem context that influence their understanding of emergence.

Primarily, this is an epistemic theory as one central piece is a sketch of epistemological resources relevant to students’ explanations of complex systems. I focus on students’ prior knowledge and characterizations of that knowledge. I also focus on four features of the problem context that can influence students’ emergent thinking about these phenomena. Throughout this sketch I focused on prior knowledge that is related, and potentially supportive in capturing the emergent nature of the complex phenomena.

This is also a theory of how the epistemic pieces are connected together within the dynamics of generating an explanation. In the second section I focused on the student generated
explanatory patterns. The central idea is that in the moment explanations are constructed based on these epistemological resources and these resources are assembled into the explanatory patterns. Of course students generate all kinds of explanatory patterns, but in this section I focus on the ones that are potentially helpful in the recognition of complex systems and the emergent processes they give rise to. In this way, this is a theory about student generated explanatory patterns about the behavior of complex systems, as based on their prior knowledge with an emphasis on explanations that capture the emergent nature of the complex phenomena.

In subsequent chapters I will be using this analysis machinery. In Chapter 4 I use it to illuminate the small moment-by-moment shifts in individual students’ explanations over a short time period. In Chapter 5 I use this machinery to compare and contrast many students’ explanatory patterns across the seven problem contexts, for example, I compare student generated explanations about the pattern of threshold across sand dunes, traffic jams, birds, fish, viruses, forest fires, and diffusion. Finally, in Chapter 6, rather than focus on the previously discussed explanatory patterns, I instead focus on several indicators of decentralized causality and use the prior knowledge part of this machinery to investigate how students’ prior knowledge supports explanations that are based on decentralized causality but are quite specific to the problem contexts. Thus one theme running through the analysis chapters is about the role of prior knowledge in influencing students’ explanations that capture the emergent nature of these problem contexts.
CHAPTER 3: METHODS

Methodology Overview
In this Chapter I discuss my data collection and analysis methods and then I compare my methodological approach with other related studies that also focus on students learning about complex systems. First, I discuss the scientific content area that was the focus of this study, complex systems. I discuss the domain specific scientific perspective and the complex system perspective on seven problem contexts whose behavior is associated with complex systems: the movement of sand dunes, the formation of traffic jams, fish swimming in schools, the spread of a virus, the spread of a forest fire, birds in flight, and diffusion of water. For example, in this section, I discuss a geologist’s perspective on the movement of sand dunes and a complex system perspective on the same phenomena, illustrating some differences in two perspectives on how this phenomenon works. Also, as part of this section I also discuss some similarities and differences across the seven problem contexts and my rationale in choosing these seven problem contexts. Second, I discuss my clinical interview approach. I discuss the planning process for the interviews and I provide an overview of a typical interview in chronological order. As part of this section I also discuss the kinds of interview questions asked. Third, I discuss the data analysis process in terms of two simultaneous analyses, the knowledge analysis of the knowledge elements students activated when explaining how complex systems work and the indicators analysis of centralized and decentralized causality. Throughout this analysis discussion I attempt to highlight how I enacted general analytical principles in my specific analysis in an attempt to be explicit about the relationship between the theoretical goals of the analysis and the implantation of those goals. Finally, I conclude with a discussion of some similarities and differences between the methods of this study and other methodological approaches used in the literature that also investigate students learning about complex systems.

Seven Problem Contexts
The goal of this section is to provide an overview of the seven phenomena from both a domain-specific scientific perspective and from my perspective of centralized and decentralized causality. While there are many ways to conceptualize these systems, in this section I discuss each problem context from a domain-specific perspective so that the reader has a sense of the various ways that scientists construe these phenomena. I also discuss each phenomenon from the perspective of centralized and decentralized causality, which is the perspective discussed throughout the dissertation.

From the perspective of the scientific field that specialized in any given area (e.g. transportation studies, aeolian processes, forestry, etc.) the important characteristics and attributes of the phenomena is determined by their emphasis and importance to the current state of the art in the field. For example, geologists who specialize in aeolian processes, which is the study of how the wind shapes the surface of the earth, focus on categorizing the different shapes of dunes and how dunes change their shape over time, because they are interested in questions about the evolution of dune types, how one type of dune is transformed into another type of dune.
Researchers who specialize in traffic jams use aggregate statistics about traffic in order to understand factors that contribute to congestion because their goal is reduction of congestion.

From the centralized-decentralized perspective, which was introduced in Chapter 1, all of these seven problem contexts exhibit complex systems behaviors that can be construed through decentralized causality. For any of these problem contexts, the phenomena at a macroscopic level (e.g. sand dune or traffic jam) are determined by the interactions of the subparts, individuals (sand particles or individual cars) at the microscopic level. What is unique about these kinds of systems is that the macro level pattern is decentralized, it occurs without any single controlling factor, these systems are often said to exhibit self-organizational or emergent behavior.

Sand Dunes
In this section I am going to first discuss the geologists perspective on sand dune movement in terms of Newtonian mechanics, and then I will discuss my perspective as a learning scientist, which focuses on centralized versus decentralized causality and their role in explaining emergent phenomena. From the geological perspective, one main mechanism for how wind moves sand is known as saltation. Saltation is the process by which the wind moves sand particles through successive small jumps. When a particle lands it may be ejected or it may collide with another particle resulting in that new particle being ejected. Using Newtonian mechanics each jump can be modeled as a projectile. This process is thought to account for the majority of sand moving up the less steep side of the dune and being deposited on the lee side. Hence dunes often, but not always, move leeward, in the direction of the wind (Pye & Tsoar, 2009). However, there are many types of sand dunes with different shapes and different behaviors. A central research direction emphasizes categorizing these dune shapes and investigating how dunes of one shape change into another shape, for instance, how crescent shaped dunes turn into parabolic shaped dunes (Pye & Tsoar, 2009).

Focusing on the issue of centralized versus decentralized causality, the movement of sand dunes occurs through the local interactions of individual sand particles. The movement of the entire dune (collection of many particles) is determined by the movement of individual particles that act as independent agents with no external cause orchestrating their movement. Each particle has a particular behavior, for example it can join a dune, leave a dune, or be stationary. The macro-level behavior of the entire dune, moving, staying still, or staying in the same location but changing size, is due to the collective behavior of all individual sand particles.

If I were to explain the movement of sand dunes using centralized causality, I might focus on the wind controlling the movement of sand particles, for example a gust of wind blowing all the sand particles simultaneously and moving the sand dune at once. While this idealized explanation might sound implausible, a different version of a centralized explanation that I have seen in the data is that there must be a boulder in the desert, acting as a seed or leader, so that when sand hits the boulder it stops moving and a dune forms at that location. In contrast, I could explain the movement of sand dunes using decentralized causality by assuming that wind moves each sand particle a distinct and random distance independent from surrounding sand particles. In that perspective, the desert is composed of many sand dunes and innumerable sand particles, all acting quasi-independently. Also, within this perspective it becomes irrelevant whether a new dune is composed of the same sand as in the old dune, since all dunes are indistinguishable from one another.
Traffic Jams

The formation and movement of traffic jams is a classic problem context in the learning sciences literature on complex systems (e.g. Resnick, 1996). This topic is interesting because it is relevant to our everyday lives, but it does not align with core academic curricular topics, for instance, physics or biology. First I discuss one perspective on research within transportation studies that emphasize the aggregate statistics of jams with a goal of reducing congestion. Then I discuss my perspective on traffic jams through the lens of centralized and decentralized causality.

Within transportation studies, research uses aggregate statistics in order to analyze and reduce congestion. Information on traffic jams tends to come from governmental reports produced by the US Census, Federal highway administration and Department of Energy. This research focuses on analyzing patterns of relationship between variables that influence congestion, for instance: population size, density of population, population growth, and annual hours of delay per person. Traffic is a complex situation and there are other related factors, such as, concentration of trips during certain times of day, population growth, density of the metropolitan area, and household income growth because it correlates with people’s desire and ability to own private vehicles. The central goal of this research is reduction of congestion. Many approaches have attempted to reduce congestion, usually either market or regulatory driven and usually addressing either supply or demand. For example, building more roads address both supply and is regulatory. Imposing road tolls that are raised during peak hours or charging high taxes on gasoline address demand and is market-orientated. See Downs (2004) and Vanderbilt (2008) for a more detailed discussion of transportation studies research on congestion.

Beyond discussing congestion reduction, a sub-field within transportation studies focuses on incidents and strategies to reduce them. Incidents are defined as “any non-recurring event that causes a reduction of roadway capacity or an abnormal increase in demand” (Downs, 2004, p. 62) and this including accidents, disablements such as flat tires, weather conditions that restrict visibility, and any other event causing slower speeds. Strategies for reducing incidents are varied, but tend to include, improving current roads, coordinating traffic better, providing better information to drivers, educational outreach to prevent driving under the influence, and more rigorous enforcement of existing traffic laws.

I can also explain the formation of traffic jams from the perspective of centralized and decentralized causality. The formation of traffic jams occurs through local interactions of individual cars. The movement of the entire jam, collection of many cars, is determined by the movement of individual cars that act as independent agents with no external cause orchestrating their movement. From a decentralized perspective one can explain traffic jams in regards to each car having its own behavior, speeding up, slowing down, joining or leaving the highway, or stopping. All of these individual behaviors are influenced by other factors including the behavior of the surrounding cars and the motivations of the person driving the car. From a centralized perspective one can explain that a traffic jam is caused by one car having a flat tire or because of rush hour. These explanations sound plausible, but they are attributing the cause of a traffic jam to one single event as opposed to a multifaceted distributed cause.

Fish Swimming in Schools

Similar to the discussion of sand dunes and traffic jams, in this section I am going to first discuss a biologist perspective on fish behavior in schools, and then I will discuss my perspective as a
learning scientist, which focuses on centralized and decentralized causality when explaining this phenomena.

The formation and movement of fish swimming in schools is influenced by four sensory facilities that affect fish’s ability to sense the environment: olfaction, hearing, lateral line, and electricity and magnetism. The following discussion is a summary of Reebs (2001). First, fish olfactory sense comes from specific chemicals sensors. Many fish, such as minnows, have skin cells that contain a substance that when released act as a chemical alarm warning other fish. This chemical is released when the skin of a fish is cut, but it can also be released by the fish rubbing its skin. Second, although fish ears do not contain cochlea, they are able to hear via particle displacement waves or pressure waves. Anatomical features of the fish, such as the swimbladders sense the vibrations through a compressible gas and then transmit that information to the inner ear. Fish also produce sounds by knocking bones together or using swim blades like drums in order to create vibrations. Third, many fish contain a later row of pores, known as a lateral line, which senses patterns of flowing water around the body. This is used to detect the presence of other fish, the presence of physical objects, the presence of surface waves, and the direction of water flow. Finally, there are a few species that generate electric currents around their body; this can be for communication, to perceive changes in near-by objects, or to stun prey. Any of these sensory facilities allow fish to observe changes in their environment and in turn influence their schooling behavior.

Beyond sensory facilities, another important factor is the function of different types of schools. There are advantages and disadvantages for choice of school size and an individual’s position within the school. Bigger schools may provide more protection against predators because there are more eyes to detect predators. Also, schooling behavior increases hydrodynamic efficiency. Another factor is food, larger schools may be advantageous for finding food, but if a school is too large there may be a great deal of competition. Thus there may be an ideal size for schools depending on various factors. From the point of view of an individual, there is some evidence that individuals who appear to be proficient in finding food can act as a leader for other fish who are unaware of the food source. Also, there is some evidence that front, back, and peripheral positions confer different advantages in regards to encountering food and vulnerability to predators.

Overall, there are many ways in which the four sensory factors influence fish behavior and there are a series of advantages and disadvantages for choice of school size and an individual’s position within the school. A general trend is to focus on the sensory facilities and the function of different configurations of individuals. This might be motivated by biologist orientation towards understanding the anatomy of different species of fish.

One can also conceptualize how to explain movement of schools of fish through the centralized-decentralized distinction. Within that perspective, the formation and movement of schools of fish occurs through the local interactions of individual fish. The movement of the entire school, which is collection of many fish, is determined by the movements of individual fish. If explaining the phenomenon through decentralized causality one would focus on individual fish acting as independent agents with no external cause orchestrating their overall movement. Each fish has its own behavior, speeding up, slowing down, and changing directions, all of these behaviors are based surrounding fish and other environmental factors. The macro-level behavior of the entire school, moving a specific direction, growing bigger, getting smaller, or breaking apart is due to the collective behavior of all individual fish. If one were to explain the formation and movement of schools of fish through centralized causality one
would focus on a single leader fish controlling the behavior of all other fish or an external cause. An external cause might be a predatory or an inanimate object, for example, the walls of an aquarium tank or a pile of rocks, any of which can influence the phenomena.

**Birds in Flight**

Similar to the discussion of fish swimming in schools, the biologist perspective on birds emphasizes the sensory facilities. The centralized-decentralized perspective emphasizes the relationship between the movement of individuals and the macro level behavior and how the macro level phenomena emerges from the micro-level interactions. Below I discuss both of these perspectives.

Among researchers who study birds, there is an emphasis on senses and bird navigation. Specifically, a central research direction focuses on understanding how birds navigate and the role of magnetism, gravity, smell, and sound in navigation. Although this literature tends to not focus on why birds fly in a V-shaped formation, answers to this question about why birds fly in a V-shape formation focus energy conservation or ways to facilitate orientation and communication. The importance of either of these factors seems to vary depending on the length of the migration. Also, another relevant variables is that the individual bird that flies in the position that is at the apex of the V, varies over time as the birds take turns flying in the apex position, but the exact factors influencing this change in position are unknown (Batt, 2007).

From the centralized perspective there would be a single leader bird instructing all other birds in a specific position or a single external causing the particular arrangement, for instance, a predator. From the decentralized perspective the birds fly in a flock because of the local interactions between individual birds. The movement of a V-shape flock of birds is a complex process as it is determined by the individual actions of each bird, which acts independently. The apparent macro-level change, such as a flock forming, turning, or falling apart is due to the collective behavior of all individual birds.

**Spread of a Virus**

A biological and medical perspective on the spread of viruses focuses on a variety of dimensions in terms of how the virus spread at the microbial level, how it spread from human to human, and which viruses are more or less harmful to humans. The centralized-decentralized perspective focuses on local interactions between individual people resulting in the spread of a virus.

Viruses are everywhere; they are the most numerous microbes on earth, and despite common perceptions to the contrary, very few viruses are harmful to humans but research on viruses emphasizes issues influencing human health. Viruses contain a protein surrounding some genetic material, either RNA or DNA. Virus are considered to be very adaptable because of their ability to mutate quickly and spread rapidly. There are many viruses that are potentially harmful to humans and they spread in a variety of ways with varying levels of consequences. Given a desire to identify, track, and prevent outbreaks of harmful viruses, there is a focus on understanding how specific microbes in animals evolve to infect humans as many viruses that are harmful to human have origins in animal populations. Viruses spread in a variety of ways, some viruses only spread from animals to humans, others viruses spread from human to human, and others are airborne. Some of the central variables of interest to researchers trying to understand and contain the spread of viruses that influence human health include the transmission time and human response time because some viruses are lethal while others are relatively harmless. For a non-technical introduction to the spread of viruses as related to human health see Crawford (2011) and Wolfe (2011).
I can also conceptualize how to explain the spread of viruses through the centralized-decentralized distinction. From the decentralized perspective, the spread of a virus is determined by the movements and interactions of individuals that act independently with no external cause orchestrating their movement. Each person has his or her own behavior. The macro-level spread, such as moving from one town to another town is due to the collective behavior of all individual people. From a centralized perspective I could explain this phenomena in terms of a single ill individual spreading the virus throughout the population.

Spread of a Forest Fire
In this section I discuss a forestry perspective on forest fires and the centralized-decentralized perspective on forest fires. The forestry perspective focuses on the factors that influence fires, the fires behavior, and the effects of the fire on the surrounding environment with a goal of predicting and controlling hazard. In comparison, the centralized-decentralized perspective focuses on the relationship between individuals, such as individual trees on fire, and how that contributes to the macro level spread of the fire.

A forestry perspective views forest fires as a naturally occurring phenomenon, and research in this area addresses variables influencing forest fires with a goal of predicting and controlling danger. Forest fires are primarily influenced by fuel, topology, and weather. There are three main types of fuel, ground fuel such as tree roots and peat, surface fuel such as dead leaves, downed logs, and grasses, and aerial fuel, such as tree branches and shrubs. In addition fire are influenced by tree susceptibility, which is determined by factors such as: temperature of the tree, age of the tree, character (thickness) of the bark, and season/growth cycle. Topology also plays an important role as it relates to air moisture and movement because the slope influences the spread of the fire. Finally, seasonal weather patterns and daily variation also influence fires. Beyond investigating the factors that influence fires, forestry researchers focus on fire behavior, fires have several phases, ignition, build up, propagation, and decline, and these phases have a bearing on fire control and suppression. However, a challenge is that each fire is unique, often said to have it’s own “personality.” From the forestry perspective, all of these details are important because they are used to develop a rating system for predictability of danger and they are used to develop specific procedures for forest fire detection, suppression, control, hazard reduction, and policy. A more extended discussion of these ideas is presented in Brown and Davis (1973).

From the decentralized perspective, the spread of a fire occurs through local interactions, for instance, between individual leaves or trees. The spread of a fire is determined by the movements and interactions of individuals that act independently with no external cause orchestrating their movement. Overall, the macro-level spread of a fire moving across a large area is due to the collective behavior of the fire spreading across many leaves or trees. Notice that from this perspective one could include information about the topology, types of fuel, fire personality and fire danger or one could minimize this information and view the spread of fire as a process not dependent on these variables. From a centralized perspective, one might view the spread of a fire as based on a single causal factor, such as a lightening strike or a smoldering cigarette butt.

Diffusion of Water
The physicist perspective on diffusion emphasizes the random walk of particles. At the molecular level the molecules within the two liquids are in constant motion and there is a random
distribution of the molecules speeds due to their kinetic energy. Overtime a uniform mixture is produced as molecules from both liquids spread out in a random and uniform manner.

From a centralized perspective there would be a single causal factor controlling all the molecules motion. From a decentralized perspective the molecules each have their own speed and there are local interactions between molecules. The diffusion of water is a complex process as it is determined by the individual actions of molecule. The apparent macro-level change in the color of the liquid is due to the collective behavior of all molecules motion.

While there are many ways to conceptualize these systems, in summary, in this section I have aimed to provide an overview of the seven phenomena from both a domain-specific scientific perspective and from my perspective of centralized and decentralized causality.

Criteria for Problem Contexts
Now that the reader has a sense of the seven problem contexts, in this section I present a discussion of my five criteria used in choosing these problem contexts. There are innumerable problem contexts I could have chosen to use when investigating students’ explanations and learning about complex systems. In this section I discuss several criteria that I used when evaluating which contexts to include in this dissertation. These criteria were not applied in a rigorous manner. Instead this list should be viewed as a rough guide to the factors influencing my choice. Generally these criteria are relevant to the Knowledge in Pieces theoretical commitments, and these criteria are relevant to the literature on students learning about complex systems. Below I discuss five criteria: productive and visible levels, easily accessible knowledge resources, a lack of rigid rules controlling the behavior, strong vocabulary, and a tendency for anthropomorphization.

**Productive and visible levels:** First, I aimed for contexts in which it is very likely that student will be able and willing to discuss the particular phenomena at both the agent (microscopic) and aggregate (macroscopic) levels. In other words, I wanted both levels to be potentially salient, productive for students’ understanding, and potentially visible to the students. For example, in the sand dune context the agent level is the sand particles and the aggregate level is the entire dune; the reason why this context is productive is that students have prior experiences with both levels. From playing with sand and dirt I expect students to have an intuitive understanding of granular flow so that they have a sense of the behavior at both levels. A hypothesis is that for electricity and diffusion, the micro level of the water molecules and electrons is not as visible to the students. This issue, of the micro level not being necessarily visible is discussed elsewhere. For example, Hmelo-Silver, Marathe and Liu, (2007) discuss that many aspects of the systems are not necessarily accessible with unaided perception, and to address this problem they have used the Structure-Function-Behavior conceptual representation to make all aspects of the system more accessible. Similarly, others have dealt with this challenge by using computational tools such as agent-based models where one of the affordances is making the less visible agent level more accessible (e.g. Sengupta & Wilensky, 2009). For this dissertation, my general goal has been to choose problem contexts where many aspects of the systems are visible. This goal of mine is similar to the heuristic used in Penner (2000) where the author chose to interview students about emergence in the context of the cellular automaton game known as Life because it makes both levels visible to students. In the cellular automaton game of Life game there is a two-dimension grid with black and white cells and a series of predetermined rules that control when cells switch color (modeling cellular birth and death). As will be discussed below, having explicit rules can help connect levels so that they are all are visible to the student.
In my choice of problem context, there was one case of a strategic exception to the criteria of having both levels be potentially productive and visible for students, diffusion of water. For diffusion of water, I expect that students might not find the molecular level of water visible, thus suggesting that perhaps diffusion should not be included in the dissertation. However, I also have a competing heuristic of wanting to include a range of problem contexts covering both situations in which I expect students to have difficulties and situations in which I do not expect students to have difficulties. Diffusion of water is one of the problem contexts in which I might expect students to have difficulties, based on existing research documenting students’ difficulties with diffusion (e.g. Chi, 2005; Slotta & Chi, 2006). Thus even though I expect students to not find the molecular level visible, I included this problem context because I wanted to insure coverage of problem contexts in which I do and do not expect students to have difficulties, and from prior research I expect students to have difficulties with diffusion.

Easily accessible knowledge resources: Another criteria in choosing problem contexts is that I want to include ones where students do and do not have difficulties, more specifically I aimed to pick problem contexts where students can access many knowledge resources. I am aiming to avoid problem contexts in which students are limited in the knowledge resources that are accessible. This criterion is influenced by the practicalities of clinical interviewing and KiP principles. During the interviews, I would like students to be able to discuss the problem contexts for upwards of 10 minutes. I am aiming to avoid situations in which students say, “I don’t know anything about that” and this results in the conversation not progressing. For this reason I have picked problem contexts that students might have interacted with or experienced in their everyday lives as it increases the likelihood of students being able to access many knowledge resources. This choice is also influenced by the Knowledge in Pieces principle of obviousness (diSessa, 1993). This principle suggests that there are familiar and everyday physical events that need explanations and where p-prims are appropriate. Hence, I was aiming to choose situations that are familiar everyday events, for instance traffic jams, forest fires, sand dunes, and the movement of schools of fish. Traffic jams are an obvious case. Many people experience them on a daily basis. Even for other contexts like forest fires, that might initially appear to be removed from familiar events, I expect that students have spent time outdoors in locations where there are trees and I expect students to be familiar with fire from everyday experiences such as birthday candles and pilot lights. Forest fires are also discussed in the media, especially in places like California that are dry, which increases students’ familiarity with the phenomenon. For sand dune context I expected that students have seen sand dunes at the beach or in the desert and many students have seen pictures of sand dunes. For schools of fish I am expecting that students have seen schools of fish in aquariums, and for birds I am expecting that students have noticed birds flying in flocks. In my criteria for choosing problem contexts, I am choosing ones where I expect students to have some familiarity and be able to access relevant knowledge resources.

As my goal has been to choose problem contexts where students can access lots of knowledge resources, there is a related but slight different goal in the literature of choosing problem contexts where specialized domain-specific knowledge is not needed. Choosing problem contexts where specialized domain-specific knowledge is not needed is a reasonable goal; Jacobson (2001) has been critiqued by Levy and Wilensky (2008) for choosing problem contexts, such as evolutionary processes, where some students are not able to access necessary domain specific knowledge. Given a similar motivation of avoiding problem context where specialized knowledge is needed, Penner (2000) investigated the emergence in a cellular
automaton game known as Life. As mentioned before, in this game there is a two-dimension grid with black and white cells and a series of predetermined rules that control when cells switch color (modeling cellular birth and death). The advantage of this problem context is that the rules are explicit and do not rely on prior domain specific technical knowledge. However, a potential drawback on this problem context is that it is artificially constructed and thus students might find some of their everyday intuitions not as relevant. Also, in this context the rules are explicit. This explicitness is advantageous as the underlying logic is clear. However, a potential drawback of this problem context does not as easily provide opportunities for students to figure out what prior knowledge is relevant. Compare the explicitness of this problem context to an open-ended contexts like sand dunes and traffic jams where students would need to figure out the relationships and potential rules for themselves. Thus there is a spectrum of approaches about what kind of prior knowledge is optimal for research on students’ learning and instruction of complex systems. In this study I take the approach of choosing problem contexts where I hypothesize that students can draw on relevant intuitions and, the students need to figure out what prior knowledge is relevant rather than have me tell them which variables are relevant.

A lack of rigid rules controlling the behavior: Continuing with my criteria for choosing problem contexts where students can access lots of knowledge resources, I also have a third and related criterion of avoiding problem contexts where there are strict rules. Although there are advantages and disadvantages of problem contexts where there are rules controlling the behavior. For example, many of the NetLogo simulations, including those discussed in Sengupta and Wilensky (2009) and Wilensky and Reisman (2006) are built based on a set of pre-determined rules that control the behavior. There are advantages to choosing systems with well-defined rules as often those rules can be incorporated into a digital computational medium. Also, once students have an understanding of the rules they may be able to reason from them in a predictable and clear manner. This was apparent in Penner (2000) when investigating students’ learning through the cellular automaton game known as Life. However, as should be apparent from the previous discussion, there are no clear rules that completely define the scientific behavior of any of these phenomena, for any of these phenomena there are many ways one can conceptualize the behavior. Thus I claim that providing students with a set of rules to reason from can have both advantages and disadvantages: advantages include supporting predictability and clarity in students reasoning, and disadvantages include supporting students reasoning about a limited number of variables or perhaps not the central or important variables. Given the goals of this dissertation, I am interested in students’ prior knowledge, and the choices they make when cueing different prior knowledge resources. I hypothesize that it might constrain students’ prior knowledge if I were to provide them with a predetermined list of rules. In making this choice I am using the Knowledge in Pieces principle of impenetrability (diSessa, 1993), which suggests that if people are satisfied making an explanation by simply asserting a description without a complicated causal relationship, this may be an indication of a p-prim. In choosing problem contexts I was focusing on ones where students might turn to p-prim based explanation, rather than pre-dominantly reason from pre-determined rules.

Strong vocabulary: A fourth criterion when choosing problem contexts is that I looked for ones where I expected students to be able to access robust verbal descriptions and where students might engage in some mental modeling activities. This is based on the principle of a strong vocabulary (diSessa, 1993). This principle suggests that p-prims are often found in areas where students have rich descriptions and rich representational capabilities to represent their
understanding. This criterion is relevant to the interviews as I asked follow up questions that might support mental modeling activities.

**Anthropomorphization:** The final and fifth criterion when choosing problem contexts is that I was aiming for a spectrum of examples along the dimension of whether or not students activate psychological resources or have a tendency to anthropomorphize the agent. I wanted some problem contexts in which I though students were likely to anthropomorphize the agents and some problem contexts where I thought this was unlikely. My hypothesis of this spectrum is as follows: sand dunes, diffusion, and forest fires (little tendency to anthropomorphize), birds and fish (intermediate tendency to anthropomorphize), traffic jams and viruses (strong tendency for human-based reasoning). This spectrum is based on the results of Carey (1985), Inagaki and Hatano (1987), and Inagaki and Sugiyama, (1988), whose results suggest that students may be more likely to anthropomorphize birds and fish than trees or water molecules because the former are animals and more similar to humans. For the two problem contexts that involve humans, traffic jams and viruses, I expect an emphasis on students activating intuitions about psychological resources.

Overall, in this section I discussed five criteria that influenced my selection of problem contexts: productive and visible levels, easily accessible knowledge resources, rules, strong vocabulary, and anthropomorphization. When discussing these criteria I also discussed the reason for a given criteria, as influenced by my theoretical commitments to Knowledge in Pieces along with the literature on students learning about complex systems. This list of criteria should not be viewed as rigid, as discussed above, sometimes there were conflicting criteria. The main purpose of this list is to illustrate to the reader that my choice of problem context was not idiosyncratic, and to illustrate how this list of criteria relates to other methodological choices including my theoretical perspective.

**Clinical Interview**

I take clinical interviews to be a form of social interaction, which, as discussed in diSessa (2007c), goes along with a particular set of goals, roles, expectations, and assumptions that are describe below. The approach to clinical interviewing used in this study is also similar to the generative approach described in Clement (2000), which leads to interpretative analyses. As will be discussed in subsequent sections, this is an exploratory study as in the analysis I generate new observational categories of knowledge and new model elements about the relationship between prior knowledge and problem contexts. The goal has been to work towards a new theoretical model and descriptions of processes of changing explanations, rather than an approach that leads to coded analyses and empirical findings that can be experimentally tested for particular hypotheses. These goals, expectations, and assumptions guided my planning and recruitment of participants along with particulars of the interview, for instance, the interview questions. Elsewhere in the literature a variety of researchers including Ginsburg (1997), Clement (2000), and diSessa (2007c) have attempted to defend this technique against various critiques; I direct the interested reader to those papers for a discussion of these critiques and counter-critiques. Below I focus on describing my methodological approach.

**Goals, Expectations, and Assumptions**

My overarching goals when planning and carrying out these interviews were to set up a situation in which I could probe students thinking about phenomena whose behavior is aligned with complex systems. These interviews were exploratory in nature. I did not have set hypotheses to prove or disprove. I was not evaluating their performance. My goal was to investigate ranges of
ways students might think about these phenomena. I wanted the students to make sense of the particular phenomena. I was and continue to work under an assumption that problem contexts, such as sand dunes are phenomena that students can make sense of, and I assume that in this setting I can probe students thinking, per se.

Next I discuss some more specific goals, which pertained to various points along the planning and carrying out of the interview spectrum, and some expectations about the interaction—all of which are meant to support the larger goal of probing students thinking about phenomena.

At the beginning of the interview I do my best to set the students at ease and make my expectations clear. I expect that it may take students a little while to settle into the interview situation. To ease this transition I began all interviews with a warm up activity, which is described in the following section and involves the surprising motion of a wooden disk with uneven weight. Possibly the student may initially expect the interviewer to be in a position of authority. For this reason it is extremely important that the interview is framed in such a way that the student feels comfortable expressing their ideas and exploring the phenomena. For example, I begin the interviews telling the student a bit about my goal and I say something about these questions not having a right or wrong answer and the fact that I am interested in how they think about the phenomena. I also assume that they might be a bit nervous about the interaction. They might be curious about the setting, what is this place? Why do I do this? What is expected of them? I do my best to address many of these issues at the very beginning as clearly and quickly as possible. My goals in doing this are to arrange the interaction in such a way that students are comfortable and willing to engage with the problem contexts and reveal their thinking with ease.

I bring with me expectations and assumptions about differences across individual students, thus the interviews are deliberately non-standardized in certain ways as I treat each student as an individual. I expect that students will have varying levels of comfort and ease, varying levels of willingness to talk, and varying background experiences and prior knowledge. For this reason I allowed some flexibility in terms of the length of our discussion about each problem context and the length of the entire interview. Also, this is a reason that the number of turns I take speaking varies across the interviews. Depending on how comfortable students appeared during the interviews I gave more or less encouragement. In some cases where the students were comfortable with the material and setting, I would let them talk for a couple minutes without me interrupting them. However, in other cases in which the student appeared unsure I provided more frequent encouragement in the form of phrases such as “uhh,” “okay,” and “I see.” This approach is in agreement with what Ginsburg (1997) describes as literally treating each child as different, which then necessities a clinical interview that is deliberately non-standardized. I view these differences as a necessary complexity to be accepted and managed by listening closely to individual students and following their lead.

One specific way in which I follow their lead is by giving students freedom and flexibility to define the boundaries around the phenomena. After presenting them with the initial story (see Table E), I often purposely gave students a bit of space to explore the question before prompting them with additional follow-up questions. For example, often students would ask if earthquakes or water erosion were relevant to the sand dune moving question, I would do my best to not answer and instead let them decide what information is and is not relevant. Often after briefly pondering that direction they would realize that earthquakes and water erosion are not good fits to explain sand dunes movement and then move on to another topic, usually the
wind. In this way by giving the students space they were able to define the boundaries without me defining boundaries for them. I did my best to always be straightforward and not ask trick questions. The couple of times when I got a sense that a student thought that I was asking a trick question, I did my best to persuade them immediately that it was not a trick question and be clear and straightforward. For example, in the Laurel interview, after I had presented the initial sand dune story she was a bit unsure about the question and said, “I feel like it’s, it’s one of those puzzle game where you have to like ask, you know those, where someone tells a story and you have to ask all the questions to find out… It does like, matter if it’s half a mile south?... Or it doesn’t?” I responded, “no it doesn't matter that it's half a mile south and it doesn't matter exactly how many months it is…this isn't meant to be a trick question. Or a puzzle…No, it's not a math problem. Not a numerical problem.” In these ways I worked to give students authority and responsibility to choose intellectual directions while providing some basic constrains.

During the in-progress interview I make assumptions about the students’ thinking about the task and goals for the interaction. I assume that the students’ primary goals in this setting are the same as in another naturally occurring activity—to make sense of a problematic situation as best one can (diSessa, 2007c). Under this assumption a clinical interview is meant to be an extension of a naturally occurring activity, not an exotic laboratory based activity.

Within these goals and assumptions, there were many successful interviews, and there are also some less successful interviews. In successful interviews the student would often do some of following: be curious about the phenomena, be willing and able to engage with it, explore, and make judgments for themselves. There were many ways in which an interview was successful. The most common kind of unsuccessful interview is one in which I could not make sense of or trace the students thinking despite my best efforts during the interview.

In summary, in the above section I have tried to describe my goals, expectations, and assumptions in carrying out these interviews in which I aim to probe students thinking. I worked for these interviews to serve as interactions where the students were at ease. I also view these interviews as a type of naturally occurring activity and I also deliberately conducted the interviews in a non-standardized way, thus each participant was treated as an individual. I would follow their lead when providing flexibility for them to choose relevant intellectual directions. In making these choices I am recognizing students’ goals for the interview. These interviews do not comprise a monolithic group; some were more or less successful based on my central goal of supporting students in making sense of the phenomena. Despite these differences the purpose of these interviews is so that I can probe the students’ thinking.

**Planning for Interviews**

I planned for the interviews by conducting nine pilot interviews with fellow Ph.D. students who at the time were enrolled in various education programs. During these pilot interviews I refined the problem contexts to be discussed and the interview questions. In doing this I was aiming to prepare myself to be able to ask better and more informative questions during the final interviews and to be better prepared to make sense of students’ thinking.

During the planning process I refined the particular problem contexts, some problem contexts were dropped and some were added. I also refined my protocol and interview questions. For example, an initial question was, “how do sand dunes move in the desert?” This then turned into a story about a sand dune moving in the desert. The initial version of the story did not mention a GPS unit and one student got distracting thinking that perhaps the main character in the story was lost in the desert. For this reason the sand dune problem context was eventually refined to the sand dune story presented in Table E. In making these choices about the sand dune
story I was narrowing the bounds of the phenomena to be explained, and I was doing this in a particular way in which I aimed for the students to focus on the mechanisms of sand dunes moving as opposed to things were not as relevant. For the other problem context, I worked to develop a story that was both parallel to the sand dune story and also focused on the details of the particular problem context in ways that I hoped would be clear and direct. All of these stories are in Table E. Another way in which the protocol was refined is that an initial problem context was dropped, that problem context was about moths changing color over successive generations. Preliminary interviews suggested that in this problem context students found evolutionary issues to be very salient and there was mention of several common evolution based alternative conceptions while the more emergent aspects of the phenomena were not viewed as relevant. For these reasons the moths question seemed not optimal and it was dropped.

Motivation for Choice of Participants
As this was an exploratory study, participants were included who had a variety of backgrounds. This was motivated by both assumptions about commonalities and differences across the participants, and this was motivated by an analysis goal of comparing explanations across participants. In terms of the differences, one motivation for this choice was an interest in how students with access to different knowledge resources would use their respective knowledge resources to explain and understand these systems. For example, I expected students who have backgrounds in physics that have been exposed to formal explanations of diffusion to have different knowledge resources to access about this topic than students who have not been exposed to formal physics. In regards to the commonalities, one motivation was a sense that for many of these topics, such as forest fires and sand dunes, it was expected that none of the students would have learned about these topics in school and thus students reasoning about these topics could be considered as examples of them reasoning about something that is new to them. I was aiming to see how students with varying academic backgrounds would all reason about something new to them. The aim was to investigate how students with different academic backgrounds activate both different and similar knowledge resources when reasoning about something new, rather than when reasoning about something that they have previously extensively considered. Finally, another motivation for this choice of participants with varying backgrounds was an analytic interest in comparing explanations and understandings across students with access to various prior knowledge resources. Among students with different backgrounds, do their explanations reflect an understanding of emergence in similar or different ways? For all of these reasons, participants were recruited with a variety of academic backgrounds from high school through Ph.D. students.

Recruitment and Participants
In the final study there were 8th-12th graders, undergraduates majoring in physics, a masters credential student in mathematics education, and Ph.D. students in physics and astronomy. There were two rounds of interviews, one round was during the summer of 2010 and the other round was during the summer of 2011. The participants had a variety of academic backgrounds, see Table C for the particulars of each students’ background. For each student an appropriate pseudonym is used.

Given that the participants have different academic backgrounds, they were recruited through different approaches. Most of the 8th-12th graders were recruited through a summer academic program for motivated students. I made announcements at the student and parent orientation at the beginning of the summer. There were also notices posted in the weekly
In addition, a few students were recruited through a nearby private middle school by a notice that was posted in their electronic newsletter. The undergraduates majoring in physics were recruited through emails forwarded by a member of the physics department staff to a list-serve of undergrad physics majors. Similarly, the Ph.D. students in physics and astronomy were also recruited through emails forwarded by department staff to list-serves of Ph.D. students.

<table>
<thead>
<tr>
<th>Name</th>
<th>Academic Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joshua</td>
<td>8th grade</td>
</tr>
<tr>
<td>Michael</td>
<td>10th grade</td>
</tr>
<tr>
<td>Raj</td>
<td>10th grade</td>
</tr>
<tr>
<td>Morgan</td>
<td>10th grade</td>
</tr>
<tr>
<td>Lily</td>
<td>11th grade</td>
</tr>
<tr>
<td>Priyasha</td>
<td>11th grade</td>
</tr>
<tr>
<td>Katarina</td>
<td>11th grade</td>
</tr>
<tr>
<td>Song-Hee</td>
<td>12th grade</td>
</tr>
<tr>
<td>Laurel</td>
<td>Masters/teaching credential student in mathematics education</td>
</tr>
<tr>
<td>Samuel</td>
<td>Undergraduate physics major</td>
</tr>
<tr>
<td>Shannon</td>
<td>Graduate student in physics</td>
</tr>
<tr>
<td>Keaton</td>
<td>Graduate student in physics</td>
</tr>
<tr>
<td>Drew</td>
<td>Graduate student in physics</td>
</tr>
<tr>
<td>Damien</td>
<td>Graduate student in physics</td>
</tr>
<tr>
<td>Kyle</td>
<td>Graduate student in physics</td>
</tr>
<tr>
<td>Nathan</td>
<td>Graduate student in astronomy</td>
</tr>
<tr>
<td>Brandon</td>
<td>Graduate student in physics</td>
</tr>
<tr>
<td>Leah</td>
<td>Graduate student in physics</td>
</tr>
<tr>
<td>Hailey</td>
<td>Graduate student in astronomy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Academic Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erik</td>
<td>8th grade</td>
</tr>
<tr>
<td>Cara</td>
<td>8th grade</td>
</tr>
<tr>
<td>Abhi</td>
<td>9th grade</td>
</tr>
<tr>
<td>Neil</td>
<td>9th grade</td>
</tr>
<tr>
<td>Sarabeth</td>
<td>11th grade</td>
</tr>
<tr>
<td>Lena</td>
<td>12th grade</td>
</tr>
<tr>
<td>Melissa</td>
<td>Undergraduate physics major</td>
</tr>
<tr>
<td>Antonia</td>
<td>Undergraduate physics major</td>
</tr>
<tr>
<td>Blake</td>
<td>Undergraduate physics major</td>
</tr>
<tr>
<td>Ravi</td>
<td>Undergraduate physics major</td>
</tr>
<tr>
<td>Stephen</td>
<td>Graduate student in physics</td>
</tr>
<tr>
<td>Jared</td>
<td>Graduate student in physics</td>
</tr>
</tbody>
</table>

Table C: List of participants arranged by academic background and interviewing round.

3 all names are pseudonyms
Chronological Narrative of the Interview
The overarching trajectory of the interviews involved a series of discussions about problem context whose behavior is associated with complex systems. As will be discussed below, generally the students in round one were asked about two complex system problem context and the students in round two were asked about seven complex system problem contexts. Each problem context was introduced through a narrative story (see Table E). In this section I am going to chronologically present a narration of what happened during the interviews.

At the beginning of the interview I introduced the students to the setting and the plan. Specifically, this would involve me first introducing myself, thank them for coming, and collect the IRB forms. Then I would show them the equipment (video camera on a tripod, external microphone, and back-up digital audio recorder). Next, with their permission, I would turn on the equipment. Then, I would then tell them a bit about my background, my goals for the interview, the things I wanted to talk about, and that there is no single correct answer, just many ways to think about the phenomena. I would distinguish this setting from a typical classroom as that I cared most about their thinking and understanding, I was not grading or otherwise evaluating them.

Then I would ask the student a couple introductory questions about their background. For the 8th-12th graders, many of whom were in the summer academic program I asked them about current summer courses and prior high school courses in math and science. I also sometimes asked about what topics they studied in the prior academic years courses and what they planned on taking in the fall. For the university students majoring in physics, the master credential student, and the Ph.D. students, I asked about their current academic trajectory, what courses they had take or planned to take, and if relevant, their area of research.

Each problem context was discussed for a short while and then I would switch to a new problem context based on cues from the students about when they were ready. We would spend anywhere from 3 to 25 minutes discussing a particular behavior and then move onto a different behavior. I would switch when I got a sense from the student, based on various cues that they had exhausted discussing that topic. For example, at the end of the traffic jam discussion with Raj he said, “that’s the only thing I can think of.” The entire interview took anywhere from 45 minutes to an hour and a half.

For the first question, which was a warm up question, I would ask students about the behavior of an uneven wooden disk, discussed below. At this point I would also offer paper and markers in case they wanted to draw anything while talking. The wooden disk is about 20 inches in diameter and there is a piece of lead, approximately three inches in diameter embedded off center. Rather than roll in a uniform manner, the disk exhibits a damped oscillatory motion because of the uneven distribution of weight. Student often found the behavior surprising as one expects disks to roll in only one direction once released, and this disk rolls in two directions once released. For this disk there is a turn-around point that is not a point of equilibrium. I would place the disk on a wooden ramp (with minimal slipping) in order to demonstrate the motion and then encourage the student to play with it. Sometimes we would vary the height of the ramp (using large books) and vary the starting position of the disk. Meanwhile I would ask students to explain the behavior. I asked questions such as: Why does the disk go back and forth? Why it stops moving? How does it motion change when the ramp is raised? I generally found that the wooden disk was a good warm up activity given that the behavior was surprising and it involved something tangible to interact with.

As mentioned previously, there were two rounds of interviews. In both rounds the
wooden disk was used as a warm up question, but the subsequent complex systems questions were slightly different. As this is an exploratory study with a focus on students’ explanations, there was an evolution in specific questions as I worked to find appropriate questions given the analysis goals. In the first round of interviews I was interested in students’ explanations about both topics within complex systems and other phenomena in physics. During that round I asked students about two complex systems, sand dunes and traffic jams, along with other questions such as rayleigh scattering, the resonance created by sound in a wine glass, thermal heating, planetary gravity, and others. These other questions are listed in Table D under the heading, “other topics.” During the second round of interviews I found the two complex systems questions, sand dunes and traffic jams to be valuable, and in the second round of interviews I added five additional complex systems questions and dropped the other questions, with the exception of the wooden disk question, which was the warm up question for all interviews.

In this section I am going to more specifically discuss the sequence of the interview questions. Following the initial warm up questions, students were asked about a series of problem contexts, as discussed previously, whose behavior is associated with complex systems. Although not all students were asked about the same problem contexts, there is a general pattern that applies to the majority of the interviews, with the main exception being the case of Sarabeth. Sarabeth was one of the first interviews done in round two and I asked her about an additional complex system problem context that was subsequently dropped, changing color of moths. For round one, students were generally asked about sand dunes and traffic jams in a counterbalanced sequence, there were three exceptions for cases in which students were only asked about one problem context (Brandon, Joshua, and Laurel). These three interview cases occurred early in the data collection before I had added the traffic jam question to the protocol. For round two, students were first asked about either the sand dune or traffic jam problem context, then the other problem context, and following that, the remaining five problem contexts through one of five sequential ordering patterns of the remaining problem contexts. Overall roughly similar numbers of students were asked about each problem context, for instance, birds, fish, forest fires, diffusion, and viruses, in the third, fourth, fifth, sixth, and seventh places. The rationale for this was two fold. First, given the choice of adding five more problem contexts in round two and a desire to try and maintain some similarities in question order across the two rounds of data collection it seemed pertinent to start the interviews in the second round with the same question order as the interviews in the first round. Second, given the relatively small expected number of interviews for round two and the relative large number of interviews that would be required for complete counterbalancing of the five additional questions, the following question order was chosen as a compromise. Overall, the goal was to keep the two rounds of data collection parallel in their questioning as much as possible given the differences in questions. Two exceptions to this pattern in round two were for cases in which we did not get to the last one of two problem contexts due to timing constraints (Blake and Lena). The chronological ordering of the seven questions for each one of the students is shown in Table D.

<table>
<thead>
<tr>
<th>Student</th>
<th>Chronological Order of Interview Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ravi</td>
<td>Wooden Disk</td>
</tr>
<tr>
<td>Erik</td>
<td>Wooden Disk</td>
</tr>
<tr>
<td>Blake</td>
<td>Wooden Disk</td>
</tr>
<tr>
<td>First Name</td>
<td>Last Name</td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Stephen</td>
<td>Wooden</td>
</tr>
<tr>
<td>Jared</td>
<td>Wooden</td>
</tr>
<tr>
<td>Lena</td>
<td>Wooden</td>
</tr>
<tr>
<td>Cara</td>
<td>Wooden</td>
</tr>
<tr>
<td>Neil</td>
<td>Wooden</td>
</tr>
<tr>
<td>Antonio</td>
<td>Wooden</td>
</tr>
<tr>
<td>Melissa</td>
<td>Wooden</td>
</tr>
<tr>
<td>Abhi</td>
<td>Wooden</td>
</tr>
<tr>
<td>Sarabeth</td>
<td>Wooden</td>
</tr>
<tr>
<td>Samuel</td>
<td>Wooden</td>
</tr>
<tr>
<td>Nathan</td>
<td>Wooden</td>
</tr>
<tr>
<td>Brandon</td>
<td>Wooden</td>
</tr>
<tr>
<td>Keaton</td>
<td>Wooden</td>
</tr>
<tr>
<td>Leah</td>
<td>Wooden</td>
</tr>
<tr>
<td>Kyle</td>
<td>Wooden</td>
</tr>
<tr>
<td>Shannon</td>
<td>Wooden</td>
</tr>
<tr>
<td>Hailey</td>
<td>Wooden</td>
</tr>
<tr>
<td>Drew</td>
<td>Wooden</td>
</tr>
<tr>
<td>Damien</td>
<td>Wooden</td>
</tr>
<tr>
<td>Lily</td>
<td>Wooden</td>
</tr>
<tr>
<td>Song-Hee</td>
<td>Wooden</td>
</tr>
<tr>
<td>Raj</td>
<td>Wooden</td>
</tr>
<tr>
<td>Priyasha</td>
<td>Wooden</td>
</tr>
<tr>
<td>Morgan</td>
<td>Wooden</td>
</tr>
<tr>
<td>Michael</td>
<td>Wooden</td>
</tr>
<tr>
<td>Katarina</td>
<td>Wooden</td>
</tr>
<tr>
<td>Joshua</td>
<td>Wooden</td>
</tr>
</tbody>
</table>
Table D: Chronological ordered list of interview questions by participants.

As previously mentioned, for each problem context, it was introduced to the students through a story about the behavior. These stories were meant to focus the student on the particular behavior and the mechanisms that cause this behavior. Part of the reason to use these stories was to set up a focus on the specific mechanism and to dissuade a focus on intellectual directions that were not central to this focus. These questions were designed precisely to be relatively clear examples of a complex system, and these questions were designed to be ones in which students might be inclined to cue knowledge resources about the underlying mechanism and possibly then be able to bootstrap themselves towards emergence. The stories for each of the seven problem contexts can be seen in Table E. Notice some parallels between the narratives, for each story, the person in question is observing the phenomena from a bystander perspective.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Introductory Story</th>
</tr>
</thead>
<tbody>
<tr>
<td>The movement of sand dunes</td>
<td>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 same point and you notice that the permanent marker, the flagpole, is still in the exact same place where you left it, and your 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?&quot;</td>
</tr>
<tr>
<td>The formation of traffic jams</td>
<td>Say you're on one side of a big highway, say 980 or 880 or one of those big interstate highways. You're watching all the cars go by. Sometimes the cars are going faster and sometimes the cars are going slower and sometimes you see a traffic jam form. Why is that? Why does a traffic jam form?</td>
</tr>
<tr>
<td>Birds in flight changing directions</td>
<td>Say you are outside in a park and you see a flock of birds fly overhead. You watch all the birds fly overhead. You notice the birds are all flying north in a V-shaped formation. Then a couple minutes later you notice that all the birds are flying east. How did the flock of birds change direction?</td>
</tr>
<tr>
<td>Fish swimming in schools changing directions</td>
<td>Say your watching some fish in a big aquarium. When you first begin watching the fish you notice that they are all swimming in a school. Say all the fish are swimming to then left in a tight group, there isn't much room between the fish. Then a couple minutes later, the exact time doesn't matter, you notice that the fish are all swimming to the right. What happened? How did the school of fish switch directions?</td>
</tr>
<tr>
<td>The spread of the cold virus</td>
<td>Say there is an outbreak of a virus, like the common cold or the flu. At first all the people who are sick live in one town. Then a couple weeks later, the exact amount of times doesn’t matter, lots of people get sick and they live all over the state, like all over the state of California. How does that happen? How does the virus spread all over the state?</td>
</tr>
</tbody>
</table>
The spread of a forest fire

Say one day you are out hiking, and say you are pretty high up the side of a mountain. Your exact location doesn't matter. Say you are at a location where you get a view, down to a valley filled with trees or brush or other plants like that. You sit down to look at the view and you notice that there is a small forest fire. A few trees are burning. You sit for a long time, maybe a couple hours, the exact amount of time doesn't matter. Later you notice that the fire has spread, now many trees are burning. How does that happen? How does a forest fire spread?

Water and juice mixing

Say you have two glasses, one is half filled with water, and one is half filled with juice, maybe orange or cranberry, the exact kind of juice doesn't matter. You pour the juice and the water together. The juice and the water molecules mix, how does that happen? How do they mix?

Table E: Introductory story with initial interview question for all seven problem contexts.

Follow-up Interview Questions

As this was a semi-structured interview follow up questions took a variety of forms, primarily they can be broken into two groups questions that are pre-determined and asked to most students and questions that were unique to each student. For the pre-determined questions, I had a list of pre-determined questions for each problem context and these questions were meant to be similar across the problem contexts. The rationale for doing this, similar to other design choices, was to support a possible analysis of comparing students explanations across problem contexts. For example, one question asked about how each of the problem contexts, sand dunes, traffic jams, flocks of birds, forest fires, etc., could get bigger and one question asked about how they could get smaller. In Table F I present a list of these questions about sand dunes, there were similar pre-determined questions for all of the other six problem contexts. These specific pre-determined questions were chosen because during the pilot study these questions captured issues that seemed to be both relevant to the underlying mechanism and relevant to topics that were initiated by some students spontaneously. Although all students were asked some of these questions when discussing each problem context, not every student was asked all six of these pre-determined questions for each problem contexts. The choice of which pre-determined questions to ask a student was made in the moment during the interview depending on how it was progressing and depending on what topics the student brought up spontaneously. For example, if a student had already discussed how a dune got bigger or smaller or how a dune began forming I did not ask those follow up questions. Also, if the interview was on productive path with a focus on the underlying mechanism and I felt like it was going in the direction of emergent thinking, I would sometimes postpone interrupting the flow with one of these questions. My goal when making these in the moment decisions about the follow-up questions was always driven by my goal of probing students’ understanding of complex systems. In this way the interviews were deliberately non-standardized in my attempts to understand each student’s thinking.

<table>
<thead>
<tr>
<th>Question Theme</th>
<th>Example Pre-Determined Interview Question for Sand Dunes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bigger/ Smaller</td>
<td>I want to change up the story. Instead of the sand dune moving, say there are two dunes, when you come back the second time, one has gotten smaller and one has gotten bigger. How does a dune get bigger/ smaller?</td>
</tr>
<tr>
<td>Static Macro Level</td>
<td>I want to change up the story a bit. Say you come back to the same location the second time, but instead of the dune having moved, now the sand dune stayed the same size. Given everything else you've said so far, how could</td>
</tr>
</tbody>
</table>
that happen? How could the sand dune stay the same size?

<table>
<thead>
<tr>
<th>Origin</th>
<th>How could a sand dune begin forming?</th>
</tr>
</thead>
<tbody>
<tr>
<td>How change happens?</td>
<td>How does the [wind, sand] change?</td>
</tr>
<tr>
<td>Combination of Two Macro Level Phenomena</td>
<td>I want to change up the story a bit. Say instead of one dune, you had two sand dunes sitting next to each other, and this time you noticed that when you came back for the second visit that one of the sand dunes had gotten bigger and one of the sand dunes had gotten smaller, how might that have happened? Could that happen?</td>
</tr>
<tr>
<td>Anything else?</td>
<td>Can you think of anything else that might influence how sand dunes move and change size?</td>
</tr>
</tbody>
</table>

Table F: Sample of the five pre-determined interview questions for the sand dune problem context.

Many of the follow-up questions were not pre-determined and were unique to each student, but they can be categorized into several common types. This approach is relatively common within the type of clinical interviews used by researchers who use similar methods to those used in this study, such as Ginsburg (1997), diSessa, Greeno, and Michaels (2012), and Lee, Russ, and Sherin (2008). Lee, Russ, and Sherin (2008) explicitly discuss many types of follow-up questions that are used in these kinds of interviews. Below I discuss some of the more common types of follow-up questions they mention, although this list is not exhaustive. Many of the types of follow-up questions I used fall under the category of revoicing, which is a common interactive strategy used by teachers in classrooms and discussed O’Connor and Michaels (1993). Recently revoicing has been discussed in the context of clinical interviews (diSessa, Greeno, & Michaels 2012).

Challenging questions: One approach to deal with some uncertainty in students thinking is to ask a challenging question. One kind of situation in which this worked in my data was in cases where students explanations were very detailed and elaborate, but I still was unsure if they were thinking about the phenomena in a way that was more aligned with centralized causality or more aligned with decentralized causality. In these cases I often asked a challenging question that was a new version of the same situation to see if they were thinking about the phenomenon in a more centralized or decentralized manner. For example, if we had been previously talking about one sand dune in the desert, I might ask them to consider two sand dunes. In this case the purpose of this question is to see how their answer might change given a small perturbation of the situation. When asking these questions, I usually have a hypothesis in mind. If their answer goes in one direction it suggests a certain kind of thinking. If their answer goes in another way, it suggests a different kind of thinking, and if their answer goes in neither of those ways, it suggests my momentary understanding of their thinking is off-base. For example, during the Keaton sand dune discussion, he explained how a dune could be in equilibrium if the wind was going either one direction or all directions. I then asked how the situation would change if the wind were going in only two directions. I said, “before you were explaining it with just wind going in one direction, say you had a situation where like wind went like one direction in the morning or one direction in the afternoon? Or, like rather than think about a whole bunch of different directions, lets just think about two directions.” In asking this question I was aiming to see if his dune equilibrium idea would still be applicable.

Pruning Extraneous Information: Often during my interviews, especially at the beginning of a discussion of a new topic, students would mention some extraneous information
that could pull the conversation in topics that are unrelated to the research goals Lee, Russ, and Sherin (2008) refer to the kinds of moves done in response to this as “pruning.” Sometimes, not always, I would ignore certain comments and ask a question that focused on other comments. In general this occurred because I wanted to focus on discussing the underlying behavior of the phenomena and the conversation had drifted to another topic. For example, when discussing sand dunes, many students mentioned where they had seen dunes, beach trips, desert trips, and other activities that were often not relevant to the focal topic. Then I would often re-focus them on the process of sand dunes moving and how that occurs. However, sometimes students’ comments would drift slightly to another topic and I would not prune because I could see the relationship between the tangent and the focal topic. For example, one student went on a long tangent during the virus discussion about her little brother not regularly washing his hands. After complaining about his actions she then used this experience to explain different likelihoods of disease spreading in different situations.

Selection and Zooming: As discussed in Lee, Russ, and Sherin (2008), often students’ explanations will be complicated, and their explanations may contain many pieces, one common approach to address these kinds of explanations is to ask a student to explain one part of the explanation fully. When this occurred in my data I would often focus on the piece of their prior statement that was most aligned with how and why the specific phenomena works. For example, when discussing sand dunes, Stephen at one point said

“but in terms of actual physical process, I guess geological counts as physical process, but as things isolated, that particular thing, so, yea, it depends, if the grains are particularly fine, say, the dune is built in the first place, if the grains are carried by the wind for instance, then they wouldn't collect on the windward side entirely, but then how would the dune be built in the first place. Well, I guess if it was built, with say some particular type of sand there, that had a tendency to, I guess if it were wet say, then how would that be in the dune, hmm. I guess there could be variation in the wind that results in that sort of thing, I'm not.”

Using a selection and zooming follow up question, I then asked, “what do you mean by variation?” Within this general type of follow-up question, I also made a habit of anytime a student spontaneously mentioned one problem context being similar or different from another problem context, I would also focus on that piece of their explanation and request that the student explain that piece more fully.

Clarifications and prompts for more information about meaning: There are many kinds of questions I asked based on a desire for clarification. Lee, Russ, and Sherin (2008) discuss explicitly asking for clarification by embedding what the student said in a question about it’s meaning. Sometimes I would ask for clarification by simply repeating a word and using the tone of my voice to imply that it is a question. Also, sometimes I explicitly asked a student to clarify the meaning of a word, for example, “so can you remind me again, what do you mean by ‘diffusion’?” I also sometimes asked for clarification about the phrasing of an idea, for example, “you said it was the same idea you've been using over and over again. What did you mean by that?”

Throughout the entire interview, when generating follow-up questions and making decisions about directions to follow my choices were guided by some of the heuristics for identifying p-prims that apply to conducting clinical interviews, as discussed in diSessa (1993).
Students generated all kinds of explanations that may have come from all kinds of prior experiences, science classrooms, textbooks, everyday experiences, among many other situations. No matter what kinds of explanations students provided, I did my best to accept them all and not judge or evaluate them, this is aligned with the principle of discrepancy, which is discussed in diSessa (1993). According this principle, when students provide non-physics explanations in cases where physics explanations would be appropriate, there might be an opportunity to investigate p-prims. In asking all of these questions about each problem context I was on the lookout to scaffold alternative explanations, in doing this I was using the principle of dynamic which is also discussed in diSessa (1993). According to this principle, the change in students’ explanations can shed light on p-prims. Often the first explanation may draw on the most easily accessible vocabulary, the path can reveal features of the context that invoke other p-prims, and latter explanations may provide some sense of the reliability.

Data Analysis

For this dissertation there were simultaneously two analyses, one focused on identification and schematization of knowledge elements using the developing knowledge analysis families of methods, and the other focused on identification and schematization of student generated explanatory patterns based on the existing coding schemes for centralized and decentralized causality. In general agreement with the qualitative video analyses process described in Derry, Pea, Barron, Engle, Erickson, Goldman et al., (2010) and Schoenfeld (2007; 1985) both analyses were heavily dependent on my theoretical commitments, and both involved a highly iterative processes of watching the videos, developing initial coding schemes, and as will be discussed below, a process of list making and refinement.

Knowledge Analysis

Knowledge analysis is an empirical analysis method associated with the Knowledge in Pieces epistemological perspective and it aims to identify the content of students’ prior knowledge. An important reference point for this analysis method is Sherin (2001) as that article discusses the tight relationship between the theoretical commitments of the Knowledge In Pieces epistemological perspective and the analytical aims. Sherin (2001) argues that in knowledge analysis the theoretical commitments is about the importance of knowledge, specifically the importance of the content of individual knowledge pieces rather than large-scale and general forms of knowledge. For example, as was discussed in Chapter 2, this commitment to the content of knowledge can be seen through the sketch of epistemological resources, specifically by my focus on specific kinds of knowledge pieces, such as p-prims, and knowledge about the pragmatics of a situation. As will be discussed further below, this theoretical commitment to the content of the knowledge pieces has wide reaching influences in my analysis process.

The goal of this section is to illuminate the knowledge analysis process. However, as it is highly iterative in nature I will begin by discussing the cyclical nature of the process. The iterative nature of this analysis has been discussed within the context of microgenetic learning analysis as a cycle of observation, schematization, and systematization (OSS) (Parnafes and diSessa, in press). This is an iterative and bootstrapping analysis process meant to lead to the development of new theory or adaption and extension of existing theories. This iterative analysis process shares many similarities with what Engle, Conant, and Greeno (2007) refer to as “progressive refinement of hypotheses” because both processes involve a continual interaction between theory and data during the analysis process. As will be discussed below my analysis process begins with observations of students’ explanations. Then there is a period of
schematizing what happens. This involves generating descriptions of students’ explanations and cyclically working to improve the descriptions. Also, during this period I asked questions about the types or categories of explanations, for example, I asked: What are their essential properties? How are these different categories related? Finally, there was a third period of systematization in which the prior categories from the schematization period were formalized and there was an explicit coding of all data for the categories of explanations. See diSessa (2008) and Parnafes and diSessa (in press) for further discussion of this process. In what remains of this section I am going to discuss this process in detail as it was used in this specific project. The purpose of this discussion is to be clear about my methods and to provide some guidance for other researchers. In this section much of the discussion will focus on specifics of how I used this process, there maybe differences among how other researchers use this general analytical process.

For me, the observation phrase involved watching and transcribing the video and identifying segments of potential interest with a focus on knowledge resources. Initially watching and transcribing the video is a bit unusual as a common initial step is to create a content log (Derry, Pea, Barron, Engle, Erickson, Goldman et al., 2010; Jordan & Henderson, 1995). A content log is an indexed description or play by play field notes that can easily be searched in order to find major events of interest. However, I have found that a content log does not have enough detail to begin the analysis at the detailed level of my interest. I need a rough transcript that includes enough of the English words that I can gather the main meanings of an explanation in order to help me make decisions about what analysis directions to pursue and how to pursue them (Jordan & Henderson, 1995). Once I had a rough transcript I worked to identify the segments where potentially students were accessing some relevant knowledge resource. Identifying segments of interest in regards to knowledge resources was influenced by the knowledge pieces described in diSessa (1993), and this was influenced by some of my preliminary analysis on identifying knowledge resources used in students’ explanations of complex systems. Some times I would name or describe these preliminary knowledge pieces so that I could easily find them again. Often I would write notes and descriptive account of what happened and notes about possible analysis directions. Sometimes these notes turn into paragraph long descriptions or mini essays about segments of interests. These paragraphs and mini essays are similar to what Barron & Engle (2007) describe as narrative summaries. Working from these notes and summaries I began to develop a preliminary list of knowledge elements that was potentially relevant to the data analysis. As mentioned before, this was influenced my theoretical perspective, Knowledge in Pieces. For example, one thing I was primed to pay attention to is cases of specific p-prims that are discussed in diSessa (1993) and might be found in this data set. One piece of knowledge I noticed early on was the idea of the dune blocking the wind. From my theoretical orientation I immediately recognized this as something of potential interest given that it was possibly an example of a p-prim discussed in diSessa (1993), the blocking p-prim. Remember, I was interested in analyzing students’ knowledge about how complex systems work, this was interesting because diSessa (1993) focuses on identifying p-prims in the context of Newtonian Mechanics and I was potentially seeing these p-prims in complex systems. Another potentially interesting knowledge resource noticed early on is the idea of efficiency of sand dunes in terms of gaining and loosing sand. One student discussed how big dunes were efficient in both loosing and gaining sand.

Next, there was a period of schematization in which I generated descriptions of these potential knowledge resources and then iteratively worked through the data trying to improve the
descriptions as they turned into categories. This involved an iterative analysis process of list-making, rough coding, and refinement. From the observation phase I was aware of the kinds of knowledge resources I saw in my data that were of interest. But I had yet to systematically survey all of the data, and I had not yet formed categories. In this stage I first systematically went through the data and made lists of all possible knowledge resources activated by a student within a discussion of particular problem context. The result of this analysis was that for each student interviewed, I had lists of knowledge resources, one list corresponding to each complex system problem context discussed. The elements on these lists of knowledge are based on content areas that students touched upon within their explanations. See in Appendix A a sample of a list about the possible knowledge resources activated by one student in the forest fire explanation. This list was very preliminary. Not all items are the same kind nor are they all equally important. Once I had made all of these lists, I next began a pattern matching exercise in which I compared and contrasted across all students’ forest fire lists looking for similarities and differences. This turned into a series of categories of forest fires knowledge elements. See Appendix B for a list of categories of forest fires knowledge elements that were common across many students’ explanations. As part of this exercise I would often try to identify more and less proto-typical elements and work towards grouping similar elements together. I would try to identify examples of transcript excerpts that illustrate the phenomena, in this case a particular knowledge element, in the most lucid manner possible. Thus over time the lists were organized and re-organized as I worked to refine the descriptions of the knowledge elements.

Finally, the third phase involved a period of systematization in which the prior categories from the schematization period were formalized and there was an explicit coding of all data for the categories of explanations. During this phase the sketch of epistemological resources, which was presented in Chapter 2, was built from the proceeding lists. To do this I again engaged in a pattern matching exercise in which I looked across all of the categories for all of the problem contexts. Remember a sample from forest fires is shown in Appendix A. I looked for commonalities in the kinds of categories across problem context. Once some commonalities were identified I then began a more formal and explicit bounding of the categories. Once these categories within the sketch of epistemological resources were finalized I then did another pass through the data working to document the specific knowledge resources within these new categories. This concludes the main discussion of the process I went through in conducting the knowledge analysis. However, before I move on to the indicators analysis I want to next discuss a couple additional ways in which my theoretical assumptions influenced this analysis.

This entire process was influenced in many ways by my theoretical assumptions about a complex mental ecology of many knowledge elements and by other principles and heuristics as derived from Knowledge in Pieces. First, I worked under an assumption of students’ knowledge as a complex system of many knowledge elements that interact in complicated ways. This is known as a conceptual ecology. The notion of a conceptual ecology originates with Strike and Posner (1992) and, more recently it has been used by diSessa (2002) in order to conceptualize a myriad of mental entities. This assumption influenced my work, for example, when making lists of potential knowledge elements I was attuned to a large number of elements that interact in complicated ways. Some of these lists had upwards of 100 or more elements. This number of elements might appear overwhelming, but given an assumption of a complex mental ecology this large a number of elements is a reality to be managed. Second, in making these lists I was also attuned to assumptions about the diversity of knowledge and was focusing on the content of students’ knowledge, not the general form of knowledge (diSessa, 1993; Sherin, 2001).
captured many kinds of knowledge, including references to academic and textbook knowledge, reference to common-cultural knowledge, and everyday knowledge. I also made inferences about students’ knowledge based on what they verbalized around their drawing, and I made inferences about their knowledge based on their gestures. Finally, another heuristic was focusing on students’ level of commitment to a knowledge resource and this would lead me to triangulate across the transcripts. For example, was the student unsure or hesitant during the explanation? Or did their explanation contain some confidence or swiftness about it? All of these attributes of the data influenced me in drawing conclusions about specific knowledge elements and the vast diversity of knowledge students could access within their conceptual ecology.

In this section I have discussed my knowledge analysis process through the observation, schematization, and systematization cycle. For each stage of the cycle I have worked to describe my analysis process and provide some examples of the kinds of segments of interests, lists, and categories that emerged. In doing this process I was also highly influenced by various other theoretical assumptions from Knowledge in Pieces. This was a highly iterative and bootstrapping analysis process meant to lead to the development of new theory or the adaption and extension of an existing theory. However, the iterations are not arbitrary—the iterations are systematic and linked to my theoretical perspective.

**Indicators of Centralized and Decentralized Causality Analysis**

As mentioned above, in addition to the knowledge analysis, there was a second analysis that focused on the indicators of centralized and decentralized causality. In many ways this analysis transpired through a process similar to the knowledge analysis. However, a central difference is that the starting point for this analysis was both the data and an existing coding scheme in the literature. This existing coding scheme focuses on various heuristics or what I call “indicators” of centralized and decentralized causality. Below I discuss this in further detail. First there was a period in which I observed the kinds of explanations students’ generated, and what I chose to observe was influenced by the coding scheme. Then there was a period in which I worked to generate descriptions of the different explanatory patterns and cyclically worked to improve these descriptions. During this period the categories shifted as I focused on capturing their essential properties, and I investigated how the various categories are related. Finally, there was a third period in which the categories were more formalized and I did a more explicit coding of the entire data corpus for those categories. In many ways the process is similar to the observation schematization, and systematization process. However, a difference is that in this case the unit of analysis is not the knowledge elements, instead it is the explanatory patterns.

In the first phrase I worked with both the data and the existing coding schemes for the indicators of centralized and decentralized causality as I observed students’ explanations based on the coding scheme. This phase of the analysis was characterized by switching back and forth between the data and the existing coding scheme schemes. From the literature point of view, the coding scheme is explicitly used in some papers (Jacobsen, 2001; Levy & Wilesnky, 2008; Sengupta & Wilensky, 2009) and parts of the coding scheme are mentioned as relevant to the analysis, methods, and findings in other papers (Resnick, 1994; 1996; Penner, 2000; Wilensky & Resnick, 1999). Also, there are a couple papers from the complex systems perspective that discuss aspects of complex systems in ways that I found useful for conceptualizing students thinking (Casti, 1994; Goldstein, 1999). However, given that there is variation across the coding schemes used in these papers, as part of the analysis process, to organize this literature I built a table that was meant to capture many of the possible indicators of decentralized thinking from this literature. A selection of this table is shown in Appendix C. Simultaneously, I also watched
the video data and make notes about cases in which I saw students’ explain the behavior of one of the seven complex systems in a manner that either resembled one of these literature identified indicators or in a manner that seemed to capture the underlying mechanism of how or why the phenomena behaved and had the possibility of being related to centralized and decentralized causality. For example, in this phase I observed several explanations based around the idea of *accumulation*, such as sand particles accumulating on a dune leading to it getting bigger. I also observed examples of explanations based around the idea of *threshold*, such as the size of a dune reaching a point where no more sand can collect on it, it just becomes so steep that it collapses. Neither of these ideas, *accumulation* or *threshold* was explicitly discuss in this literature, but these ideas capture pieces of the underlying mechanism for how the phenomenon behaves. During this phase I went back and forth between the literature and my data, often asking myself if what I saw in the data was an example of what the literature discusses or was something else.

Then, there was a period in which I worked to refine the categories and improve their descriptions by focusing on their essential properties and relationship to each other. To do this I wrote descriptions of what hypothetically an explanation based on each of the indicators, meaning each row in Appendix C, might look in each problem context. See Appendix D for a sample of two indicators. I also took the patterns, such as *threshold* and *accumulation*, which I saw in my data and were not explicitly discussed in this literature, and began to try and schematize what those looked like across all seven problem contexts. From these activities I began to develop a series of categories of potential explanatory patterns. In doing this process some categories or indicators were added or dropped. There were some cases in which an indicator from the previously mentioned literature had not been observed in the data. Keeping this in mind, I would do another survey of the data explicitly looking for that indicator. If I still did not see evidence for that indicator then I dropped it, for example this happened to *negative feedback*. Also, there were some indicators that were dropped, not because there was zero evidence for them, but instead because I could not reliably distinguish the centralized version of the indicator from the decentralized version in the data. This happened with the indicator, *environment as interacted with*, which is associated with decentralized causality, and, *environment as interacted upon*, which is associated with centralized causality. I saw cases in my data in which the students were citing the role of the environment in the behavior, but I was unable to distinguish if it was the more centralized or more decentralized version. During this period, I also added some categories based on various types of periodic and limiting behaviors. I observed in my data lots of cases in which students cited some kind of equilibrium or periodic or limiting behavior, however, the existing coding scheme focused on only two kinds of these behaviors, *dynamic equilibrium* and *static equilibrium*. I discovered that these two existing categories did not cover the breadth of the kinds of equilibrium, periodic, or limiting behaviors I saw in the data, so I added some categories in order to best capture what I saw in the data. The result of this was that initially there were six categories of periodic and limiting behaviors (*changing composition, steady state, convergence to a limit, periodic motion, balancing, unstable equilibrium*) and then the later two were dropped (*balancing* and *unstable equilibrium*) due to insufficient number of cases of that indicator being used in my data corpus. The remaining four, along with *threshold* and *mid-levels* consisted of the group of six explanatory patterns that serve as the basis for the final analysis. In choosing these six I was also concerned about choosing ones that could be identified in the data, to carry this out I needed clear descriptions and I needed them to be ones that I could clearly distinguish from each other in the data. Given my overarching goal of focusing on students’ competencies with complex systems, I
also focused on ones that I believed had the potential to support students in coming to understand decentralized causality. Overall, during this period the categories were refined so that by the end I had six categories that are independent, that I had clear descriptions of, that I could identify in the data, and that met some of my overarching analysis goals. In the next section I then did a more formal coding using these six categories.

The final stage involved using these six categories and conducting a more explicit and formal coding of the entire data corpus. For this stage I carefully surveyed the entire data corpus and made lists of each occurrence of each explanatory pattern, for these lists I included notes about the piece of data, video and time, along with some notes about the specific instance of each explanatory pattern. In these notes I documented details such as the relative clarity of an example, whether there was another explanatory pattern near by, and some notes about the kinds of prior knowledge used within that explanatory pattern. An example of one of these lists is shown in Appendix E. In doing this coding I had to find ways to organize the data that provided ease in being able to look across many students transcripts at once, for example in order to compare threshold in different students sand dune explanations, and look across an individuals transcript, in order to see how they may have used threshold at different points in time. The final results of this stage and the more formal coding of the data can been seen in Tables 5.1, 5.2, and 5.3 in Chapter 5.

In this section I have discussed my indicators analysis process through three stages that resemble the observation, schematization, and systematization cycle of the knowledge analysis process. In this analysis process I began from both the existing coding schemes for indicators of centralized and decentralized causality and from the data. I first went back and forth between the data and the literature in an open fashion. Then I worked to refine the categories of interest, adding and dropping categories, and I worked to improve my descriptions of the categories, their essential properties, and their relationship to each other. Finally, in the last phase I did a more explicit and formal coding of the six final kinds of explanatory patterns. As hopefully is clear, this was a highly iterative and bootstrapping analysis process meant to lead to the development of these six student generated explanatory patterns. Finally, one more concluding note, I do not view these codes or the process of developing them as error-free, and I therefore view the coding scheme as part of the analysis, not data itself. The purpose of this discussion is both to be clear about my methods and to provide some guidance for future researchers as I discuss both the general analytical framework and some specifics of how it was applied in this specific project.

Summary
In summarizing the data analysis section I have discussed my two analyses, the knowledge analysis process and the indicators analysis process. The knowledge analysis process focused on identification and schematization of knowledge elements using the developing knowledge analysis families of methods. I presented this process through the iterative cycle of observation, schematization, and systematization. The indicators analysis process also proceeded through a similar cycle, but a central difference is that it began with me looking at both the data and an existing coding scheme for centralized and decentralized causality. Both analyses utilized common qualitative video analysis approaches as both were heavily dependent on my theoretical commitments, and both involved a highly iterative processes of watching the videos, developing initial coding schemes, along with a process of list making and refinement. Also, I have emphasize in the previous narrative that the iterations are not arbitrary—there is a general pattern in which the coding, analysis, transcripts, the choice of focal excerpts, and the theory development becomes more and more refined over time.
Throughout the discussion of the two analyses I have explicate how the analysis was guided by my theoretical orientation with a goal of helping the reader understand my process and develop a sense of the overall methods associated with my goals. In terms of my theoretical orientation, I have tried to provide specific examples of how my actions and choices were guided by my theoretical orientation, and when possibly, point to underlying principles. With these goals in mind, I talked through my initial steps, the process of developing a coding scheme, list making, and refinement, all while recognizing the highly iterative nature of my analysis process. In presenting this narrative I have also aimed for the reader to develop a sense of the essential methods used given my focus on moment-to-moment shifts within students understanding, which, as is discussed below, is one of the major differences between this study and other approaches in the literature. I also aimed for the reader to develop a sense of the steps one goes through when investigating students’ knowledge elements.

A limitation of this analysis is that it was difficult to train someone else to reproduce my coding with a goal of assessing reliability, for this and other reasons running statistics was difficult. Future research should address this issue, some of the difficulties include the following: The parsing of the transcript is complicated as the size of each transcript excerpt that contained an explanatory pattern varies widely across the data set, from a couple seconds to many minutes. Identification of each explanatory pattern was also complicated because often a transcript segment included multiples patterns simultaneously and often there were multiple versions of a particular pattern across the data set. The level of detail of each pattern varied, the general trend is that students’ academic background influence the amount of detail included in the explanations, the 8th-12th graders’ explanations often including the least amount of details. Finally, within each interview, each instance of an explanatory pattern being used is likely not independent, but the exact relationship between each instance is unknown.

Now that the reader has a sense of the methods used in the current study, I am going to switch to a discussion of how my methods are similar and different from other approaches to students learning about complex systems.

**Comparisons of Methodology for Students Learning of Complex Systems**

Having now discussed the specific methodology used in this dissertation I turn to comparing my method with others methodology. Although the literature on students learning about phenomena that can be thought of as complex systems is very large, in this discussion I focus on researchers who explicitly describe their work in terms of complex systems and emergence, and I particularly emphasize those who focus on the centralized/decentralized distinction. A general trend within research on students learning of complex systems is to use mixed-methods, sometimes with clinical interviews, to investigate students learning and understanding. Although many researchers qualitatively document specific kinds of understanding about complex systems, few use micro-genetic methods or focus on the process of change. In this section I aim to illuminate some of the differences between these methodologies and the emphases in the existing literature and the current study. Three centrally important lines of distinction between this study and the existing literature revolve around, 1) the process of change, 2) the role of students’ prior knowledge, and 3) the role of similarities and differences across problem contexts. Below I highlight each of these points and discuss some similarities and differences in terms of the approach enacted in this study as compared to those found in the literature. These lines of distinction between studies are important because focusing on moment-by-moment changes in
student’s explanations within the current study allows one to answer questions about how change occurs and what factors influence change in a more detailed manner than is done in prior studies. Focusing on the role of prior knowledge is also important because it allows one to do an analysis of the changing activation of knowledge resources over short time period. Finally, focusing on similarities and differences across problem contexts is important as the prior literature has tended to assume complex systems problem contexts are equivalent. This is problematic because it can lead to assumptions of uniformity of learning across problem contexts where none has been shown to exist.

**Process of Change**

The current study uses microgenetic methods to capture the moment-by-moment changes in student’s explanations. When students’ generate explanations within a short time period in the range of 10 to 15 minutes, I am able to document changes in their understanding. I emphasize cases in which students’ explanations shift from being less and less prototypically centralized to be more and more prototypically decentralized. In conducting this analysis I am able to capture how changes occurs and identify some factors that influence the change. See Chapters 4 for the relevant analysis about the lines of continuity between these two ways of reasoning about complex systems. This analysis is important because it illustrates the lack of dichotomy in these two categories, centralized and decentralized causality.

The approach to changes in students understanding in the literature can roughly be divided into two categories, 1) those studies who focus on changes in students’ understanding of complex system using a pre-/post-instruction evaluation, they can be further subdivided into those that use surveys and those that use interviews. 2) those studies who collect process data. As will be discussed below, the current study is a hybrid of the later two as participants were interviewed once and given the lack of any teaching intervention, this approach can be thought of as documenting students understanding at a single point in time. However in addition, the current study involves some analysis of students moment-by-moment changes in understanding over a short time period, thus it can also be considered an example of process data.

First, there are several studies that use short answer survey questionnaires (e.g. Jacobson 2001) or a mixture of interviews with pre-/post surveys (e.g. Frederiksen, White & Gutwill, 1999; White & Frederiksen, 1990) in order to study students understanding. For example, Levy & Wilensky (2008) investigate students reasoning about everyday complex phenomena and they observed the widespread use of a strategy known as the “mid-level construction” in which small groups of individuals are formed. The authors argue that this strategy is related to students understanding of complex systems principles. As part of a larger four-month implementation in a 6th grade classroom of 27 students, 10 students were randomly selected for interviews. The students were interviewed twice, each interview lasted between 30-45 minutes. The first interview took place after the first activity, a disease participatory simulation. During the interview students were asked questions based on a taxonomy of question categories that was meant to draw out students thinking, also, students’ were given the option to draw pictures and interact with coins to model the systems evolution. All interviews were videotaped, transcribed, and as discussed below, coded. This study is quite different form the current study in terms of its pre-/post-intervention approach over a multi-month period.

Second, there are a few studies that collect process video data of students interacting and learning with various computational models of complex systems over a longer time period. One case of this approach comes from Penner (2000) who investigates middle-school students’ understanding of emergent systems. In this study four students met with the researcher once a
week for 9 weeks, each session lasted between 45-60 minutes. The author describes students’ initial understanding of emergence and then describes that their understanding came to reflect heuristics of emergence, including: recognition of a lack of a single causal factor, making distinctions between micro and macro levels, and understanding that small changes at one level can lead to large effects at a different level. In some ways the analytical approach used in Penner (2000) is similar to the current study given the focus on thinking changing over time and the common use of heuristics of emergence, but the time scale of once a week sessions for nine weeks in Penner’s study is much longer than one session used in the current study.

Thus I argue that there are differences among the approaches to analyzing change in the literature, but yet few focus on moment-by-moment changes in students’ explanations during the short time frames as was done in the current study. Above I discussed that the current approaches to analysis of changes in students’ understanding can roughly be divided into two categories: First, studies that use pre-/post-instruction surveys or interviews in order to gauge changes in students’ understanding of complex systems. Second, studies that collect process data, often over many weeks. The current study is more similar to the first group. Participants were interviewed once and given the lack of any teaching intervention, this approach can be thought of as documenting students’ understanding at a single point in time. In addition, the current study involves some analysis of students’ moment-by-moment changes in understanding of a short time period, thus it can also be considered an example of process data, but is of a shorter time period than used elsewhere. By focusing on moment-by-moment changes in students’ explanations during the short time frames the current study is able to answer questions about how change occurs and what factors influence change in a more detailed manner than is done in prior studies.

Prior Knowledge
A second line of distinction between the current study and much of the prior work on students’ understanding of complex systems centers on the role of prior knowledge in the analysis. In the current study the analysis of students’ prior knowledge is of great importance to the central goals and motivation for the study and this influences many of the methodological choices. Among prior studies on students’ learning about complex systems, first, there are some who mention students use of prior knowledge, but there is no systematic analysis of prior knowledge, sometimes using the KiP perspective. Second, there are some studies on students’ learning about complex systems that do explicitly focus on prior knowledge taking an ontological perspective. Below I am going to briefly summarize the role of prior knowledge in this study, then I will discuss the two other kinds of approaches to prior knowledge commonly adopted.

Students’ prior knowledge resources are a central construct in this study. A central goal of this study revolves around the role of students’ prior knowledge in their understanding and explanations. This study is using a specific theoretical perspective on prior knowledge, Knowledge-in-Pieces, and from that general perspective I have built a sketch of the kinds of prior knowledge resources activated within students’ explanations of complex systems. As was previously discussed in this section, this emphasis on prior knowledge has also influenced all aspects of the methodology from the choices about which problem contexts to include to the interview protocol and the analysis. Prior knowledge being such a central construct in this study of students’ understanding of complex systems is different from some other studies that do not explicitly emphasize prior knowledge.

There are a group of studies focusing on students’ understanding and learning about complex system and mention students use of prior knowledge, but are not doing a systematic
analysis of prior knowledge. For example, Resnick and Wilensky (1999) argue that role-playing activities can support students exploring the behavior of complex systems and they discuss that these activities can support students developing relevant strategies and intuitions. Similarly, in Wilensky and Resnick (1999), the authors argue that confusion of the micro and macro level maybe the source of misconceptions and that working with a medium that is designed to explore the concept of level may support them in developing better intuitions about which levels are appropriate for a given purpose. Finally, one more example of a study using a similar approach is Levy and Wilensky (2008) who observe the widespread use of a strategy known as the “mid-level construction” in which small groups of individuals are formed and then used in reasoning about the entire complex phenomena. In doing this analysis the researchers were investigating an intuitive strategy for making sense of complex systems. From a similar orientation but using a different analysis, Sengupta and Wilensky (2009) discuss a pilot implementation of an agent-based curriculum about electric current and resistance, they argue that it supports students bootstrapping rather than discarding their intuitive knowledge, such as p-prims. These studies are not explicitly taking on students’ prior knowledge as an analytical lens, with the exception Sengupta and Wilensky (2009), which does do a coding for one kind of prior knowledge (p-prims), but they are not doing microgenetic analysis nor do they focus on the process of change.

Also, there is a different group of researchers that focuses on students’ learning of emergence in terms of knowledge by taking an ontological categories perspective. Similar to the current study, this perspective is explicitly focusing on knowledge and conducts analyses around explicit constructs that are meant to capture knowledge, similar to the current study; however, the theoretical orientation is different from the current study. The central assumption underlying the ontological categories perspective is that there are different types of ontological categories of knowledge in the world, such as events and processes. The driving hypothesis is that a main cause of robust misconceptions stems from categorizing a phenomenon in the incorrect ontology. For example, within this perspective there is an assumption that students’ difficulties with diffusion stem from incorrectly classifying diffusion as a direct processes rather than an emergent process (Chi, 2005; Slotta & Chi, 2006). This approach has also been taken up by Jacobson and colleagues (Jacobson, 2001; Jacobson, Kapur, So, & Lee, 2011) investigation of learning of complex systems. Jacobson (2001) investigates experts and novices problem solving of eight complex systems. Their responses were coded based on the series of component beliefs that are thought to be associated with either a clockwork mental model or a complex systems mental model. When using the phrase “mental models” they cite Vosniadou and Brewer (1992; 1994). Recently, Jacobson, Kapur, So, and Lee (2011) used the same clockwork/complexity distinction as in Jacobson (2001) with some small modifications, and in this latter paper they refer to the two categories not as mental models, but instead as “ontological categories.” In Jacobson et al., (2011) the authors found that students who enriched their conceptual network around an ontology of complex system performed better on transfer tasks. This collection of papers is focusing on students’ knowledge surrounding complex systems, but as was discussed in Chapter 1, they de-emphasize focusing on individuals prior knowledge using a different perspective on learning and conceptual change than this study.

As was discussed in this section, a second line of distinction between the current study and much of the prior work on students’ understanding of complex systems revolves around the role of prior knowledge in the analysis. The current study uses students’ productive prior knowledge resources as an explicit emphasis that influences all aspects of the theoretical perspective, data collection, and analysis. Among prior studies on students’ learning about
complex systems, first there are studies do not explicitly take on moment-to-moment changes in the activation of knowledge elements as an analytical lens, but they do have an orientation that accounts for the details of students’ productive prior intuitions. Second, there are other studies that do explicitly focus on prior knowledge taking an ontology perspective. However, none of these studies have as explicit focus on the role of productive prior knowledge resources as is done in the current study nor on the role of the changing activating of knowledge resources in the moment.

Comparison Across Problem Contexts

In the current study I explicitly compare and contrast students’ understanding across problem contexts within different domains, looking for similarities and differences and asking questions about how the nature of the problem context influences students thinking about emergence. The analysis that explicitly focuses on these similarities and differences across problem context is subsequently presented in Chapter 5. In comparing my emphasis on students’ understanding across many problem contexts, there are few other studies that engage in this explicit type of comparison. Within the literature there are generally two approaches, first those that compare students’ learning of emergent systems with non-emergent systems, and second those that look at students’ learning of several complex systems, but do not explicitly compare and contrast across systems. The authors of these studies that do not compare and contrast across complex systems are generally assuming that students’ understanding and learning about these different problem contexts is equivalent. This is problematic because it can lead to assumptions of uniformity of learning across problem contexts where none has been shown to exist.

This point about comparisons across problem contexts is important because without it one might easily assume uniformity. If one does not compare students’ understanding across problem contexts, or ask questions about if students’ understanding across problem contexts is similar or different, one may easily assume that students’ understanding of emergence across problem contexts is uniform. This is potentially problematic because it may obscure areas where students have more or less difficulty, thus not allowing students to get optimal supports.

Much of the previously described research by Chi and colleagues (Chi, 2005; Slotta & Chi, 2006) investigates students’ learning of two situations, one of which is emergent, such as diffusion, and one of which is a direct or sequential process, such as the human circulatory system. Within this collection of studies there is an explicit focus on comparing students’ understanding across these two problem contexts, but the purpose in doing it is to illustrate the different kinds of misconceptions and change required for learning across emergent and direct processes. An exception to this is that recently in Chi, Roscoe, Slotta, Roy, and Chase (2012) the authors focused on two emergent processes, diffusion and natural selection but they did not explicitly investigate differences between students’ explanations and understanding in these two processes.

Second, there is a collection of research that does investigating students’ learning about multiple complex systems but does not explicitly investigate similarities and differences, instead there is often an assumption of homogeneity across the two problem contexts in terms of specifics about complex systems. For example, Resnick (1994; 1996), Resnick and Wilensky (1999), Levy and Wilensky (2008), Jacobson (2001), Jacobson et al., (2011), Grozter and Perkins (2005), Penner (2000), and Wilensky and Resnick (1999) all include at least two emergent or complex system problem contexts, but in none of these studies do the authors question the differences and similarities in students’ learning across these problem contexts.
Instead there is a pervasive assumption of equivalency. These authors are generally assuming that students’ understanding and learning about these different problem contexts is equivalent.

The approach used in this literature is different from the current study in which I explicitly compare and contrast students’ understanding across problem contexts within different domains. I am looking for similarities and differences and asking questions about how the nature of the problem context influences students thinking about emergence.

**Summary of Comparison of Methods for Students Learning of Complex Systems**

In this section, I have outlined three main differences between the methodological and analytical approaches used in the existing literature and the current study.

First, one difference centers on the process of change. The current study looks in detail at small shifts changes in students’ explanations during the short time frame. In comparison, much of the prior work focuses on pre-/post-instruction surveys, focuses on interviews in order to gauge changes, documents students’ understanding at a single point in time, and looks at process data over a longer time scale, although the current study also uses a subset of these approaches too.

Second, there is a difference around the role of students’ productive prior knowledge resources. The current study uses students’ productive prior knowledge resources as an explicit emphasis that influences all aspects of the theoretical perspective, data collection, and analysis where prior studies often have a rough orientation towards prior intuitions but do not use it as an analytical lens or take an ontology perspective. This emphasis on the productive prior knowledge resources supports analyses of the moment-by-moment process of change and supports investigations into similarities and differences across problem contexts, which is the third difference between the current study and prior work.

The current study emphasize similarities and difference in students’ understanding across many problem contexts in different domains while the prior work tends to assume that students’ understanding and learning about these different problem contexts is the equivalent and thus is not an empirical focus. This point is important as prior authors are often assuming that students understanding and learning about these different problem contexts is equivalent. This is problematic because it can lead to assumptions of uniformity of learning across problem contexts where none has been shown to exist.
CHAPTER 4: LINES OF CONTINUITY BETWEEN CENTRALIZED AND DECENTRALIZED CAUSALITY

Introduction
This analysis presents two cases of students’ shifting explanations and understanding about how sand dunes move in the desert. I focus on a particular type of shift, in which the students’ explanations and understandings shift from becoming less and less prototypically centralized to becoming more and more prototypically decentralized. The goals of this analysis are to first illustrate that such a shift can occur, and second begin to address issues of how such a shift occurs.

The results illustrate that this shift can occur during a short time period. To understand how this shift occurs, I identify a variety of student-generated intermediate explanations. For the case of Laurel I investigate two intermediate explanations that explain mechanisms of sand dune movement, and I trace the lines of continuity through these explanations as they support shifts in her understanding. These two intermediate explanations are sand-stickiness and sequential layers. I also do an analysis of the moves, made by both her and myself, that supported these shifts. Specifically, I focus on the Laurel-initiated moves that support her shifting understanding, including major shifts in what phenomena is being explained, this is often referred to as an explanandum, and small critical changes in topic. For the Keaton case I also investigate intermediate explanations; specifically I focus on three intermediate explanations that involve the direction of the sand grain and dune movement relative to the wind. Because this analysis is comprised of two cases, Laurel and Keaton, I also discuss some similarities and differences in the nature of the students’ shifts. Thus I illustrate that although they traverse similar paths, given a general shift from explanations that are less prototypically centralized to explanations that are more prototypically decentralized, their intermediate explanations are quite different and thus there are at least two different paths and this suggests that there many be many more paths associated with the common shift.

These results have implications for future work that is interested in supporting students’ reasoning about complex systems. First, Chi et al., (2012) present a series of specific hypotheses about misconceived causal explanations. Their argument is that students’ develop from everyday experiences a schema that is based on direct or sequential processes. From prior work about the ontological theory of conceptual change they claim that students’ difficulties with emergent processes are due to an incorrect categorization of those processes as a direct process (Chi, 2005) or categorizing diffusion through the Direct-causal Schema (Chi, et al., 2012). They claim that students’ revisions of those explanations continue to be incorrect due to the inter-level relationships between the interactions at the agents’ level and the pattern, or due to the inappropriate application of the Direct-causal Schema. The analysis presented in this paper shows otherwise. Laurel and Keaton revised their own explanations based on their prior knowledge resources and, as will be discussed later, their final revised explanations were associated with decentralized causality. Second, some of the prior work on students’ learning
about complex systems or emergence (e.g. Chi, 2005; Jacobson, 2001; Perkins & Grozer, 2005) has tended to emphasize the divisions between centralized and decentralized explanations and understandings. In comparison, one contribution made by the current chapter is an illustration of the lines of continuity between these two ways of understanding and showing how change can occur. Implications of this work emphasize the need for instructional activities that support students’ gradual shifts along lines of continuity between these two ways of understanding. Finally, the interviews in this study used an open-ended method. A characteristic of this method is that it allowed students some flexibility to negotiate which particular phenomena was to be explained. This will be discussed further below, but the central idea is that Laurel’s moves promoted a shift from explaining how dunes move to explaining how dunes get bigger and smaller, and that shift is important for her final explanations. I argue that allowing students some flexibility in deciding what to explain, and recognizing that, during this type of interview, they may not be explaining whatever the researcher intended them to be explaining, is potentially an important piece of supporting students’ reasoning about complex systems.

Case of Laurel
For the case of Laurel, a masters-credential student in mathematics education, the analysis first characterizes her initial and final explanations in order to clarify the difference and then the analysis focuses on her intermediate explanations. During the intermediate period, there was a gradual process of relinquishing prior explanations, and putting together new explanations, that led to a shift in her overall explanations from less prototypically centralized to more prototypically decentralized. In the analysis I focus on describing two of the intermediate explanations she generates that account for mechanism of sand dune movement. This analysis is done using the theoretical machinery presented in Chapter 2 in order to capture some of the changes in Laurel’s explanations.

Methodologically this analysis is delicate because her understanding did not shift in a linear, sequential manner. There are several lines of continuity associated with her shifting understanding, which I explore simultaneously in this analysis. Similarly, her initial understanding, which is more centralized, is also explored many times during the interview. Often she prefaces explanations with comments that emphasize that she used to think about the phenomena in a certain way (more centralized), such as, “I was thinking of it…” Thus, this analysis is not sequentially presented, but instead is presented thematically. The entire transcript is presented in sequential order in Appendix F

More Centralized Initial Explanation
At the beginning of the 13-minute discussion, Laurel’s understanding of sand dune movement focused on the idea of the wind moving the entire dune at once and the initial and final dunes being comprised of the same sand particles. As discussed in Chapter 3 the initial sand dune story phrased the phenomena in terms of a sand dune moving in the desert and a person documenting the two locations of the sand dune at two different points in time. As part of this initial, more centralized explanation Laurel conceptualized the phenomena in terms of there being, 1) literally the same sand dune at both points in time and, 2) all of the sand from the final dune being the exact same sand that the initial dune was comprised of. Mid-way through the interview, Laurel reflects on her initial understanding in terms of it being the same dune at two points in time saying, “I was thinking of it as like the same sand dune. [Gesture emphasizes direct movement of one sand dune]” (line 79). Later when again reflecting on her initial understanding, Laurel explains, “I guess I was just assuming that all the things from this sand dune would make the
new sand dune” (line 69). The two key points about Laurel’s initial conceptualization of sand dunes are that she viewed this process as literally the same sand dune changing locations and that she viewed the initial and final dunes as being comprised of the same sand particles.

This understanding of sand dune movement is aligned with the mindset of centralized causality. As discussed in Chapter 1, centralized causality is the idea that for a complex processes there is a central cause directing or orchestrating the behavior of all individual agents. In the case of sand dunes this would most likely look like the wind (or another controlling phenomena) moving all of the sand dunes or sand particles, simultaneously, possibly with equal force and direction. Obviously there are many specifics ways one could conceptualize the sand dune’s moving behavior so that a specific explanation would be associated with centralized causality. When I claim that Laurel’s initial understanding of sand dune movement is associated with the mindset of centralized causality I mean that her explanation accounts for a process or mechanism that contains characteristics that are viewed as implications or results of an a centralized causal process. In this case, two factors are suggestive of centralized causality: there being the same sand dune at two points in time and the old dune being comprised of the same sand as the new dune.

More Decentralized Final Explanation
At the end of the discussion, Laurel generated an explanation that was aligned with the mindset of decentralized causality. Her new explanation accounted for the variation in the rate of sand particles joining and leaving the dune resulting in changes in the size of the dune. This final explanation is based on changing composition. As discussed in chapter 2, this is the idea that the composition of the sand dune is constantly changing as particles join and leave the dune. When the rates of sand joining and leaving are equal, the dune remains a constant size. At the very end of the discussion, Laurel says

“maybe it depends on like, cause if things are being, like joining in and some things are being blown away, I'm thinking that if that’s happening equally then it's 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.”

And when there is a greater rate of sand joining than leaving, the dune will get bigger. Also, her final explanation accounted for the wave-like behavior of the sand dunes changing size. Laurel said, “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). She also recognized the continuity in the process of the dunes changing size as they become bigger and smaller repeatedly over time. As discussed in Chapter 1, changing composition is decentralized, and thus associated with a relatively normative understanding of how complex systems behave.

Application of the Sketch of Epistemological Resources to Laurel’s Initial and Final Explanations
The differences between Laurel’s initial and final explanations can be further illustrated by revisiting the sketch of epistemological resources presented in Chapter 2. As a reminder, in Chapter 2, I discussed the specific epistemological sketch built for the analysis in this dissertation. It is a partial sketch of the epistemological resources that may support students in
their ability to understand emergence. First, I present a catalogue of kinds of knowledge, for example, pragmatic knowledge, p-prims, and agent knowledge and I present a list of characterizations of knowledge, which includes, boundaries of knowledge, performances of knowledge, and the process of creating knowledge. Second, I present a list of features of the problem context that often influences students’ understanding of emergence, for instance, the arrangement of agents and the relationship between agents and humans. The central idea in this sketch is that the students’ activation of the prior knowledge, based on characterizations of that knowledge is influenced by features of the specific problem context that students may or may not find salient. This entire set of epistemological resources then subsequently influences the things that students can do which might support them in their recognition of emergence. For example, depending on the set of epistemological resources activated, students might connect the macroscopic and microscopic levels of the phenomena, thus possibility supporting their recognition of emergence. Or, the set of epistemological resources activated might support the students in focusing on a relevant underlying mechanism that in turn might support their recognition of emergence.

From this mini-though, two natural questions occur at this point in the Laurel analysis: What epistemological resources did Laurel activate in her initial and final explanations and why did those resources support her or not support her recognition of emergence? In Laurel’s initial sand dune explanation in which she describes the dune literally moving at once, she activates prior knowledge and focuses on the entire dune, not individual sand particles. Also, the question of a dune literally moving is visibly salient. By examining these two pieces of prior knowledge, we can see that they did not support her ability to pay attention to features of the problem context, such as recurrence, physical arrangement of agents (sand particles), initial and final behaviors among others—all of which could possibly have helped her to do things such as connecting levels or focusing on the underlying mechanism, which could have, in turn, helped with her recognition of emergence. In other words, these particular epistemological resources did not help her in recognition of emergence because they did not help her find certain aspects of the sand dune problem context salient that are supportive in helping her do things that would support recognition of emergence.

In Laurel’s final sand dune explanation, which is associated with decentralized causality, she activated prior knowledge about the individual sand particles and the entire dune existing as important things that are seen as relevant. This is in line with claims by other researchers, including Frederiksen, White, and Gutwill (1999), that what is often required to understand emergent phenomena is understanding processes that are operating down at the particle level and how those lead to emergent phenomena at the aggregate or macroscopic level. Also, she activates some knowledge about the importance about the relative rates of sand particles joining and leaving the dune. By examining these knowledge resources, we can see that they did support her ability to see the equality of the initial and final behaviors as important features of the problem contexts given that they emphasized the individual sand particles relative rates. For the same reason, these knowledge pieces also supported her ability to see the invariance of the size of the entire dune and the non-invariance of the sand particles. All of these epistemological resources, both the general ones and the features of the problem context that she found salient, supported her ability to 1) connect the macro sand dune and micro sand particle levels, 2) focus on the relative rates of sand particles arriving and joining the dune. Her ability to do these two things may have supported her in recognition of emergence. In conclusion, in this section I have used the sketch of epistemological resources as presented in Chapter 2, in order to illuminate the
different kinds of epistemological resources activated in Laurel’s initial and final explanations and thus illustrates why those resources did or did not support her recognition of emergence.

Analysis of the Mechanisms of How Sand Dunes Move
During the intermediate period between her initial and final explanations Laurel relinquished several explanatory pieces that are associated with the initial explanation and added several pieces, some of which are associated with decentralized causality. I argue that the associated shift consisted of a gradual multi-step process. There were attributes of explanations that were relinquished, some of which are associated with the centralized explanation. There were also attributes of the explanations that were added, some of which are associated with decentralized causality. In the following section I discuss two of the clearest instances of what knowledge pieces were relinquished, what knowledge pieces were added to her explanations, and why. In doing this I am capturing two lines of continuity in Laurels understanding. Each of the two changes to her explanations is centered on a mechanism used to explain the phenomena: sequential layers and sand-stickiness.

Sequential Layers
During the discussion, Laurel added an explanation of how the dune might move in sequential layers. This explanation accounts for a particular mechanism of how the dune moves, with the wind hitting the outermost layers of sand and moving those layers in a sequential order. Laurel said:

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] 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.
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 this transcript excerpt, Laurel is explaining that the sand moves in layers with the wind blowing the top layer of sand to a new location while drawing the picture shown in Figure B. Once the top layer is gone, the wind blows the next layer, and the next layer, until the entire dune has moved from one location to another. Notice that this explanation accounts for the multi-step process of dunes moving in layers, but it also presumes a rigid order to that process, first the top layer, then the next layer down, continuing until the dune moves. As I next discuss, this explanation was generated in response to her having relinquished a previous and more centralized explanation.
Specifically, the sequential layers explanations were generated based on her relinquishment of prior explanations that were more centralized. The sequential layers explanation was added based on an expectation about the prior more centralized explanation, dunes moving at once, being implausible. Once she recognized that the previous explanation as being implausible, she searched for a mechanism that was more plausible. The way this occurred is that she generated the sequential layers explanation in reaction to her prior expectation that the wind would go in a particular direction, and push the dune in that direction somehow “reformulating” the sand into a new dune. I asked how this might happen and then Laurel explained that if there is a sand dune and the wind is blowing in that direction, it would not work.

48. Laurel but then, but then, then 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]
49. maybe that’s why it all goes in the same direction when the wind is blowing in a certain strength or something
50. And then it blows it all, kind of in the same area and makes them somehow reformulates [moves hands in a circular motion] that sand into like a new sand dune. I don’t know.
51. Lauren How would the wind reformulate the sand into a new sand dune? [Moves hands in cyclical motions similar to Laurel's gesture].
52. Laurel 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.
53. or well, that doesn't really work anyways. Whatever.

Laurel explained that the wind blows in a particular direction pushing the sand in that direction (line 48). In doing this the wind some how reformulates the sand into a new dune (line 50). I then asked, “How would the wind reformulate the sand into a new sand dune?” (line 51). Laurel then explains while drawing (see Figure B) that “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.” (lines 52-53). In summary, in the first part of this excerpt Laurel has explained the sand dune movement, in a way that is roughly aligned with centralized causality, in terms of the wind blowing the entire dune at once. Then Laurel activates some knowledge about the sand dune
being reformulated. While mentioning this idea she is simultaneously generating a gesture that implies some kind of cyclical motion. This suggests some kind of motion that is not the wind directly blowing the entire dune at once and is different from the initial centralized sand dune motion. Next, she more clearly expresses the idea that the prior explanation of how the wind blows the entire dune does not work. She explains that she has an expectation that the wind would not work in a manner that would directly blow the entire dune at once. This expectation leads her to generate the sequential layers explanation. As mentioned previously, this entire excerpt immediately proceeded the prior section, in which she generated the sequential layers explanation.

Parallel to how the sequential layers explanation was generated after rejecting the more centralized explanation of dunes moving all at once, the sequential layers explanation was rejected because it relies on an assumption that the wind stays consistent which she views as also implausible.

58. Laurel: 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
59. it's always blowing in exactly this direction
60. because if it were that would make sense right?
61. 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.
62. But sometimes it would be not blowing as hard so then the sand wouldn't go as far,
63. or sometimes it would kind of change directions and then it would blow it into a different direction.

Immediately after generating the sequential layers explanation, Laurel relinquished the idea of the sand moving in a sequential order because the wind is not constant in terms of strength or direction. She first explained that when it is windy, the wind is not constant in terms of direction or strength (line 58, 59) although if it were, it would make sense (line 60). She had had an expectation that it would make sense for the wind to blow in a constant direction and at a constant strength, but she also recognized that this is implausible. Continuing with this expectation of the wind, Laurel explained that if it were this way she would have expected the sand particles to move in a sequential order (line 61). While explaining this she is also drawing with a purple and green marker; in line 61 she refers to the sand particles by the color used in the drawing (see Figure B). Then she next explained that the wind can be variable. Sometimes it is not blowing as hard and then the sand would not go as far (line 62). Sometimes the wind changes directions and then the sand will blow in a different direction (line 63). In summary, in this section Laurel has relinquished the idea of the wind moving sand in a sequential order, despite it making sense, because she does not expect the wind to maintain constant strength or direction.

So far I have discussed Laurel’s addition of an explanation about the dune moving in sequential layers of sand that are most exposed to the wind. This explanation was added due to her expectation that the previous, more centralized explanation, in which she expects the wind to move the entire dune at once, is implausible. Laurels eventual relinquishment of the sequential layers explanation occurs because she has an expectation that the wind will not be constant in
either strength or direction. As presented, this shift might appear relatively straightforward, but in fact it is muddled by a combination of circumstances: the most centralized explanation was deemed implausible on several occasions, the sequential layers explanation was added several times and was relinquished more than once, and the resulting shift of these additions and relinquishing did not occur in a linear order.

An important attribute of this shift in Laurel’s explanation of the phenomena is that it strongly depends on her particular prior knowledge about sand dunes and wind as well as her changing expectations about how she believed the phenomena would work. All of these factors influenced the shift from more centralized to more decentralized explanations. This shift can be best illustrated from the sketch of epistemological resources presented in Chapter 2.

From the sketch of epistemological resources we can see a difference between 1) the initial explanation, which influenced Laurel’s generation of the sequential layers explanation, 2) the sequential layers explanation, and 3) the final explanation, which relinquished aspects of the sequential layers explanation all in terms of varying epistemological resources. As was discussed previously, her initial explanation focused on the idea of the dunes moving at once and an assumption of the wind being constant. Similarly it does not incorporate any features of the problem context that might be associated with decentralized causality. Also, this explanation is based on prior knowledge about dunes moving as a single unit and of wind being consistent. As such, the sketch of epistemological resources captures the non-emergent nature of her initial explanation. In other words, in this explanation she is not accessing the kinds of prior knowledge that could potentially result in an explanation that reveals an understanding of emergence on her part. However, as mentioned previously, this explanation is then rejected in favor of the sequential layers explanation.

I next argue that this sequential layers explanation includes key aspects from the sketch of epistemological resources that does support the recognition of emergence. Within the sequential layers explanation she connects two levels; the intermediate layers of sand and the entire dune level. In this explanation she also incorporates a mechanism for dunes moving and focuses on the intermediate sand dune level. Her ability to connect these levels and incorporate this mechanism depends on certain prior knowledge pieces, specifically certain features of the problem context that she is paying attention to. She pays attention to the arrangement of sand particles. She also pays attention to the dune level and intermediate level (layers of sand), and she cues knowledge of the pragmatics of which layer of sand is exposed to the wind. In other words, her activation of these knowledge pieces based on what she pays attention to supports her ability to do things such as connecting levels and incorporating a mechanism for dunes moving—that are key for the construction of the sequential layers explanation.

The final explanation, in which she rejected the idea of sequential layers, is based on a different key piece of prior knowledge: the knowledge that is the wind is not constant. Specifically, she finds the existence of the wind as relevant, and more specifically she activates some prior knowledge that suggests that the variability of the wind is an important characteristic to pay attention to. Activating this piece of knowledge is important because it changes which features of the problem context she deems important to pay attention to. More specifically, activating this knowledge about the variable wind leads her to stop focusing on the physical arrangement of layers of sand and instead focuses on the variable movement of sand particles, which she deems to be an implication of that prior knowledge. This piece of knowledge essentially forces her change her explanations, to relinquish the prior emphasis on the physical arrangement of layers of sand and instead focus on the variable movement of sand particles.
Focusing on the variable movement of sand leads to the generation of the *changing composition* explanation, which is emergent. In this section I have argued that, depending on which epistemological resources are activated within different explanations, we can see that some of these knowledge resources force her to focus on aspects of the behavior that are either more centralized or more decentralized.

**Sand-Stickiness**

The second line of continuity illustrates that Laurel’s shift in understanding through the process of relinquishing and adding new explanations is based on a mechanism I refer to as *sand-stickiness*. This is a mechanism for why sand joins the dune, based on a need to explain the dune’s increase in size. The idea is that sand joins a dune because it is sticky, resulting in the dune getting bigger. Also, sand leaves a dune because it is no longer sticky, resulting in the dune getting smaller. In this section I argue that explanations based on the sand-stickiness mechanism are key for her understanding of why the dune increases in size as well as for the final *changing compositions* explanation. First I will discuss an explanation based on the stickiness mechanism, then I will discuss a shift in which phenomena are being explained, which contributed to her generating this explanation, and finally I will conclude by discussing how this explanation supports the final, more decentralized explanation.

Explanations based on sand-stickiness connect the behavior at the micro (sand particle) and macro (dune) levels in order to explain how sand joins the dune as it gets bigger and how the sand leaves the dune as it gets smaller. By focusing on the motion of the individual sand particles as they join the dune, the sand-stickiness explanation accounts for a part of the *changing composition* explanation, which, remember, relates to the inverse rates of particles joining and leaving the dune.

81. Laurel: Umm, yea, 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 [gesture outwards], right? It's not 
83. like it's glued together or compacted or something [holds hands together]. 
84. 
85. Laurel: Cause I can imagine if there was a little pile of sand that somehow forms 
86. somewhere 
87. then the other sand that was being blown would kind of get stuck there, or not 
88. 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? 
89. It would kind of join in, in a way, with that, like, little pile and then it would 
90. start get bigger and bigger and then more sand would kind of I don't know if it 
91. would be like, 
92. you know, it's flying along then hits it, and then it stops there [gestures flying 
93. around and hitting something] and it then forming a bigger sand dune [gesture 
94. big dune]. 

In this excerpt Laurel explains that when sand is not glued together, it can fly off the dune resulting in the dune getting smaller, and when sand sticks to the dune, it joins it, resulting in the dune getting bigger. In line 81 Laurel explains that she has been to sand dunes before; this prior experience may be supporting much of her underlying prior knowledge. Then in line 82 she mentions that the sand is loose, not glued together, and her gestures imply that loose sand would fly off the dune. She then goes on to explain that if a small pile of sand forms (line 85), it will
get bigger as more sand is blown onto it in such away that the sand sticks to the dune (line 86). This idea is then reiterated in line 88. To summarize, Laurel is saying that the sand being blown will join, or stick to, the dune, resulting in the dune getting bigger, and that when the sand is not glued together it will fly away resulting in the dune getting smaller.

Notice that in this excerpt Laurel is explaining how a dune increases in size. In other words, this explanation is answering the hypothetical question, how does a dune increase in size? But remember, my initial question was not about dunes increasing or decreasing in size, it was about dunes moving. I never explicitly asked her about dunes changing size. So, in order to get to the point where she chose to explain how dunes increase in size, she had to somehow relinquish the goal of explaining how dunes move. In other words, her generation of an explanation based on the sand stickiness mechanism depended on a shift in what behavior was to be explained: either dunes moving or dunes changing size. This type of Laurel-initiated shift in what phenomena is being explained is discussed further in the next subsection, but here I am going to focus on what pieces of the initial, more centralized explanation needed to be relinquished in order for this shift in what phenomena was being explained to occur.

The foundation for this shift in what the phenomena was to be explained, or critical change in topic, relied upon the relinquishing or addition of two other explanations. First, she relinquished a prior explanation in which all the sand in the new dune was the exact same sand the old dune had been comprised of. Explanations based on sand-stickiness involve new sand joining the dune; this is in direct conflict with her prior idea in which all the sand from the old dune moves with the new dune (e.g. Lines 69 and 79). Second, she added an expectation that there would be many sand dunes in the desert rather than one isolated sand dune in the desert.

70. Laurel: but maybe its like, I mean, there was other sand,
71. And, I'm guessing, it wasn't just like a random pile of sand in the middle of the desert.
72. Lauren: Yeah. You're right.
73. Laurel: So I don't know if it's actually like this sand dune moved over,
74. or if its like this one just disappeared and then a new one formulated.
75. Maybe. I don't know.
76. Lauren: So, usually we don't see sand dunes isolated: usually you see lots of sand dunes.
77. And so, in that kind of case, where, you know, there is a whole bunch of sand dunes, how does, you know, one, you know, kind of, if you see one sand dune at one place at one point in time and you go back and it's not there and there is a new sand dune someplace else. How does that happen if there is, you know?
78. Laurel: So there is just a lot of them and yeah, you know, [gesture implies many sand dunes] okay.
79. Yeah, okay, I was thinking of it as like the same sand dune. [Gesture emphasizes direct movement of one sand dune]

In this excerpt Laurel generates an expectation that there would be other sand in the desert, not one isolated dune, which conflicts with her prior, now relinquished, assumption that there is one dune that literally changes location. Laurel mentions that there is other sand (line 70) and the dune is not a single, random pile of sand in an otherwise flat desert (line 72). I then confirm this
idea (line 72). Laurel then generates two possibilities. One, that the dune literally moves over (line 73) which, as discussed previously, is her initial, more centralized explanation. Or, two a dune somehow disappears, and then a new dune appears (line 74). Given these two possibilities, I then nudge Laurel by mentioning that usually we see many dunes in the desert (line 77). The role of my nudges will be discussed further in a subsequent subsection, but notice that I am building on her prior ideas, and suggesting a new piece of knowledge about many dunes in the desert. Laurel takes up this idea (line 78), commenting that, “there is just a lot of them,” and she was previously thinking about the phenomena as the literal same sand dune at two points in time (line 79) similar to what she discussed in her comment in line 73. In this excerpt I have shown that Laurel, with some nudges by me as the interviewer, has come to add an expectation of there existing many sand dunes in the desert, relinquishing the idea one isolated dune. This is an important piece of the sand-stickiness explanation because, when there are many dunes in the desert, one is forced to begin thinking about how the different dune’s impact other dunes behavior as well as the behavior of the wind and sand particles, which, in turn, leads to questions about the entire system, which includes dunes changing, getting bigger or smaller, and relinquishes focus on the shifting of a single dune.

So far I have argued that the shift from explaining a single dune’s movement to explaining dunes getting bigger or smaller is a key shift that supported the addition of the sand-stickiness mechanism. Specifically, this shift was supported by Laurel’s 1) relinquishment of a prior explanation in which the new dune is comprised of the exact same sand as the old dune, and 2) relinquishment of a prior idea about there being only one dune in the desert, while simultaneously adding an idea about there being many dunes in the desert.

Finally, I argue that Laurel’s explanations based on sand-stickiness are key for the final, changing composition explanation. This next excerpt begins with me asking her to reiterate her ideas about sand-stickiness. She again explains that sand leaves a dune because it’s no longer sticky, and joins a dune because it sticks, or collects, on the dune.

103. Lauren: You mentioned at one point that it would like the sand would stick to it.
104. Laurel: How would that work?
105. Laurel: Yeah. Well, I know that at the beginning I said that, like, because it's not stuck together so then the outside layer can like, fly away, right
106. So then, umm, but then when the sand is blowing, like, if there is already, like, part of a hill, or something
107. Lauren: Yeah
108. Laurel: Then, well, I guess the way I was thinking or it,
109. Laurel: Let’s say there was an individual piece of sand and it’s being blown by the wind this way, and then there is already a sand pile, and then if it [non-verbal noise implies ‘hitting’] hits it its not going to be able to keep going. So it would, like, it would kind of collect there.
110. But then I guess since it wouldn't, like, [pause] sorry it wouldn't, like, I guess that’s what I mean by it sticks; it would stop moving so then it would join the little pile there
111. and then but then the wind could come and its not stuck there so it could be blown away.
Notice, that overall the above sand-stickiness explanation is similar to the first one I discussed, from lines 81-88 as she focuses on sand particles sticking to and becoming unstuck from dunes. In this section of our discussion, in line 103 I ask Laurel to reiterate her prior statement about sand sticking to a dune and how this would work. She first explains that when the sand particles are not stuck, the outside layer of sand can fly away (line 105). Then she explains that if there is an individual grain of sand being blown by the wind and there is a small pile of sand, the grain will hit the pile and join it (line 109); this behavior, in which the grain of sand stops moving and joins the pile, is what she mean by the word ‘sticks’ (lines 110-111). The reverse behavior can happen too, the wind comes, and the grain is no longer stuck so it gets blown away (line 112).

In the prior excerpt, in lines 111 and 112, the explanations for how the sand grains join and leave the dune are sequential; in the following excerpt, these two inverse mechanisms, how grains join and leave, are more explicitly combined. Her focus on the inverse behaviors of sand sticking to the dune and becoming unstuck, sets her up to focus on the relative rates of sand particles joining and leaving the dune. Laurel compares the rates of sand joining and leaving the dune so that the dune can stay a constant size. Then, in the final explanation of the entire discussion, she mentions what could lead to the dune moving to a different location—unequal rates of sand joining and leaving the dune.

113. Laurel: So then, maybe it depends on, like, cause if things are being, like, joining in and some things are being blown away, I'm thinking that if that’s happening equally then it's just never going to change. Right?
114. Gona be the same size.
115. But then, the fact that you said, like, if it seems like the hill you saw before is gone and now it’s in a different place,
116. that makes me think that it doesn't happen completely equally, that, like, you know, like two things of sand fly away and two come, like that.
117. But maybe it’s more like at some points more is being added then is being taken away, and then at other points the wind somehow is taking more, more sand away than is joining that little pile. I guess that’s it.

In this final excerpt of the entire sand dune discussion Laurel generates an explanation based on the pattern of changing composition. She mentions that the dune’s size depends on the rates of sand joining the dune and being blown away from the dune; when these rates are equal, the dune does not change (line 113). The dune will stay the same size (line 114). These lines contain an explanation that uses the pattern of changing composition; the particular sand particles that the dune is composed of are constantly changing, but the overall size of the dune is constant. Then Laurel moves beyond this explanation, to consider how the relative rates of sand particles could result in other behaviors, namely the dune moving. She mentions that the rate of sand particles joining leaving as not equal to the rate of particles leaving (line 116). A situation could occur in which for some period of time more sand is being added than is being taken away, and at another point in time the situation could change so that there is more sand being taken away than is being added (line 117).

In conclusion, in this section I discussed a second line of continuity in which Laurel’s understanding shifts as she relinquishes and adds new explanations as related the mechanism of sand-stickiness. Sand-stickiness was used to explain how dunes increase and decrease in size.
At the end of the discussion, this mechanism played an important role in her final, changing composition explanation as it supported her ability to focus on the behavior of sand dunes joining and leaving the dunes. To get to the point at which she generated explanations based on this mechanism, I argued that there was a shift in what phenomena is being explained. She shifted from explaining how a dune moves in the desert to explaining how a dune gets bigger or smaller. The former is associated with her more centralized explanation, and the latter is associated with changing composition and the sand-stickiness mechanism. I also argued that this shift was supported both by her relinquishment of two prior ideas: the expectation that all the sand in a new dune is the exact same sand as comprised the old dune, and the expectation that there would be a single dune in the desert, and by the addition of knowledge pieces about the existence of many dunes in the desert.

Now, having followed Laurel’s intermediate and shifting explanations along two lines of continuity, sequential layers, and sand-stickiness, I move away from discussing various mechanism for how dunes move and transition to discussing the kinds of interactional moves that supported these shifts.

Moves that Support Shifting Explanations
Laurel’s shifting explanations of how sand dunes move and how sand particles move were supported by various interactional moves. This analysis is different from the prior one in which I focused on lines of continuity in order to explain the shifts in her understanding. In this analysis I focus on the moves, specifically the things that Laurel or I did, that supported her shifting explanations. In the first part of this discussion I focus on the moves Laurel initiated. I discuss the major shift from her explanation of how dunes literally move to her explanation of how dunes get bigger and smaller. Then I discuss five smaller changes in topic that she also initiated, and which also shifted the boundaries of the phenomena to be explained, often opening new avenues for what aspects of the sand dune behavior to address. I try to connect each of these smaller changes in topic to the large shift of moving from explaining how dunes literally move and the more centralize implications, to explaining how dunes get bigger and smaller, and the more decentralized implications. In this second part of this discussion I focus on the nudges that were initiated by me as the interviewer. These are examples of common kinds of discourse and conversation moves that may have subtly shifted Laurel’s thinking in specific ways.

Major Shift in What Phenomena is being Explained Initiated by Laurel
At the beginning, my interview question asked about a single dune moving locations, this question is aligned with centralized causality because of an embedded assumption that a single dune does in fact move locations without changing its composition. As expected, and discussed previously, Laurel’s initial explanation about a single dune moving as a whole unit incorporated this assumption (see lines 69 and 79).

Over the course of the discussion my initial question was supplanted by Laurel asking a different question: How do dunes get bigger or smaller? As discussed in the sequential layers and sand-stickiness subsections, the focus on explaining a dune getting bigger or smaller turned out to support the emergent, changing composition explanation as she wound up focusing on the movement of the individual particles joining and leaving the dune. Also, the sequential layers explanation accounts for both how dunes change locations and how dunes change size. This explanation can be thought of as an intermediate step-wise process in which two dunes move in orderly layers, the initial dune decreases in size, and the new dune increases in size. By the end of the discussion, Laurel focused on explaining how a dune changes size. This change can be
seen in two ways. First, it is revealed in her explanations and by what phenomena she was previously trying to explain; many times during the later parts of the discussion she was explaining how a dune got bigger or smaller (e.g. lines 85-88, 95-97, 101-102, 105-112). Second, her final explanation, which focuses on dunes exhibiting a wave-like behavior (line 102) and changing composition (lines 110-117), are both based on an assumption that the question or phenomena to be explained is, how do dunes get bigger and smaller?

There are two other important features of this major shift. First, this major change in the phenomena to be explained was initiated by Laurel. In this interview I never explicitly or implicitly stated this new question. The nature of this type of clinical interview did not presuppose that my question was the only important question to answer. Although my initial question about sand dunes moving was clearly more associated with centralized causality, this major shift was initiated by Laurel.

Second, this major shift in what phenomena are explained—dunes moving or dunes getting bigger and smaller—can be seen across the entire 13-minute discussion. There is not one moment that captures this shift; it is distributed throughout the entire discussion. This observation leads into the next sub-section. Within this larger shift there are also many other smaller changes in the topic of the discussion. In the next sub-section I discuss a series of the smaller critical changes in topic that occurred within the larger shift from explaining how dunes move to explaining how dunes increase and decrease in size.

Small Critical Changes in Topic Initiated by Laurel
As previously mentioned, over the course of the discussion there were many other small critical changes in topics that were initiated by Laurel. Many of these changes in topic served the purpose of opening up the scope of the phenomena to be discussed. These smaller changes involve shifting the boundaries of what is to be explained by trying on and testing out new knowledge elements and then deciding if they are relevant or not. This was generally done through Laurel asking herself rhetorical questions about the dunes’ behavior. She also questions some of her prior assumptions, such as the assumption that there would be only one dune in the desert. In this section I present a series of five things Laurel did, which includes asking herself rhetorical questions or questioning her prior assumptions in ways that might have shifted her understanding. Each time I note her doing one of these things I discuss how her actions may relate to the overall shift from more centralized explanations to more decentralized explanations. This list does not necessarily include every small critical change in topic she initiated, but it is meant to provide coverage of many of them.

I. How does all the sand collect in a pile in one location? Why is it not evenly distributed, resulting in a flat desert? Early on during the discussion Laurel asks herself the question, how does all the sand wind up concentrated in the same place and why wouldn’t the desert just be flat? This is an important question; Laurel is asking about a mechanism or process that would result in the wind blowing all the sand into one pile as compared to blowing in every direction. This question is framed slightly in opposition to her expectation that, perhaps, the wind would blow sand everywhere so that it would be relatively evenly distributed over the desert, resulting in the desert appearing flat. Laurel says: “But I don't know how they would all end up in the same place either; why wouldn't it just be flat? Like, cause if the wind was just blowing the sand around then it would just blow it around everywhere, you'd think, but then I don't know why they would all concentrate in a form, like a big pile. You know if the wind is blowing it.” (lines 30-35). In this excerpt, Laurel has raised an expectation that the wind would blow the sand everywhere, which is counter to her sense that somehow the sand is concentrated into a big pile,
and she is asking how this surprising thing occurs.

This question is important because it illustrates a case of conflicting expectations one of which is more centralized and the other more decentralized. Laurel’s rhetorical question is based on an expectation that, somehow, many sand particles end up in the same location, in a dune, and an expectation that the wind blowing sand all over the desert would distribute it relatively evenly. The former expectation about sand particles being concentrated into a dune is more centralized because this question may include an underlying assumption that a finite amount of sand in the desert will blow together. The latter expectation that the wind will blow sand everywhere so that the desert appears flat is more decentralized because it begins to recognize the individual motion of each sand particle with some amount of underlying randomness.

II. How does a dune begin forming initially? Another change in topic occurs when Laurel asks herself questions about how dunes initially begin forming. This issue is mentioned several times during the interview. This question is asked in conjunction with cuing prior knowledge about the role of chance in the beginning of dune formation. First, Laurel explains that maybe it is by chance that there is a little pile of sand and then more sand is blown onto it and gets stuck: “Maybe it's by chance or something that, like, cause I can imagine if there was a little pile of sand that somehow forms somewhere 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?” (lines 84–86) In this excerpt, Laurel is explaining that a dune begins forming due to chance and then the dune gets bigger as more sand joins the dune due to the stickiness mechanism. In the following, second case of Laurel discussing how a dune begins forming she mentions that initially, by chance, there is a threshold for the amount of sand particles needed in one location in order for more sand to be caught by the dune. “Maybe it's by chance that, like, maybe some, you know, some number, some vital number of sand molecules or whatever got all in one place [gestures implies all in one place] and then that was enough to start catching more [gestures catching more] more deliberately” (lines 92–93). In this excerpt Laurel explains that if, by chance, enough sand particles are in one location, then that might lead to the dune growing bigger.

Similarly to some of the other critical changes in topic, this one was completely initiated by Laurel and potentially important for her final, decentralized explanation. She recognized the importance of the question, how does a dune begin forming? It may not be an accident that both times Laurel mentioned the issue of how a dune begins forming, she also, simultaneously, cued some prior knowledge about the role of chance in that process. I cannot be sure what she means by “chance” but the underlying randomness and probability of sand moving is associated with a more decentralized explanation.

III. After a dune moves, what is left over? Another topic arose when Laurel asks herself about what happened after a dune moves, what remains at the old location? Laurel is unsure whether that old location would be flat or whether a shorter dune would remains. “I don't know. [pause] So then would the originally where there was a sand dune would it be flat or something? Or? Just shorter and then another sand dune?” (line 68). The possibility that after a dune changes location, the original location is flat, is more centralized perspective because this is also associated with the assumption that the entire dune would literally move from one location to another. The assumption that a dune is a self-contained thing that can shift in its entirety. The possibility that after a dune changes location, the original location still contains a small dune might be a more decentralized perspective because this possibility is associated with her ideas about dunes changing size in a wave-like manner. This idea of dunes changing size in a wave-
like manner was discussed at the end of interview in conjunction with her final changing composition explanation.

IV. Big dunes get even bigger when they stop other sand particles. Another topic Laurel initiated the discussion of is the question of how a big dune could get even bigger. Many times she discussed dunes getting bigger or smaller, but she also mentions a dune big enough to stop other sand particles can get even bigger. “I'm think of it, like like, they all just happen to fall, but then once it gets big enough then it actually maybe the, it's big enough to kind of start stopping other molecules, or sand, which makes its bigger” (line 95). In this case, Laurel is initiating a focus on the issue of how a dune gets even bigger once it’s already big. Laurel cues a threshold type explanatory pattern in which a big dune gets bigger because it is big enough to stop other sand particles, which results in it getting bigger. The role of the explanatory pattern of threshold in students’ understanding of complex systems is discussed further in Chapter 5, but in this case it might be helpful for Laurel’s understanding of decentralized causality because it includes a mechanism for how dunes get bigger. As will be discussed later, focusing on the underlying mechanism maybe helpful in coming to understand decentralized causality.

V. Why don’t dunes disappear? The final small critical change in topic that I will discuss is that Laurel asked herself why dunes do not disappear. She expects that instead of becoming totally flat, a given location would always have a small cone of sand remaining, and that the small amount of remaining sand will influence the dune being built up again. “But it wouldn't get flat probably, there would still be a little, you know, a little cone there yeah, and then maybe that would start collecting more [gestures implies sand collecting on a dune] and growing [gestures implies dunes growing] and then the wind could take it away, get smaller [gestures implies a dune getting smaller] and like this.” (lines 98-101). In this excerpt, similarly to how she explained the first small critical change, Laurel explains that the former location of the dune will not get flat because there will be a little cone or pile of sand remaining. She also explains that this pile can collect more sand and the dune will get bigger, or sand will leave, so that the dune gets smaller. In this excerpt, the issue brought up by Laurel, of why the location does not get flat leads to further discussion about the cyclical nature of dunes getting bigger and smaller (line 102). As discussed in the previous section her final, more decentralized explanation, contains a sense Laurel has of the dunes changing size in a cyclical manner which leads to her the final, changing composition explanation. Notice that this small, critical change in topic of why dunes do not disappear emphases the old location of the dune. In comparison, the first small, critical change in topic emphasizes the new location of the dune, yet they both address dune movement. Also, the third small critical change in topic is similar to this one because it emphasizes the possibility of there being a flat desert at the dune moves while this one emphasizes the fact that the original location would not be flat.

Moves Initiated by Laurel Summary
In the preceding two sections I discuss critical changes in topic that were initiated by Laurel. First I discussed a major shift in the question to be explained. At the beginning of the discussion she was explaining how dunes move, an explanation which was prompted by my initial question; at the end of the discussion she was explaining how dunes get bigger and smaller. I argue that this shift in the question to be explained is associated with the shift from more prototypically centralized explanations towards more prototypically decentralized explanations. Hence I am arguing that an important part of this shift in her understanding and explanations is related to what question she is explaining at a given point in time. Second, I also discussed a series of five smaller, critical changes in topic that also supported the larger shift. These smaller, critical
changes in topic took the form of her questioning her prior assumptions and rhetorical questions 
that she asked herself about the dune behavior: How does all the sand end up in the same 
location in a big pile, rather than spread out and flat? How does a dune begin forming initially? 
After a dune moves, what is left over? Why do big dunes get even bigger when they get big 
enough to stop other sand particles? Why don’t dunes disappear? Many of these questions 
revolve around her recognition of new attributes of the general sand dune behavior to be 
discussed, thus they resulted in Laurel metaphorically opening the space of what phenomena is 
to be discussed, not only dune movement, but also dune origins and dune’s end behavior. The 
emphasis on these topics was initiated by Laurel in each case. I argued that many of these small, 
critical changes in topic may have also supported her overall shift from more centralized 
explanations to more decentralized explanations.

**Interviewer Nudges**

Lest someone assume that my role was minimal, it is also important to note that during the 13-
minute discussion, on several occasions I made comments about the behavior of sand dunes that 
might have nudged Laurels thinking in specific ways. I refer to these as “interviewer nudges.” They were not judgments about her thinking or the phenomena in any way. Nor were they 
new questions to be answered. They were instead subtle nudges. All of them can be considered 
examples of common kinds of discourse and conversational moves discussed in Lee, Russ, and Sherin (2008). The moves I made during the Laurel interview are similar to the kinds of moves I 
made in the other interviews. Below, I discuss two specific nudges from the Laurel case.

One example of a move I made was to ask questions that pushed her to unpack in more 
detail how she understood something that she had already addressed. For example, at one point 
Laurel had mentioned the idea of some sand sticking to a dune (lines 86 and 109). Later, 
towards the end of the discussion, I reiterated that idea and asked her for more information about 
what she meant. This move occurred in line 103 and was previously discussed above, in the sub-
section on sand-stickiness. The key thing that supported this move is that she mentioned the idea 
of sand sticking several times. Then, a couple minutes later I asked her for more details about 
what she meant by the phrase “sand stickiness”. In making this move I was pushing her to 
unpack this idea of sand stickiness further. After my question, she explains that sand particles 
leave the dune because they are not stuck together (line 105), and as discussed previously, this 
led into the discussion about the relative rates of sand particles joining and leaving the dune: the 
more decentralized explanation. The main point here is that my question in line 103 in which I 
asked her to re-focus on the issues of how sand particles stick to the dune may have resulted in 
her focusing further on this issue than she would have otherwise. I did not add anything new to 
the discussion, but I did nudge her in a specific manner. This is similar to the discursive move 
that Lee, Russ, and Sherin (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.

A second example is when I nudged Laurel to recognize that there are likely many dunes 
in the desert, not only one sand dune. At this point in the discussion Laurel mentioned several 
opportunities, she was unsure about the phenomena being more centralized (a single dune moving 
locations) or being more decentralized (old dunes disappearing and new dunes being formulated). 
She said, “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 73-73). Recognizing the tension between 
these two possibilities and not wanting to explicitly make a judgment about one or the other, I 
instead suggested the addition of some new information about sand dunes. Specifically, I 
mentioned there being many dunes in the desert. “So, usually we don't see sand dunes isolated;
usually you see lots of sand dunes. And so, in that kind of case, where, you know, there is a whole bunch of sand dunes, how does you know, one, you know, kind of, if you see one sand dune at one place at one point in time and you go back and it's not there and there is a new sand dune someplace else. How does that happen if there is, you know?" (lines 76-77). With this statement I nudged Laurel to consider the presence of many sand dunes in the desert as something that could potentially influence sand dune movement. After this statement Laurel said: “So there is just a lot of them and yeah, you know, [gesture implies many sand dunes] okay. Yeah. Okay, I was thinking, of it as like the same sand dune. [gesture emphasizes direct movement of one sand dune]” (lines 78-79). Laurel is agreeing with my comment about there being many dunes in the desert, and then she explains that she was previously thinking about the phenomenon as the same sand dune changing location. Now she is allowing for the instance of many dunes in the desert. Hence she accepts my suggestion and explains how it is influencing her thinking; she no longer thinks about a single dune in the desert changing locations. At this point, the reader might assume that my statement in lines 78-79 was unexpected and unlike anything Laurel had previously said, but this is not the case. A couple lines before Laurel actually initiated the idea of other sand in the desert rather than only one dune. Laurel said, “but maybe it’s like, 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). My statement in lines 78-79 is actually building on and elaborating her prior idea that there would not be one random pile of sand in the desert. This particular move may be an example of what in Lee, Russ, and Sherin (2008) refer to as insertion of new information, in which the interviewer provides new information that was not stated in the initial question. However, in this case the particular new information added is a selection and restatement of Laurel’s prior idea in lines 70-71, not completely new information.

In sum, in this section I have presented two cases in which my statements might have nudged Laurel’s thinking in specific ways. In the first case I nudged Laurel to consider in further detail the idea of sand stickiness. She had mentioned this idea previously, but I asked her for further information, thus shifting the direction of the conversation. This shift in the direction of the conversation due to my nudge may have contributed to the emphasis she proceeded to put on the relative rates of sand particles joining and leaving the dune, at the end of the discussion. In the second case I nudged Laurel to explicitly consider the role of presence of many sand dunes in the desert rather than only one dune. This happened after she had already initiated the idea of there existing lots of sand in the desert and not a random pile, but I explicitly suggested further emphasis on this idea and then she agreed with my suggestion. With these statements I nudged Laurel in specific ways, however, I did not shift the conversation in dramatic ways nor did I make judgments or other strong statements. Finally, many of these moves can be considered examples of common kinds of discourse and conversational moves discussed in Lee, Russ, and Sherin (2008).

**Case of Laurel Summary**

In summary, for the case of Laurel I argue that there is a shift in her explanations from less and less prototypically centralized to being more and more prototypically decentralized. The purpose of this analysis is to document in detail Laurel’s shifting explanations as her more centralized explanation is transformed into a more decentralized explanation.

During the intermediate period, I focused on explanations based on two mechanisms for how dunes move: sequential layers and sand-stickiness. I followed both of these explanations because they serve as lines of continuity from which we can begin to trace to a certain extent the shift from more centralized to more decentralized explanations. I argue that each of these
mechanisms are important to her shifting understandings; she had to relinquish various pieces of the explanations that were more centralized and add pieces that are more associated with decentralized causality.

I also documented some interactional moves that supported the shifting explanations. First, I documented moves that she initiated so that the phenomena to be explained shifted from dunes literally moving to dunes getting bigger and smaller. I also documented several smaller critical changes that she also initiated, such as addressing how dunes form initially and why dunes do not disappear. Second, I documented moves that I as the interviewer initiated that may have subtly shifted her explanation in small ways; I refer to these as nudges.

As this case is all about the particulars of Laurel’s shifting explanations, a natural follow up question would be to ask how much of what happened is unique to the Laurel case and which pieces might be relevant to other cases? To begin answering these questions I now switch to discussing the case of Keaton. Overall, the case of Keaton shares some similarities with the case of Laurel as both students began with explanations that are prototypically centralized and shifted towards explanations that are more prototypically decentralized. However, as I will discuss below, the cases are not exactly the same, and the intermediate explanations that supported these shifts are different.

Case of Keaton

The case of Keaton shares some general similarities to Laurel’s case, but is also different in particular details. Keaton is a Ph.D. student in physics. Similar to Laurel, during a short discussion about sand dunes his explanations gradually shift from being more prototypically associated with centralized causality to being more and more prototypically associated with decentralized causality. His initial explanation focused on sand grains and sand dunes both moving in the direction of the wind, which is prototypically associated with centralized causality. His final explanation, similar to Laurel’s final explanation, accounts for the sand dune behavior in terms of changing composition, while the overall size of dunes is constant.

During the intermediate period between Keaton’s initial and final explanations, similarly to how things with Laurel unfolded, a gradual process of relinquishing and putting together new explanations occurred. Also, as with Laurel, there was not any one factor that supported the change; the shift was a gradual process with many steps. However, the details of what was relinquished and what was added in Keaton’s explanation are different than those in Laurel’s case, due to a different emphasis.

In this section, I first discuss Keaton’s initial and final explanations. The initial one describes sand particles and the dune as both moving in the direction of the wind. His final explanation describes the dunes growing or shrinking on the two sides depending on the relative strength of the wind on each side. During the intermediate period, I follow a line of continuity about the relative direction of wind relative to sand grain and dune movement through three explanations. 1) Keaton initiated a question about which direction dunes move; he temporarily concludes that dunes move into the wind. 2) There was a temporary emphasis (which I initiated) about the fact that wind could go in only two directions resulting in Keaton explaining that the dunes are spread out parallel or perpendicular to the wind. 3) A third explanation about the relationship between the direction of movement of grains of sand and the dunes, he concludes that they might have nothing to do with each other. A major theme, or line of continuity, in this analysis is that Keaton continually focused on the relative direction of the wind relative to sand grain movement and relative to dune movement.
More Centralized Initial Explanation
The sand dune discussion with Keaton occurred toward the middle of the interview, after we had discussed traffic jams, and it lasted for 14 minutes. At the beginning, his explanations focused on the wind blowing the sand in the same direction as the wind, from the windward, or upwind, side of the dune to the leeward, or downwind, side of the dune. The result of this process is that the sand particles build up on the leeward side of the dune, so that over time the entire dune gradually moves in the direction of the wind. For example, Keaton says:

3. Keaton: So, you have these little pieces of sand and they are blowing all over the place [gesture implies sand blowing all over the place]
4. and if you have like there is a dune [gestures implies a dune in front of him]
5. the wind is blowing here. [gestures wind blowing into the windward side]
6. Like. At the front of it [points to windward side],
7. the wind is hitting all the sand, going all over the place
8. and then, at the sides [points at side so the dune] the,
9. the sand, if the wind is always blowing this direction [gestures wind going in the windward direction] so more likely,
10. it's more likely for the sand to go this way [points in the direction of the wind towards the lee side of the dune]
11. than that way [points in the direction opposite the direction of the wind].
12. Cause the winds blowing it.
13. So, like, all the sand moves from one side to the other side [gestures to show moving from the windwards side to the leeward side] and then,
14. on the lee side of the dune, the, like, it's protected from the wind, so it builds up there [points to lee side of the dune],

This transcript excerpt begins with Keaton mentioning sand particles blowing all over the place (line 3). He then gestures to imply a dune in front of him (line 4) and the wind blowing from one side and hitting the dune on the upwind or windward side of the dune (lines 5-6). He then mentions the wind hitting the sand on the sides of the dune (lines 7-8) and the sand being blown in the direction of the wind (line 9). Again, he reiterates that the sand goes in the direction of the wind (line 10) as opposed to the opposite direction (line 11). If the sand moves from the windward side of the dune to the leeward side (line 13), then the leeward side of the dune is protected from the wind so the sand builds up there (line 14). The dynamics described in this explanation are illustrated below in figure C. This initial explanation of how sand dunes move is prototypically centralized, or associated with centralized causality, because it accounts for sand particles and the entire dune having similar behavior in that they both move in the same direction.
More Decentralized Final Explanation
Keaton’s final more prototypically decentralized explanation describes a way in which the dunes and sand particles might move in opposite directions. This explanation incorporates the idea that the sand particles accumulate on the windward side of the dune, resulting in the dune moving in the opposite direction from the wind. Keaton recognizes that this version of the behavior is the opposite of what is described in his initial explanation in which the sand dune and the wind moved in the same direction.

103. Lauren: So how does the wind blowing towards the dune and away from the dune, influence whether or not the dune gets bigger? Or smaller? Or stay the same?

104. Keaton: All right, so, if the wind is stronger on the windward side [points to windward side of his dune] than it is on the leeward side [points to leeward side], than it means that its gonna grow faster [emphasizes the windward side growing] than it shrinks [points to leeward side]. So it will get bigger.

105. Keaton: So lets go back to the two dunes, the wind is blowing this way, then the wind is going to be stronger over here, so this dune is going to increase and this dune like the wind is weaker here and stronger here, so, it's gonna decrease. The opposite of what I said before.

This final excerpt from the Keaton sand dune discussion begins with me asking him about how the dune might get bigger or smaller given his current views of the wind blowing the sand (line 103). He then explains that the wind is stronger on the upwind or windward side of the dune than it is on the downwind or leeward side of the dune, so the dune will grow on the upwind side and shrink on the downwind side growing bigger (line 104). Then he goes back to a situation I had previously brought up about there possibly being two dunes in the desert. In that situation he thinks that the upwind dune would get bigger and the downwind dune would get smaller, and this is the opposite of his prior explanation (line 105).

Overall, in this final excerpt from the sand dune discussion Keaton has come to recognize that sand dunes and sand particles move differently. The sand particles move in the direction of the wind while the dunes move in the opposite direction. This particular behavior is illustrated in figure D. His explanations based on this behavior are more prototypically decentralized because the movement of sand particles and sand dunes, the two levels of the phenomena, are different—they move in different directions.
Do dunes move with or against the wind?
Keaton wrestled with the relationship between the dune’s movement and the wind’s movement. Rather than viewing the phenomena to be explained as “how do dunes move?” or “how do dunes get bigger or smaller?” which was how Laurel addressed the issue, Keaton focused on the phenomena to be explained as “which direction do dunes move, with or against the direction of the wind?” He initially assumed that dunes move downwind, but then relinquished this version of events and added an explanation in which the dunes move upwind.

34. Lauren: What would happen //
35. Keaton: I don't know [gestures]. Do dunes move that way or do they move the opposite direction?
36. Keaton: Cause like the sand all around the desert, right? So wind is getting, so the sand is getting blown this way, onto the dune [points at windward side]
37. and then here it might be getting blown off of the dune [points at the leeward side].
38. So I might be totally wrong and the dunes actually move like into the wind [points in direction of the wind flow]. I don't know which is the right answer.
39. Cause, like, there is way more sand in the whole desert than there is than sand just in that dune. So, it could be that sand is always getting blown toward this side of the dune [points at windward side], and getting blown away from this side [points at leeward side]. So it moves into the wind. I'm not sure which is the real case.
40. Lauren: So, talk me through, how does the wind blow sand in each of these cases?
41. Keaton: It blows it around. Like, if there was a big flat desert //
42. Lauren: yeah //
43. Keaton: and the wind was blowing across the surface, and if pieces of sand are on the surface, you know, the wind hits it and it gets blown. [gestures in the direction of the wind]
44. Lauren: So in that case, there is some sand, the wind is hitting the sand, and the
sand is moving? [gestures to imply sand moving in the direction of the wind]

46. Keaton: Yeah

47. Let me, does that make sense, yeah?

48. The sand is all moving this way [points with right hand to the left side] but it could be possible that the dune is moving the other way [points with left hand towards the right] cause like it keeps getting made of different sand. Right?

49. Just cause the sand grains are going one way [points with right hand towards left], doesn't mean the dune has to go that way.

50. So, it could be that all the sand in the desert is getting blown onto this windward side of the dune and getting blown away from the leeward side, and it actually moves this way [gestures with right hand towards the right].

51. Lauren: I see.

52. Keaton: Yeah, I think that’s probably, more likely, now that I think about it. Okay.

At the beginning of this excerpt, in line 35, Keaton asks himself about which direction dunes move: with or against the direction of the wind. He mentions sand blowing all around the desert (line 36) with sand specifically getting blown on the dune on the windward side (line 37) and off the dune on the leeward side (line 38). Then he recognizes that this is different from his prior statement and says, “So I might be totally wrong and the dunes actually move like into the wind [points in direction of the wind flow]. I don’t know which is the right answer.” (line 39). Then he mentions some new information about evidence of lots of sand in the desert and reiterates the prior statement: sand is always being blown toward the windward side and away from the leeward side and dune moves into the wind (line 40). At this point I realized what two different possibilities he was explaining, which were dunes moving into or out of the wind, and I explicitly asked him to again talk through these two options (line 41). He next mentions the existence of sand in the desert (line 42) and that the sand would be blown in the direction of the wind (line 44) and I then reiterate this idea (line 45). Then Keaton asks himself if this makes sense (line 47). He then explains that given these dynamics, the sand might be moving one direction, and the dune is moving the other direction, so that the dune is gradually remade out of different sand (line 48). This idea is then reiterated in lines 49 and 50, and then in line 52 Keaton makes the evaluation that this option is now “more likely.”

In this section Keaton begins wrestling with the question of whether dunes move in the direction of the wind or in the opposite direction. Several times during this excerpt he explains how the phenomena would work if dunes move in the opposite direction from the wind. At the end he comes to decide that the option of dunes moving in the opposite direction of the wind is more likely. Through this excerpt we can see him relinquishing the idea that dunes move in the same direction as the wind.

Underlying this excerpt is some prior knowledge about the idea that sand grains are blown in the direction of the wind. He might be cuing a version of the p-prim “force as mover” or the p-prim “continuous force,” given that the wind is viewed as steady. Clearly, he accepts the idea of the sand grains being blown by the wind and moving in the same direction as the wind. The central issue he is wrestling with is whether this behavior results in the dune moving in the direction of the wind or the direction opposite of the wind. To try and resolve this issue he cues some prior knowledge about what he finds relevant in this situation: the example of more
sand in the entire desert than in just one dune (line 40). In the next excerpt we again see him activating some of these knowledge pieces.

**Are dunes parallel or perpendicular to the wind?**

Another one of Keaton’s intermediate explanations centers around the issue of whether dunes are spread out parallel or perpendicular to the direction of the wind. He initially assumed that dunes would get stretched out parallel to the direction of the wind, but then relinquished that version of events and instead added an explanation based on dunes spreading out perpendicular to the direction of the wind. My illustrations of both of these possibilities are shown in figure E. Then he mentions some prior experiences seeing dunes at beaches in Florida where the wind was blowing perpendicular to the shoreline and perpendicular to the dunes. Immediately before this excerpt Keaton had discussed the resulting behavior when the wind is going in several different directions, and then at the beginning of this excerpt I asked him to instead to focus on the wind only going in two directions.

59. Lauren: So, before you were explaining it with just wind going in one direction, say you had a situation where like wind went like one direction in the morning or one direction in the afternoon?
60. Keaton: Okay.
61. Lauren: Or, like rather than think about a whole bunch of different directions, lets just think about two directions.
62. Keaton: okay, okay, yes, lets say it alternatives.
63. Lauren: yeah, sure.
64. Keaton: Then, then, would it get stretched out this way [pulls hands apart] I think it would get stretched out, cause it, if the wind is blowing from the left [points to left with right hand], as often as from the right [points to the right with left hand]. But it's not blowing the other direction [points straight ahead, to signify that it is not left or right], then a grain of sand, it's gona be, move left and right a lot [moves right hand left and right], but not move in the other direction as much [moves right hand forwards and backwards]. So if all the sand is moving this way [moves both hands left and right], it seems like all the sand dunes would get stretched out as much and these lines [pulls hands apart].
65. But then again, at the beach, the wind is always blowing toward land [points with right hand in left direction] or toward the ocean [points with right hand to the right], but the dunes seem to be, like, parallel to the beach [pulls hands apart] instead of perpendicular.
66. So I don't know why that is. I never really thought about it.
67. Let me think. Maybe thats wrong. Maybe the dunes, like, go perpendicular to the wind, but why would that happen? I don't know.
68. Lauren: Where have you? Are you thinking of some particular dunes?
69. Keaton: Well, yea, at the beach in Florida, where I'm from. I remember like, I think, I remember the dunes, here's the beach [holds left arm straight in front], the dunes, the wind at the beach is always going this way or this way [points with right hand in left and right direction, perpendicular to the direction that the left arm is pointing].
70. Lauren: right, right.
72. Keaton: but the dunes are more spread out in this direction. [gestures to imply parallel to left arm/beach]

73. That contradicts what I said earlier. I don't know, it's complicated. [gestures while not speaking]

At the beginning of this excerpt I asked Keaton to think not about wind going in one direction, or many directions, but instead about the wind alternating, going two directions (lines 59-62). Keaton mentions that then the dune would be stretched out in the direction of the wind (line 64). He explains that if the wind is blowing equally often in both directions, left and right, then the sand particles would move left to right and not in the other direction, so that then the dune would be stretched out left to right, parallel to the wind (line 65). Then Keaton mentions that at the beach, the wind tends to blow towards the land or towards the ocean, which is perpendicular to the shoreline. But the sand dunes are parallel to the beach (line 66), thus being perpendicular to the wind and the opposite of his prior explanation in line 65. Given these contrasting options, he then mentions being unsure and having not thought about this before (line 67). Given these two possibilities, he then questions why the dunes would be perpendicular to the wind and what would create that behavior (line 68). Given that Keaton had previously mentioned seeing sand dunes at the beach, I then asked about particular dunes (line 69). Keaton then goes on mentioning the dunes in Florida where the wind is perpendicular to the shoreline. He expands this idea again, mentioning that he knows that in Florida the dunes are spread out parallel to the beach (line 72). At this point (line 73) he recognizes that this idea of the dunes being spread out perpendicular to the direction of the wind is contradictory to his prior idea (line 65) of the dunes being spread out parallel to the direction of the wind.

In this excerpt, Keaton is initially addressing my question, focusing on the wind going in only two directions. He recognizes that the sand particles will then move in only two directions and then assumes that in this situation the sand dune would be spread out parallel to the wind, an idea which is illustrated below in figure E.i. Underlying this explanation, as in the prior excerpt, might be the force as mover or continuous motion p-prim. This explanation might contain one of these p-prims as he views the wind, behaving as a force, and moving the sand particles, so that one would expect the sand particles to move in the same direction as the wind. However, in this explanation there is a conflict between some prior knowledge based on previous experiences with dunes that are parallel to the beach and perpendicular to the direction of the wind, which blows perpendicular to the shoreline. This version of sand dune dynamics can be seen in figure E.ii below. By the end of the excerpt he recognizes the contradiction but does not resolve it.

Figure E: Two versions of the orientation of the wind and sand dune. i) The dune being stretched out parallel to the winds direction. ii) The dune begin stretched out perpendicular to the winds direction.
This contradiction between two possibilities is important as it relates to Keaton’s shifting understanding but it is not obviously resolved. The fact that this contradiction between two possible orientations of the wind and dunes at beaches is not resolved might lead one to conclude that this issue is an unrelated diversion. However, in the next section, which occurs immediately after the prior section, he concludes that the motion of the sand grains might be totally independent of the motion of the dunes. This suggests that the prior issue about dunes being parallel or perpendicular to the wind is moot. In other words, his having raised this issue might have been helpful because he subsequently successfully relinquishes the entire issue in favor of a new idea that the motion of the sand grains might be totally independent of the motion of the dunes.

**Sand Particles and Dune Movement Might be Independent**

In this third and final intermediate explanation Keaton becomes more explicit about his idea that the movement of sand particles and the entire dune could be independent of each other. Keaton explicitly states that his prior idea about the sand particles and dunes moving in the same direction was wrong, and, in fact, the way the sand grains move has nothing to do with the way the entire dune moves.

74. Keaton: Yeah, maybe what I said before about //
75. Lauren: Yeah? //
76. Keaton: like the sand, move in the direction of the wind [back and forth hand motion in a sweeping direction with left hand], so that the dunes spread out that way [both hands moving outwards], is wrong.
77. Because like, in the way the grains of sand move [motions with left hand], could have nothing to do with the way the dune as a whole moves [motions with right hand].

This excerpt occurs immediately after the prior discussion about the dunes being possibly perpendicular or parallel to the wind. Keaton mentions that what he said before (line 74) about the sand and the wind moving in the same direction is wrong (line 76). He then is explicit, the “the way the grains of sand move [motions with left hand], could have nothing to do with the way the dune as a whole moves” (line 77). In this line he emphasizes the idea with accompanying gestures that emphasize the two directions. Notice that underlying this explanation he is still activating some p-prim-like knowledge about the grains of sand moving with the wind, similar to the previous excerpt. However, now he is adding a new piece of knowledge about what is visibly salient, that of dunes and sand grains motion being independent. This piece of knowledge and its implications for the behavior, namely that one can not predict dunes movement based on individual sand grain’s movement is helpful in his final explanation and recognition of emergence.

In this excerpt Keaton has solved the contradiction that arose in the prior excerpt, about dunes being parallel or perpendicular to the wind by adding a new expectation about sand grains and dunes movement being independent, which is helpful for recognition of emergence. Here he is recognizing the non-deterministic nature of the relationship between the movement of individual grains of sand and the movement of the entire dunes.
Case of Keaton Summary
In this section, I presented the case of Keaton as his explanations shifted from more prototypically centralized to more prototypically decentralized. His initial explanation focused on the idea of sand particles and the dune both moving downwind. His final explanation focused on the idea of sand particles collecting on the upwind side of the dune and leaving the dune on the downwind side of the dune so that the dune moves upwind. In order to understand this shift I investigate three intermediate explanations that all deal with the issue of the direction of dunes relative to that of the wind. 1) In the first explanation Keaton wrestles with whether the dune moves with or against the wind. 2) In the second explanation he addresses the question of whether the dunes are parallel or perpendicular to the wind and the shoreline. 3) Finally, in the third explanation he comes to accept that sand particles and the dune can move independently of one another. All of these explanations, particularly, the third one about sand particles and dunes moving independently from one another contribute to his final explanation in which the dunes move in the opposite direction from the wind, as sand particles collect on the upwind side of the dune and leave the dune on downwind side of the dune. Across these explanations, we can see that a central theme, or line of continuity, in Keaton’s shifting understanding is the relative direction of the wind as compared to the movement of sand particles and the movement of dunes.

Similarities and Differences in Laurel and Keaton Cases
In this chapter, I have presented two similar cases; both students’ explanations shift from bring more centralized to more decentralized. But the specifics of the paths of shifting explanations are different. Thus a main point of this analysis is that there could potentially be many specific paths that can be associated with the shifting explanations. In this section, I will first discuss the similarities of their overall shifts, and then I will discuss some differences, both in terms of their overall shifts and in terms of their intermediate explanations. Both Laurel’s and Keaton’s initial explanations were more centralized and their final explanations were more decentralized. Laurel’s initial explanation focused on the wind literally moving the entire dune at once. Keaton’s initial explanation focused on the wind moving both the entire dune and the individual sand particles in the same direction. These two initial explanations were clearly not exactly same, the student were likely activating some different knowledge elements when generating them, but they were both associated with centralized causality. Laurel’s final explanation focused on the size of the dune remaining constant while sand particles join and leave the dune, I referred to this as changing composition. Keaton’s final explanation focused on the dunes moving upwind as sand particles, suspended in the wind, collect on the upwind side and leave the dune on the down wind side, thus the dune moves upwind and in the opposite direction from the sand particles. Again, these two final explanations were obviously not the same, they are likely based on some different knowledge elements, but both are associated with decentralized causality.

During the intermediate period, both Keaton and Laurel generated a series of explanations illustrating his or her unique path. Two lines of continuity in Laurel’s path are the movement of sand in sequential layers and sand-stickiness. She generated intermediate explanations based on both of these ideas and I traced the upsurge of these two ideas and their connection to her final decentralized explanation. These two ideas, sand-stickiness and sequential layers, were absent from the Keaton data. Keaton, during the course of the discussion, focused on a line of continuity in the relative direction of dune movement as related to the wind and sand particle movement. He focused on issues of whether dunes moved with or against the
wind, if they stretched out parallel or perpendicular to the wind, and eventually, the independence of sand grain movement from dune movement. This aspect of the phenomena, relative direction of dune movement as related to wind and sand particle movement, which was so salient to Keaton and based on the prior knowledge he activated, was generally absent in the Laurel data. In her final, changing composition explanation there is an emphasis on dune movement relative to sand particle movement, but this issue was otherwise absent from the data.

There are also differences in the questions they were explaining. Laurel explained the dunes moving and dunes changing size. Keaton also focused on dunes moving, but it was embedded within questions about the relative direction of the dune as compared to the wind. These two cases involved different and shifting explanandum. Rather than these two cases being the same, this difference illustrates the variety of explanations and their associated explanandums.

The general patterns across Keaton’s and Laurel’s shifting explanations bear many important similarities, there was a common starting point of explanations that were prototypically associated with centralized causality, and a common end point of explanations that were more prototypically associated with decentralized causality—thus illustrating that this general shift is not idiosyncratic to a single case. The particular details of each shift were different as they focused on different questions. This difference illustrates that there are at least two paths students can travel and that the differences between their paths depend on each person’s particular prior knowledge. In the next section, I place these two cases in the larger literature context of how to conceptualize students’ changing explanations about emergence, with a focus on the role of prior knowledge.

**Discussion and Conclusion**

Throughout the Laurel and Keaton data sections I argued in both cases there was a common shift in their explanations from more prototypically centralized to more prototypically decentralized. However, the particular details of the shifts were different in terms of the specific paths taken, the particular prior knowledge and emphases put on each. While there are potentially other differences between the interviews that influences the different paths, in the analysis I showed that there were differences in their knowledge. Laurel first focused on explaining how dunes literally change position, and then focused on explaining how dunes get bigger and smaller, generating explanations based on a variety of mechanisms. There was also a series of small, critical changes in topic that opened up the space of the phenomena to be discussed. Keaton first focused on dunes changing positions, but then switched to focusing on whether dunes move with the wind or against the wind, a central line of continuity in his explanations was the relative direction of the sand particles’ movement as compared to the dune’s movement. Also, Laurel and Keaton focused on different dimensions of the individual sand grain movement. Laurel focused on the mechanism of sand stickiness resulting in the dunes getting bigger, while Keaton focused on the relationship between whether or not sand grain movement and dune movement, are independent one from the other. Thus I argued that there are many potential specific paths that can be associated with the shifting explanations exhibited in both cases, and the particular paths taken depend at least in part on students’ prior knowledge.

In the rest of this section, I discuss these results in terms of broader connections to other literature on the subject. First I discuss these results in terms of points of divergence with the hypotheses in Chi et. al (2012) about misconceived causal explanations. Second I discuss these results in terms of more general literature that has emphasized the divergence between centralized and decentralized explanations, while this chapter emphasizes the lines of continuity
between these ways of understanding. Finally, I discuss some interviewing methodological points about the role of the tension between what phenomena the interviewee is asked to explain and what phenomena they choose to explain.

First, Chi et al., (2012) present a series of specific hypotheses about what constitutes a misconceived explanation, why misconceived explanations are so common, and a series of hypotheses for how they might be overcome. In short, they argue that students’ difficulties are due to students’ overreliance on the direct-causal scheme to interpret emergent processes, such as diffusion, which leads to a misconception. They argue that instead, students need to use an emergent-causal schema. The analysis presented in this chapter suggests results that are different from those presented Chi et al., (2012) in the area of students’ revision of their own explanations, and students’ explorations of the conditions that influence emergent behaviors.

In the context of discussing ways to test or confirm their hypothesis about how misconceptions arise Chi et. al (2012) explain that they expect that when students are confronted with an incorrect prediction or explanation and then revise their own explanations, their new explanation will appear piecemeal because they are still relying on the incorrect schema.

“Sixth, our hypothesis is also consistent with findings showing that students, upon confrontation about an incorrect prediction or explanation of a particular phenomenon, can revise their own specific explanation of the phenomenon, and yet their explanations will continue to be incorrect, making their explanations appear piecemeal (diSessa, 1993). Our hypothesis suggests that this is because the revised explanations are still generated from an inappropriate Direct-causal Schema.” (Chi et al., 2012, p. 14)

The analysis presented in this paper suggests otherwise. There are examples in both the Keaton and Laurel cases in which the students revised their explanations and their new explanations were relatively correct. For example, in the case of Keaton, he initially expected the dunes and wind to move in the same direction, revised this due to specific prior knowledge, and came up with a correct final explanation in which dunes and the wind are moving in different directions, which is correct. Also, Keaton at one point generated an explanation about dunes being parallel to the beach. Then he revised this beach explanation and incorporated some prior knowledge from having visited beaches in Florida, and generated a more correct explanation about dunes being perpendicular to the beach. During the Laurel interview, she relinquished many pieces of explanations that were associated with centralized causality and added many pieces that were more associated with decentralized causality. Many of the pieces that Laurel relinquished, such as the idea of dunes moving literally at once, she recognized as an incorrect predication. I argue that in doing this she was making important progress towards the more normative decentralized explanation. Hence, I argue that both Keaton and Laurel revised their explanations during the interviews and that their final explanations were relatively correct. One confounding factor is that both Laurel and Keaton themselves instigated the confrontation about the incorrect explanation. Neither of them was confronted by the interviewer with new evidence. Perhaps the fact that in these cases the new explanations relied on knowledge resources that the students had cued previously made the new explanations more tenable.

In addition to claiming that student initiated revisions of the explanations will not be helpful and result in piecemeal explanations, Chi et al., (2012) also claim that learning more about the conditions influencing the behavior at each level, specifically more knowledge about
the behaviors at each level, is not sufficient to impact a misconceived causal explanation.

“In short, our hypothesis for what a misconception is implies that (a) learning more about the structure, behavior, and function of each level of a process, or (b) learning more about the conditions and how they affect the behavior of each level, or (c) making each level more visible through simulations, will not impact (improve or remove) misconceived causal explanations, because misconceived causal explanations do not pertain to a lack of knowledge about any single level nor are they caused by invisibility of either the pattern or the agents. Rather, misconceived explanations result from an appeal to inappropriate inter-level relationships between the interactions at the agents’ level and the pattern.” (Chi et al., 2012 p. 12.)

In the above excerpt Chi and colleagues are explaining that based on their hypotheses for what a misconception is none of the following are sufficient to improve or remove the misconception: learning more about the structure, behavior, and function at each level, learning more about the conditions at each level, and making each level more visible through simulations. With this analysis my results are disagreeing with the second point about learning about the conditions at each level. During the course of the discussion both Keaton and Laurel activated new knowledge about the conditions of sand dune behavior. For example, Laurel activated new knowledge about the conditions under which sand dunes begin forming (when randomly a small pile of sand forms), when they get bigger (when sand particles that are suspended in the wind stick to the dune), and how changes in the wind’s strength and direction influence the dune. Keaton considers the dunes behavior under the following wind conditions: the wind blowing only one direction, the wind blowing two opposite directions, and the wind blowing every which way. As I argue in this analysis, all of these pieces of their initial and intermediate explanations, which include pieces of knowledge about the conditions influencing the sand dune phenomena, influenced their final more decentralized explanations in crucial ways. As I discussed earlier for the case of Laurel there were many factors that influenced her shift in explanations, I cannot claim that any one of these factors alone is sufficient for the shift, but cuing knowledge pieces that are about the conditions at each level was an important factor in her shift. Beyond these specific points of difference between the current chapter and Chi et al., (2012), there are also some broader contributions made by this chapter to our understanding of students’ reasoning about the relationship between centralized and decentralized causality.

Second, prior work (e.g. Jacobson 2001; Chi, 2005) has tended to emphasize the divisions between centralized and decentralized explanations and understandings. In contrast, one contribution of the current chapter is to illustrate the lines of continuity between these two ways of understanding and to show how chance can occur. The afore mentioned prior work has tended not to focus on the process of change at a moment-to-moment time scale and instead they have focused on conceptualized students’ understanding of emergence in terms of an emergent or complex systems ontology (Chi, 2005) or mental model (Jacobson, 2001). Implications of my work emphasize the need for instructional activities that support students’ gradual shifts along lines of continuity between these two ways of understanding rather than instructional implications that support students in reasoning through a particular mental model or ontology.

As part of this focus on lines of continuity, this analysis has identified several student generated intermediate explanations, such as sequential layers, sand-stickiness, and varying
directional relationships between the wind, dunes and sand particles. These intermediate explanations may serve as a basis for future instruction building on how students actually come to understand these phenomena. For example, perhaps future instruction could present students with a series of intermediate explanations or models, possibly using digital technology, which highlight mechanisms such as sequential layers or sand-stickiness, or different versions of the phenomena to be explained, thus presenting possible paths towards an understanding associated with decentralized causality. This is similar to White (1993a), which advocates instruction that focuses on intermediate causal model via a progression of increasing complexity that support an understanding among different levels, such as macroscopic and microscopic, and iconic and symbolic.

Third, the interviews presented in this chapter use an open-ended method, similar to what has been described in Ginsburg (1997). One characteristic of this method is that it allows negotiation of what phenomena is to be explained. A negotiation of the explanandum. There might be a tendency to assume that during an interview the student is only generating an explanation that answers the researchers’ intended question, the researchers’ explanandum. One might assume that a student would not choose to answer a different question, one of their own design. However, one could reasonably imagine a student finding his or her own question more interesting, perhaps a question that he or she is more motivated to answer. This is exactly what is shown to have happened in these data. Laurel decided what questions to answer and that choice was crucial to her shifting understanding. In other words, Laurel initiated shift in the phenomenon to be explained, a shift in the explanandum. This tension between the researchers’ question and the question a student chooses to answer has important implications for students’ reasoning in complex systems, as well as interviewing techniques more broadly. In this case, letting Laurel decide what the phenomena is to be explained was an important piece of what made it possible for her to make progress in understanding sand dune movement—perhaps this approach of allowing students the flexibility to decide what is the interesting and important phenomena to be explained would be useful in other settings.
CHAPTER 5: VARIATION IN STUDENTS’ UNDERSTANDING AND EXPLANATIONS OF EMERGENCE ACROSS SEVEN PROBLEM CONTEXTS

Introduction

My goal in this chapter is to investigate how the nature of a specific domain influences students’ reasoning. I focus on students’ reasoning about various phenomena (e.g. sand dunes, traffic jams, forest fires) whose behavior is associated with complex systems, and I compare and contrast the similarities and differences in students’ explanations and conceptualization of these phenomena.

I compare and contrast these similarities and differences through six ways of focusing one’s attention, otherwise known as, student generated explanatory patterns. These are temporary explanatory structures, similar to dynamic mental constructs (Sherin, Krakowski, & Lee, 2012). In the analysis, I investigate the kinds of prior knowledge students activate within these explanatory patterns. I focus on explanatory patterns that may be particularly helpful in supporting students in coming to understand and generate explanations that are either potentially helpful in coming to reasoning through the phenomena in terms of decentralized causality, mid-layers, convergence to a limit, steady state, periodic motion, and threshold, or that are emergent, changing composition. For each explanatory pattern, I investigate its use across all seven problem contexts, and I use the sketch of epistemic resources, which was introduced in Chapter 2, to capture the kinds of prior knowledge activated. Using this theoretical machinery, I conduct an analysis of the similarities and differences across a variety of cases in which many students used different explanatory patterns.

The results showcase variety in terms of how students conceptualize phenomena as based on their prior knowledge and on the nature of the problem context. I find that when changing composition is used students’ access key prior knowledge about the relative rates of agents coming and going, such as sand particles joining and leaving the dune at equal rates. In prior work steady state was associated with centralized causality (Jacobson, 2001), but I find that explanations based on this explanatory pattern are often rejected due to prior knowledge emphasizing the unrealistic nature of this pattern, and this pattern is often juxtaposed next to changing composition. I find that periodic motion is most relevant to problem contexts in which students’ prior knowledge supports them in focusing on the recurrent nature of the problem context, such as traffic jams and sand dunes. When it is activated in non-recurrent problem contexts, for instance, viruses, students tend to not be focusing on actual periodic motion. I find that of convergence to a limit is often mentioned when students’ prior knowledge supports them in focusing on an underlying mechanism, for example, birds preferring to fly in formation because it is easier to fly, however, in contrast, for diffusion students suggested that convergence to a limit was a natural state with no explicit mechanism. I find that the activation of the mid-levels pattern is influenced by students’ prior knowledge about the particular arrangement of agents, for instance sand particles most exposed to the wind or a virus spreading from one town...
to another town. Finally, I find that threshold was activated in many ways, being applied to the macro level, for instance, the size of dunes reaching a threshold point when they collapse, or being applied to the micro level, for instance, the speed of cars reaching a point where they have to slow down in order to avoid accidents. Other times threshold was applied to characteristics that describe the phenomena such as temperature and energy of molecules.

The results showcase the variety in terms of students’ understanding across the seven problem contexts. I find that students’ understanding of complex systems varies across these problem contexts: forest fires, traffic jams, sand dunes, and diffusion, among others. This contributes to the literature in two ways. First, these results calls into question a general trend of de-emphasizing domain differences in students’ understanding of emergence, because students’ understanding varies so widely across the seven problem contexts. Second, I have shown the importance of variability and of different kinds of prior knowledge in students’ understanding. This calls into question the general trend of de-emphasizing the multitude of prior knowledge resources that influence students’ understanding of emergence. I find that a main factor distinguishing certain problem contexts from being easier or harder for students has to do with the kinds of prior knowledge resources activated. Specifically, I find that in problem contexts, such as sand dunes, where students are able to access a wide range of more intuitive resources that are applicable at multiple levels, coming to see the decentralized nature of the phenomena is not an enormous challenge. In comparison, in problem contexts, for instance, diffusion, students encounter many challenges, this may include a lack of intuitive knowledge about the molecular level, despite access to other kinds of prior knowledge. The specific attributes and challenges associated with each problem context are discussed in further detail in the discussion section, but the main goal of this chapter is to discuss variability in students’ understanding through the six explanatory patterns. To do this, I first review the theoretical framework from Chapter 2, the sketch of epistemological resources.

Review of the Sketch of Epistemological Resources

In this section, I provide an overview of the kinds of epistemological resources I found relevant to students’ explanations in this context as was discussed in Chapter 2. In that chapter I discussed two kinds of relevant epistemological resources, kinds of prior knowledge and characterization of that prior knowledge. I also discussed several features of the problem context that influence students’ understanding of emergence. None of these lists are necessarily complete, this is a starting point for the kinds of epistemological resources I found in this data corpus and relevant to students’ understanding and developing explanations of how these problem contexts behave in an emergent manner.

The four kinds of prior knowledge that I focus on include: experiential knowledge that is or is not cued, p-prims, pragmatic knowledge, and agent knowledge. Experiential knowledge is knowledge about ones experiences with events that includes perspectives on what influences are and are not relevant. For example, in traffic jams students have lots of experiences sitting in cars, which is often relevant, and in comparison, they have no experiences sitting on sand particles. P-prims are small intuitive causal knowledge pieces that are cued in a particular context based on the surroundings, for instance, the blocking p-prim was often cued in the context of a dune blocking the path of the wind. Pragmatic knowledge is knowledge about the underlying pragmatics of a situation based on ones past encounters. For example, in traffic jams students cued pragmatic knowledge about wanting to be safe and avoid accidents. Agent knowledge is knowledge about the behaviors, characteristics, and nature of the agent. This includes knowledge about birds and fish behaving in ways that share some similarities with humans.
In addition to kinds of knowledge, this mini-theory also includes information about depictions of how this knowledge is used, the limits of it, and how new knowledge is created, I refer to this list as “characterizations of knowledge.” First, there is performance of the knowledge, this is actions by which the knowledge is coordinated or aligned through common abstractions. For example, seeing the spreading of a virus as similar to the spreading of a forest fire because both spread through physical context. Second, there are boundaries to the knowledge, this is things that are or are not seen or construed as relevant. For many students the macro level of the fire was relevant but the micro electron level was not as relevant. Third, there is the process of creating knowledge, this is readouts of a situation that are relevant to a particular situation or problem and visible to the student. For instance, in traffic jams cars speeds are relevant and visible to the students.

Finally, there are three features of the problem context that have the potential to influence students emergent thinking. First, for some problem contexts the behavior plausibly does or does not occur again and again. For example, the same sand dunes could move back and forth even though that is unlikely. The same fire cannot burn through an area again and again. This differentiation influences whether or not students explain the phenomena in terms of periodic motion. Second, the relative arrangement of agents, for instance sand particles arranged in natural layers on a dune, which influences students generating explanations using the mid-levels pattern. Third, a close or distant relationship between agents and humans influences whether or not students have a tendency to personify the agents, such as fish or birds, which in turn influences how students construe the underlying mechanism.

**Review of the Explanatory Patterns**

In this analysis, I focus on a series of ways of focusing ones attention within the problem contexts and I refer to these as “explanatory patterns.” While there are many possible explanatory patterns, I focus on a sub-set of these pattern that are potentially helpful for students in coming to see decentralized and emergent behaviors. These explanatory patterns bear a close relationship to existing constructs, they may be locally coherent as they are dynamic, emerge from a pool of knowledge, and may hold together for only a short time period. Some knowledge configurations bear a resemblance to Dynamic Mental Constructs as they are dynamic mental states that can shift during an interview and depend on many factors including interview questions (Sherin, et al., 2012). In this chapter, I focus on six explanatory patterns. Four of them exhibit a related behavior, which I refer to as periodic and limiting behavior. These four include changing composition, steady state, periodic motion, and convergence to a limit. I also discuss the two other explanatory patterns of threshold and mid-levels. Some of these explanatory patterns, including mid-levels, have been discussed elsewhere in the literature; for example a strategy similar to the mid-levels explanatory pattern is discussed in Eylon and Daniel (1990), Frederiksen, White, and Gutwill, (1999), Levy and Wilensky (2008). Additionally, White (1993a) discusses the importance of emergent properties of systems, such as steady-state equations and flow and equilibration processes within intermediate causal models. However, other explanatory patterns, for instance, threshold is relatively sparse in the learning sciences literature.

The first one, changing composition is emergent, the others are potentially helpful for students developing explanations that capture some of the emergent aspects of the behavior as will be argued throughout this chapter. For each explanatory pattern and each case of a student’s explanation incorporating that pattern, when possible, I attempt to investigate why that particular pattern may have been helpful for that student. As was discussed in Chapter 1, some examples
of the ways these student generated explanatory patterns are potentially helpful in recognition of emergence are that they support the students in connecting levels, as well as focusing on the underlying mechanism, relative rates, intermediate levels, and being aware of high-level variableness. This part of the analysis is key because my collection of hypotheses regarding the helpfulness of certain explanatory patterns serves as the foundation for the sketch of epistemological resources. The analysis to follow is organized around these student generated explanatory patterns such that within each, I investigate cases of that explanatory pattern being used in multiple problem contexts by different students and in those cases; I investigate the particular prior knowledge that supported that explanatory pattern.

**Periodic and Limiting Behaviors**

Existing research often includes equilibrium, periodic, and limiting behaviors as one indicator referred to by different names, that might be incorporated into students’ understanding of complex systems (e.g. Jacobson, 2001; Resnick, 1994; Chi, 2005), but I find that there are variations within this family of related behaviors despite some common language. In my analysis, I found examples of the following kinds of periodic and limiting behaviors: changing composition, convergence to a limit, periodic motion, and steady state. I also found examples of damped and unstable oscillation, but I do not pursue these further in the analysis because of limited data. In the following analysis, I focus on the four explanatory patterns that occurred within the data set with some frequency and I argue that they may be productive explanatory pattern for supporting students’ reasoning about decentralized causality. I first summarize these four explanatory patterns and in table G I present a summary of the relative frequency. In the subsequent analysis, I discuss in detail many cases of students’ explanations incorporating these explanatory patterns in various problem contexts. The focus of the analysis is to demonstrate the variation in students’ understanding through these four explanatory patterns and how they depended on specific prior knowledge.

Changing composition, which is sometimes also called dynamic equilibrium, refers to situations in which the macroscopic level is unchanging but the microscopic level phenomenon is constantly changing. For example, the size of the dune is the same, but there is some sand leaving and some sand joining the dune such that the composition of the dune is always in flux. Resnick (1994) documented that this behavior is associated with decentralized causality in the context of students exploring the behavior of traffic jams.

Another related behavior is steady state motion, which refers to situations where the phenomena are unchanging at both the macro and micro levels. For example, in the traffic jam problem context a highway can be closed due to a snowstorm resulting in cars not moving, and no cars being allowed to enter or exit the highway. Jacobson (2001) discusses this kind of equilibrium as being associated with a centralized mental model (misconception). However, in my data I find more subtly, often after it is incorporated in explanations it is rejected in favor of other explanatory patterns, such as changing composition and periodic motion. Periodic motion is an explanatory pattern wherein the behavior of the system exhibits characteristics associated with oscillatory or cyclical motion. For example, the traffic jams get bigger, then smaller, then bigger again, continuing along with this pattern. In my data, I found that this pattern was applied commonly to problem contexts that students viewed as recurrent, sand dunes, traffic jams, fish, and birds, and rarely applied to the problem contexts that students viewed as non-recurrent including viruses, forest fires, and diffusion.
Convergence to a limit is an explanatory pattern in which the behavior of the system changes size, but over time gradually stabilizes. For example, one could think about a sand dune getting bigger, then smaller, then bigger again, but over time settling into one size. This can be thought of as similar to a damped cyclical motion. For example, traffic jams get bigger and smaller, but over time, they stabilize to a particular size. This explanatory pattern was only applied to three problem contexts, sand dunes, birds, and diffusion, and only in a few cases. For the sand dune and bird cases, convergence to a limit may have helped students move towards recognition of decentralized causality as it was accompanied by mechanism that accounted for why the behavior converged to a limit, for instance, desires to fly in formation (birds) and mechanism of why big dunes get smaller (sand falls off) and small dunes get bigger (sand collects).

Of these four types of periodic and limiting behaviors, I find that some are more or less common in different problem contexts. In table G, I present a summary of this analysis. To be clear, “many” refer to more than six, “some” refers to more than three, and “few” refers to more than one. From this table it should be apparent that changing composition was mentioned many times in the sand dunes and traffic jams, and sometimes in the virus problem context. Steady state was mentioned sometimes in the sand dunes problem context and a few times in the traffic jam and virus problem context. Periodic motion was mentioned sometimes in the traffic jam context and few times in the sand dunes and viruses problem context. Convergence to a limit was mentioned a few times in the sand dunes, diffusion, and bird problem contexts. In the following analysis of these four explanatory patterns, I delve into details about the similarities and differences of how these four kinds of periodic and limiting behaviors were utilized in the different problem contexts in terms of prior knowledge.

<table>
<thead>
<tr>
<th></th>
<th>Steady State</th>
<th>Periodic Motion</th>
<th>Changing Composition</th>
<th>Convergence to a Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand dunes</td>
<td>Some</td>
<td>Few</td>
<td>Many</td>
<td>Few</td>
</tr>
<tr>
<td>Traffic jams</td>
<td>Few</td>
<td>Some</td>
<td>Many</td>
<td>0</td>
</tr>
<tr>
<td>Forest fires</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Virus</td>
<td>Few</td>
<td>Few</td>
<td>Some</td>
<td>0</td>
</tr>
<tr>
<td>Diffusion</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Few</td>
</tr>
<tr>
<td>Birds</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Few</td>
</tr>
<tr>
<td>Fish</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table G: Table of four kinds of behaviors associated with periodic motion and limiting behaviors: steady state, periodic motion, changing composition, and convergence to a limit that are seen in some of the seven problem contexts, with some indications of frequency.

**Changing Composition**

Changing composition is a type of equilibrium in which the behavior at the macroscopic level appears to be stable but the behavior at the microscopic level involves change as agents (e.g. cars, sand grains) join and leave at equal rates. This behavior results in the composition of the microscopic phenomena changing over time while the macroscopic phenomena may appear constant. This kind of behavior is sometimes referred to as dynamic equilibrium. In the sand dune problem context, students discuss the size of the dune as constant while equal rates of sand
particles are joining and leaving the dune resulting in the composition changing at the microscopic level. One could extend this idea to explain the sand dune getting bigger or smaller depending on the relative rate of particles joining and leaving the dune. A sand dune might get bigger when the rate of sand joining the dune is greater than the rate of sand leaving the dune, and get smaller when the rate of sand joining the dune is less than the rate of sand leaving the dune.

Changing composition is emergent. In the context of traffic jams, Resnick (1996) noticed that students had trouble connecting the behavior of individual cars with the overall behavior of jams because the behaviors at the macroscopic (jam) and microscopic (car) levels are different. A key part of the decentralized and self-organizational nature of traffic jams is that cars move forward while jams move backwards as the behaviors at these two levels are different. Resnick observed that students often incorrectly presumed that cars and jams were both moving forwards. Building off that work Sengupta and Wilensky (2009) and Wilensky and Resnick (1999) discuss the importance of understanding the relationship between the behaviors at different levels as associated with a normative understanding of decentralized causality.

In the analysis presented below, I find that changing composition was used many times in traffic jams and sand dunes, used a few times in the virus problem, and was not used in the bird, fish, forest fire, and diffusion problem contexts. An important attribute of these traffic jam, sand dune, and virus explanations is that students’ prior knowledge supports them in emphasizing relative rates, which is a key aspect of changing composition. Changing composition was absent from the other problem contexts, likely due to the nature of what prior knowledge students cued and thus did not support a conceptualization based on changing rates. Despite this explanatory pattern not being used in the bird, fish, forest fire, and diffusion problem contexts; I hypothesize that changing composition might have been applicable to forest fires. If students had focused on the changing rates of fire spreading and contracting, they might have incorporated this explanatory pattern. However, students’ prior knowledge tended to support them for focusing on only trees catching on fire and not ceasing to be on fire. In that case, if students focused on the relative rates of trees catching on fire, they might have used the changing composition explanatory pattern similar to how it was used in sand dunes, traffic jams, and virus problem contexts, but of course, this did not occur.

**Changing Composition in Sand Dunes**

In sand dunes, many students’ generated explanations based on conceptualizing the phenomenon through the explanatory pattern of changing composition. In this context, students often mentioned that the dune stays the same size when there are equal rates of sand particles joining and leaving. In addition, students sometimes mentioned that the dune becomes bigger when more sand particles are joining rather than leaving and the dune becomes smaller when more sand particles are leaving rather than joining.

In this section, I discuss the case of Morgan, a high school student who explains that the wind runs into a dune and releases sand, thus making the dune bigger, and the wind carries sand away, thus making the dune smaller. Part way through this selection I asked Morgan what would happen if the dune were to remain the same size (line 6). She explains that there would be an equal distribution of sand being picked up and deposited by the wind.

1. Lauren: Say you have a whole lot of wind, moving around the grains the way you just described it, how might it happen that, in the past the story was that it was like, there was a sand dune and it moved to a new location.
2. How might it happen that instead of the sand dune moving, say it just got bigger or just got smaller. How would that happen?

3. Morgan: I think, the wind moves the sand and it can also bring sand and make it bigger,

4. and because the wind is trying to go through the dune it can't really work so it just runs in to it, and then it releases sand and then it just like makes the sand dune get bigger.

5. And then it carries away sand, making it smaller.

6. Lauren: What if instead of the dune getting bigger, or smaller, or moving, what if the dune just happened to stay the same size? Then what would be going on?

7. Morgan: There is equal distribution between the sand being picked up and blown into, I guess, yeah, I would think that would be it.

8. That or it's not an actual sand dune, it's just a mountain of dried up sand or whatever.

9. [Laughter] I don't know, it is just stuck.

10. Lauren: Yeah.

11. Morgan: Yeah, that’s what I would think, if it was equal distribution between going in and leaving.

In the above transcript selection, Morgan conceptualizes sand dunes changing size through the explanatory pattern changing composition and focuses on the relative rate of sand joining and leaving the dune. Morgan first explains that the dunes can get bigger (lines 3, 4) or smaller (line 5). I then asked a question about what would be happening if the dunes stay the same size (line 6). Morgan then explained “there is equal distribution between the sand being picked up and blown into” it (line 7). This is the explanatory pattern changing composition as she is accounting for the relative rates of sand joining and leaving resulting in the dune staying the same size. Then Morgan mentions another option that it is possibly not a dune just a mountain, dried up sand, such that sand is stuck to and not moving (lines 8-9). This explanation is about an unchanging dune associated with steady state as she is saying that potentially nothing is changing, no sand is joining or leaving the dune, and everything is dried up and remains in place. Then in line 11, she reiterates the changing composition explanation (“that’s what I would think, if it was equal distribution between going in and leaving”).

Within this transcript excerpt, there are two possible explanations for the dune staying the same size: changing composition and steady state. She mentions that when the dune remains the same size, there could be an equal distribution of sand being picked up and dropped off, which is changing composition (lines 7, 11), or that the dune could be static with no sand moving, which is the steady state explanatory pattern (line 8). Possibly she did not intend this comment about a static sand dune to be taken seriously. After that comment she laughs and then says “I don’t know,” (line 9) and then follows by reverting back to mentioning an equal distribution of sand joining and leaving the dune (line 11). One way to view this is that she might be recognizing that there is more than one way to conceptualize a static sand dune.

Within this explanation, Morgan is activating a variety of prior knowledge about sand dunes. Likely, she has prior experiences that suggest wind carries sand. This likely includes related pieces of knowledge, for instance, sand being picked up by the wind. She also has a sense of what is and is not a dune. She mentions in line 8, “it's not an actual sand dune, it's just a
mountain of dried up sand.” This is a bit ambiguous, but perhaps she has an unstated standard for what is and is not a sand dune. Also, she mentions in line 4 that the wind runs into the dune and releases the sand, “wind is trying to go through the dune it can't really work so it just runs in to it, and then it releases sand and then it just like makes the sand dune get bigger.” Possible this is the blocking p-prim, in which the sand dune blocks the wind, and then releases the sand, resulting in the accumulation of sand on the dune.

Morgan’s explanation may be capturing the emergent nature of the movement of sand dunes as it incorporates changing composition and it contains some recognition of the variability of the relevant behaviors. A related aspect of this explanation is that she also conceptualizes the dune through the steady state explanatory pattern. This point will be discussed further in chapter 6, but recognition of more than one way to conceptualize a static sand dune, in this case either changing composition or steady state motion, is important because it can be evidence of recognition of the self-organizational nature of the behavior that there can be qualitatively different kinds of behaviors that lead to similar results.

The case of Morgan’s changing composition sand dune explanation was one of many similar cases in the relevant data set. Many other students mentioned the relative rates of sand joining and leaving the dune with respect to dunes staying the same size, getting bigger, or getting smaller. Additionally, among the students who mentioned changing composition when discussing sand dunes, they had a variety of academic backgrounds including, high school students, undergraduates, and Ph.D. students. They also tended to activate similar prior knowledge about how the wind’s motion influences the changing sand dunes. Among these cases of changing composition explanations of sand dunes there is lots of consistency with many of the explanations being similar.

**Changing Composition in Traffic Jams**

Many students used changing composition in explanations about traffic jams and in this section I discuss an illustrative case from the discussion with Jared, a Ph.D. student in physics. In his explanation, he focused on the composition of traffic jams changing while the overall size stays the same. Jared’s explanation is in response to a question I asked about traffic jams staying a consistent size. He spent a couple minutes discussing cars slowing down as they approach and then enter the jam and then he explains that the rates of cars joining and leaving the jam have to be equal.

1. Lauren: What if you were watching the highway for a while and you noticed that at some point in time, and you notice that the traffic jam seemed to be staying about the same size, rather than, it sometimes clearing up. What would be going on then? If it seems like the jam is just staying the same size?

2. …

3. Jared: There is the same rate of cars flowing, behind the traffic jam as just getting into the traffic jam.

4. …

5. Jared: The cars are changing cause new ones are entering and the ones I'm looking at now will leave, but, as a traffic jam it's staying the same.

6. Right so, it's not getting bigger, there aren't, I'm not getting more cars in it, so, basically how ever many join has to be the same as however many leave.
Jared’s explanation focuses on cars entering and leaving the jam, but the size of the jam is constant. At the beginning of this segment, I asked about a jam appearing to stay the same size (line 1). Jared then responded in line 5 that the rates of cars entering and leaving the jam are the same but the jam will be constant. “The cars are changing cause new ones are entering and the ones I’m looking at now will leave, but, as a traffic jam it's staying the same.” This results in the jam staying the same size, rather than getting bigger (line 6). He reiterates the phrase about the same rates of cars leaving and joining the jam in lines 7 and 9, by saying “how ever many join has to be the same as however many leave. At any given second.” This explanation is based on changing composition as he is clearly focusing on the relative rates of cars joining and leaving the jam and how that influences the overall size.

Likely Jared’s explanation is based on some common underlying knowledge about traffic jams from everyday experiences, for instance, parks traveling on a highway in only one direction. Possibly he is cuing experiential knowledge about cars going in one direction and generally not going backwards on highways. This might also be based on pragmatic knowledge about where traffic becomes more complicated in parking lots where cars can go forwards and backwards. Focusing on everyone traveling in the same direction simplifies the behaviors.

There were similarities across the many cases of students’ traffic jam explanations being based on changing composition. Students often mentioned the relative rates of cars entering and leaving jams. When the rate of cars entering is greater than the rate of cars leaving, the jam gets bigger. Similarly, when the rate of cars leaving is greater than the rate of cars joining then the jams dissipate. Often these explanations were based on common kinds of prior knowledge about traffic traveling in one direction, similar to the prior knowledge Jared activated. In addition, these explanations were often based on knowledge about jams eventually dissipating, the particulars of when and why people are joining and leaving jams, rush hour, and which exits are more or less popular. All of this knowledge contribute to the changing composition explanatory pattern. Finally, these cases of explanations based on the changing composition explanatory pattern in traffic jam were generated by students with different academic backgrounds, including several Ph.D. students, one undergraduate student, and one high school student. Overall, Jared’s explanation is rather typical across this data set, many similarities existed among students’ explanations of the changing composition of traffic jams.

**Changing Composition in Viruses**

Changing composition was mentioned in some students’ virus explanations. In this section, I discuss one of those cases, an explanation generated by Blake, a Ph.D. student in physics. He first mentions equilibrium in general and then explains the behavior of viruses through the explanatory pattern changing composition. This example of changing composition is different from the prior two examples of sand dunes and traffic jams, because in this case Blake connects equilibrium (his word) across three problem contexts: traffic jams, viruses, and physics more broadly. At the beginning, he provides a scientific explanation of equilibrium, followed by a reference to the behavior of traffic jams. Towards the end of the transcript selection, he explains that the viruses could be conceptualized through the explanatory pattern changing composition with equal numbers of people being infected and getting well each day.
1. Blake: Equilibrium, that’s an important and powerful in part of physics. Maybe not super powerful, but very important. The study of equilibrium. How things tend to just settle down and end up being as boring as they can be, you know.

2. Lauren: How have you been drawing on that idea? Can you give me some examples?

3. Blake: I guess that is, I just gave you the examples I was thinking of.

4. How I explained the traffic jam, it is the same thing. If it’s not changing, it’s in equilibrium. If it’s getting smaller then, oh yeah, that is part of equilibrium. It doesn’t have to be static, it just has to be not changing. So you can have.

5. Lauren: Oh, I see.

6. Blake: So you can have a disease that looks the same. There is always a hundred million people infected

7. Lauren: Right

8. Blake: but there could be ten million people infected everyday, and ten million people get well

9. Lauren: Right

10. Blake: and it would still be kind of an equilibrium.

11. Maybe it would be a steady state, you can think of it like, as, in some sense nothing is changing.

12. But in other sense, things are changing, but they are changing together, in a way that kind of that looks like nothing is changing.

In this transcript selection, Blake is connecting his scientific ideas about equilibrium with the virus and traffic jam problem context. First, in line 1, he draws on prior scientific knowledge about equilibrium. He explains the importance of equilibrium it is about how things “settle down” (line 1). In line 4 he adds more details when mentioning that he was thinking about traffic jams which might be not changing and in equilibrium and reiterates that he means that the jam is not static and also not changing. “If it’s not changing, it’s in equilibrium. If it’s getting smaller then, oh yeah, that is part of equilibrium. It doesn't have to be static, it just has to be not changing.” This description of equilibrium appears ambiguous at first, how could something be both static and changing? However, in subsequent lines he clarifies his understanding while explaining the case of viruses being in equilibrium. He mentions that a virus can have the same behavior as traffic jams (line 6). For viruses “there could be ten million people infected everyday, and ten million people get well” which would be a kind of equilibrium (lines 8 and 10) and function as a steady state because overall nothing is changing. To clarify, when he says, “nothing is changing” what he means is that the absolute number of people who are sick each day is constant. Likely, this is what he meant in line 4 when he explained that a traffic jam is “not changing.” Then he continues to explain in line 12 that for viruses, in another sense there is a change, “things are changing, but they are changing together, in a way that kind of that looks like nothing is changing.” I interpret this line to be accounting for the changes at the micro level such that there are changes in terms of which individuals are sick or well at any given time. I also interpret this to be the behavior Blake was referring to in line 4 when he said “it doesn’t have to be static.” In this transcript excerpt Blake sees the same behavior, a static macro level in terms of the absolute number of people/cars and a changing micro level in terms of individual
cars leaving and joining or people getting sick and well across all three-problem contexts. This is by definition changing composition.

Underlying this explanation is a variety of prior knowledge. Notice that he finds both the micro and macro levels relevant when coordinating across the traffic jam and virus problem context to see the same behavior. Within his explanation, Blake is paying attention to the changing size of traffic jams (line 4) and to the behavior of individual cars. Similarly, within viruses, he finds both the changing size of the population of sick people and the behavior of individuals (lines 6 and 8) as salient. He also mentions equilibrium in the context of physics (lines 1 and 10).

Within this explanation Blake is using some prior knowledge such that he coordinates, what I refer to as changing composition, and what he refers to as equilibrium, across at least two problem contexts: viruses and traffic jams. He might also be seeing equilibrium within a more general physics problem context (based on his statement in line 1), but there is insufficient data to conclusively make this judgment. Blake has some expertise in physics and I expect him to be able to see information that is not necessarily transparent because of his prior knowledge and experiences. In this case, he finds equilibrium relevant in both the traffic jam and virus problem context, thus he readouts this information across different contexts. To do this he has focused his attention on specific features of the situation, possibly both the micro and macro levels, and created connections between them in order to get the important information, likely a readout strategy, although with this small amount of data I cannot be certain. Overall, in this excerpt, Blake is coordinating equilibrium (his language, changing composition in my language) across problem contexts.

Across the other cases in which students conceptualized viruses through the explanatory pattern changing composition, there was some overlap. Similar to Blake’s explanation, other students mentioned the relative rates of people getting sick and well. A few of the other students also mentioned related issues including the role of mutations influencing the rate of people getting well or sick. One student also mentioned the death rate as a confounding variable. Interestingly, across these cases of changing composition of viruses, this explanatory pattern was more common in high school students and undergraduates. Overall, across these cases there were many similarities, and the one difference concerned the rate, which varied a small bit and was influenced by prior knowledge.

**No Changing Composition in Forest Fires**

In this section I hypothesize why students do not use the changing composition explanatory pattern in the forest fires problem context. Potentially this is because their prior knowledge does not support them in focusing on the relative rates of trees catching on fire and ceasing to be on fire. When comparing forest fires to other problem contexts, for instance, sand dunes, traffic jams, and viruses, it is noticeable that explanations based on changing composition included key information about rate. Maybe rate was not relevant to students in the forest fire problem context. It is completely plausible for one to focus on rate in the forest fire context, but this did not occur in the data set. In this section I argue that this lack of focus on the rate in forest fires is due to students’ prior knowledge about forest fires. In sand dunes, students talked about the rate of sand joining and leaving a dune. Similarly, with traffic jams, students talked about the rate of cars joining and leaving, and with viruses they discussed the rate of people being infected and well again. Similarly, I would expect that a hypothetical explanation about forest fires based on changing composition would also focus on the rate of trees catching on fire and ceasing to be on fire. However, students did not generate this kind of explanation. In the data I see almost no
mention of the rate of trees catching on fire or the rate of trees ceasing to be on fire. The kinds of prior knowledge students commonly cued about the forest fires include the macro level spreading, the lack of individuation, and the invariance of fire. One aspect of fires that students find salient, as it was mentioned in the initial interview question and often incorporated in students’ subsequent explanations, is about the spread of fire. In comparison, students tend to not focus on individuate fire because they do not pay attention to a particular tree or leaf being on fire. Another salient aspect of fire is the invariance and indistinguishable nature of fire. In essence, all fire is treated as the same, independent of what is burning, tree, leaf, or house.

Based on the kinds of prior knowledge students activated, it appears as if rate was simply not salient. Hence, possibly they did not conceptualize forest fires through changing composition because they did not incorporate this key prior knowledge regarding rate. My hypothesis is that to generate explanations based on the explanatory pattern changing compositions one needs to find the relative rates equally relevant, the rate of trees being lit by the fire and the rate of trees ceasing to be one fire. I hypothesize that students did not see these two rates as equally relevant—students explanatory pattern around forest fires emphasized the spread of the fire more than the dying out of the fire. There are several reasons why students’ prior knowledge might not support them in being inclined to focus on relative rates. First, fire spreads very quickly, almost instantaneously, which because of the speed might be more salient than fire dying out, which takes time as things smolder. Second, there might be an intuition about fires spreading naturally and unquestionably. This intuition of fires spreading might be stronger than the intuitions about fires terminating, thus prioritizing the spread of fire. This could also be an intuitive version of momentum being applied to fire. Third, students might not have individuated the leaves or trees on fire. Not individuating the things on fire, such as individual trees or leaves, may make it harder to see the rate of fire changing, which may have impacted their ability to use the changing composition explanatory pattern.

While I cannot conclusively decide among these hypotheses, it is important to note students might have a more difficult time recognizing emergence in the forest fire problem context. As students tended to not cue prior knowledge in ways that support changing composition of forest fires, they in turn may not use that particular path towards emergent thinking, which in turn might make forest fires a more difficult problem context than others.

Changing Composition Summary
Explaining the phenomena through changing compositions was commonly seen in sand dunes and traffic jams, occasionally observed in viruses, and not perceived in forest fires. In forest fires, this explanatory pattern is not used because students’ prior knowledge about forest fires constrained them to not focus on relevant information, such as the individuates of fire or the rates of fires being ignited and going out. Possibly students focused on the invariance of fire and this may not have supported this explanatory pattern. In the sand dune, traffic jam, and virus problem contexts students often mentioned key information about the rate of sand particles joining or leaving a dune, the rate of cars entering or leaving a jam, or the rate of people getting infected and well. Embedded within traffic jams and viruses and not sand dunes, is a focus on individual behaviors. The explanatory pattern changing composition is emergent as it involves connecting levels and how the self-organization of the micro behavior relates to the macro behavior. Not using the explanatory pattern changing composition in the forest fires problem context does not imply that it is impossible for students to recognize emergence in that context, or similar contexts, only that it may be more difficult as this productive and common conceptualization is not easily accessible.
Steady State
Steady state motion is an explanatory pattern in which the behavior of the system exhibits no change. Notice that this is different from the process of settling into a steady state, which I referred to as convergence to a limit and is discussed in a subsequent sub-section. In this section, I discuss the few cases in which steady state motion was mentioned, primarily in the sand dune, virus, and traffic jam problem context, and I hypothesize why it was not used in the forest fires, birds, fish, and diffusion problem context. For example, when discussing forest fires I argue that students’ prior knowledge about the temporary nature of forest fires constrained them such that steady state motion was not an appropriate explanatory pattern for this process. Overall, I argued that whether or not steady state was applicable to particular problem contexts depends on students’ prior knowledge about that context.

There is some evidence that steady state motion may be associated with centralized causality (Jacobson, 2001), but I find a more nuanced situation. One could assume that because steady state implies an unchanging motion, that fact would inherently be unsupportive for seeing the dynamic nature of emergent processes. In some cases, after students’ generated explanations associated with steady state they continued onward and generated other explanatory patterns including those associated with decentralized causality (changing composition and periodic motion). I argue that recognition of steady state in conjunction with relevant prior knowledge, may lead the student to question this explanatory pattern, which in turn might have supported recognition of patterns associated with decentralized causality.

Steady State in Sand Dunes
Steady state motion was mentioned in some students’ sand dune explanations in the sense of the size of dunes coming to a steady state where the entire sand dune system is unchanging. In this section, I primarily focus on the case of Antonio, but I briefly discuss data from interviews with Samuel and Ravi. In the later cases, the steady state pattern may have lead to explanations based on other patterns associated with decentralized causality.

Antonio was an undergraduate physics major who explained that the sand dunes size is static over time. His explanation was in reaction to a question I asked regarding the sand dune being the same size at two points in time. Antonio mentioned that perhaps nothing happened between these two points in time because there was insufficient wind to change anything about the dune.

1. Lauren: I'm going to change up the story a little bit. So say you come back to the location a second time and instead of a dune having changed size, umm, the dune is still there and it's the exact same size as it was the first time.
2. Antonio: Alright
3. Lauren: Umm, what could be going on, in that situation?
4. Antonio: Come back and nothing is different?
5. Lauren: Yeah
6. Antonio: I would go with nothing happened. Or, just, maybe it's not a very windy area.
7. Lauren: Sure
8. Antonio: Cause always going with the wind. And it just come back and, nothing has touched it. So, nothing changed. That’s what’s going on.
In this explanation Antonio focuses on the dune being static over time based on both a lack of wind and an intuition about what causes a lack of change. This section begins with me changing the previous discussion by asking a new question about the dune being the same size at two different points in time (line 1). Antonio clarifies that “nothing is different” (line 4) at the second point in time and then explains “nothing happened” because “maybe it’s not a very windy area” (line 6). He reiterates this in line 8 saying “nothing has touched it. So, nothing changed.” In this excerpt, Antonio is explaining that during this time, the dune does not change because nothing is happening.

Underlying this explanation is some intuitive prior knowledge about phenomena not changing unless there is a specific reason. In the above transcript excerpt Antonio does not provide a reason or explanation for the lack of change. He just assumes that sand dunes work this way. While this is not obviously aligned with any particular p-prim mentioned in diSessa (1993), it has a quality that is suggestive of a prim-ish intuition as he is unproblematically assuming that unchanging dunes do not require any further explanation. In addition, the intuitive belief in which something at rest does not require an explanation is discussed in Nersessian & Resnick (1989) as potentially apart of an underlying structure for intuitive explanations in physics.

In the sand dune discussion with Antonio, none of his explanations ever appeared to be associated with decentralized causality, but this was not the case across the entire data corpus. More specifically, from the data with Antonio there is not enough information to make any claims about whether or if the above steady state explanation was helpful for him later with decentralized causality. Across the entire data corpus, there were few other cases similar to Antonio’s explanations. However, there were also other cases in which steady state explanations, in conjunction with explanations based on other explanatory patterns, may have been helpful in moving towards decentralized causality. Below I discuss two cases from interviews with Samuel and Ravi in which their sand dune steady state explanations were followed immediately by explanations based on other explanatory patterns, such as periodic motion or changing composition, and may have been helpful in moving towards decentralized causality based on the cuing of specific knowledge pieces.

An example of a student’s steady state explanation possibly helping movement along a potentially productive path towards decentralized causality comes from the discussion with Samuel, an undergraduate student majoring in physics. I asked him a similar question to the question asked to Antonio about the dune appearing to be the same size at two different points in time. Samuel first used steady state and explained that there could be no wind. Then I suggested that there could be wind and he went on to explain that the wind could be blowing evenly from two directions, leading to a dune being a consistent size. “Wind blowing in one direction and, for, sometime later the wind blows the opposite direction the exact same magnitude, the exact same amount of time. Or I guess wind is blowing in such a way that, that dune already reached an equilibrium.” In excerpt Samuel is saying that the wind can be blowing at equal strength from two different directions such that the dune feels an equal force from both sides thus cancelling the actions of each other. This explanation is based on prior knowledge about balancing, possibly the canceling p-prim in the context of wind blowing from opposite directions cancels out and leads to the dune having a consistent size. Immediately afterwards I asked Samuel for more information about what he mean by “equilibrium” and he acknowledged being a bit stuck. “I'm trying to elaborate on the equilibrium idea but I'm kind of stuck.” Samuel has some sense of equilibrium, possibly from prior academic experiences such that he acknowledges its

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relevance in the sand dune discussion but is not able to elaborate. Potentially his application of
the steady state explanatory pattern was helpful because it allowed him to recognize equilibrium
even though he got stuck. There is not enough data to be sure what he means by the word
equilibrium, but possibly recognition of the applicability of this idea, whatever it may mean to
him, could be helpful in recognition of the kinds of decentralized behaviors associated with sand
dune movement.

Another example of a student’s steady state sand dune explanation potentially being
helpful comes from the case of Ravi, an undergraduate physics major. Ravi’s steady state
explanation leads into an explanation of wind changing directions and dunes periodic motion.
Similar to the other cases, this excerpt begins with me asking a question about dunes being a
consistent size over time. Ravi first mentions that there could be no change as there is not much
wind and not much time has passed. “It’s possible that there hasn't been much wind and, if not
too much time has passed, that could be possible.” He then explains that the wind might be
changing directions and the dunes might get smaller and bigger in a periodic manner. “Some of
the wind could you know, erode the dune and make it smaller, but then if the wind like had
changed directions then the original sand would simply be brought back to the dune and so it
would just built it back up again.” In this excerpt, he first used steady state in a particular
context, when there is not much wind and only short time periods are relevant. This may have
led to him considering the changing dunes over longer times with more wind, resulting in the
dune gets smaller and then bigger again. The second explanation is based on the periodic motion
explanatory pattern, the dune size changes in a cyclical manner due to the wind. Although his
final sand dune explanations are not necessarily associated with decentralized causality, coming
to recognize that more than one kind of behavior is plausible, both steady state motion and
periodic motion, could be somewhere along a path towards decentralized causality.

Overall, some student’s in the interview data corpus mentioned sand dune steady state
motion. Generally, steady state was only mentioned in the sand dune problem context by the
undergraduates and Ph.D. students. For some cases, such as Antonio, it was potentially not
helpful in moving towards decentralized causality in any discernible manner given the available
data. However, in other cases, for instance, the cases of Ravi and Samuel these explanations
based on the steady state explanatory pattern might have been helpful, based on the specific
knowledge that was cued and how that knowledge connected to later explanations. In those
cases, the explanations were generated in conjunction with other patterns, such as periodic
motion and they may have helped move them along a possibly productive path. Whether or not
the steady state pattern was potentially helpful may have depended in part on the kinds of prior
knowledge activated. In both Antonio and Samuel’s cases there was some intuitive knowledge
cued in the explanation. In Antonio’s case he did not feel the need to justify the lack of change.
However, Samuel saw the dunes lack of change because of the wind canceling out, which may
serve as an intuitive reason for the apparent lack of change.

**Steady State in Viruses**
In the context of viruses, there are few cases of steady state motion; in this section, I discuss one
clear case from the interview with Stephen, a physics Ph.D. student. He was asked an interview
question about what might happen if the number of people sick remains constant. Stephen first
explains that this has to do with the incubation period (he uses the term “gestation period”) during which someone is contagious and the length of time someone is sick. Then he explains
that perhaps everyone in the town gets sick simultaneously and then everyone stays home
preventing others from being infected.
1. Lauren: What happens if there is an epidemic, but, instead of, there is a constant, or a consistent number of people who are sick. Rather than an epidemic that begins and then ends. How could it be that you could have a constant number of sick people in an epidemic?

2. Stephen: There is the question of, for how long it takes for someone to be cured of the disease? Either naturally or through whatever means or use.

3. Lauren: Right

4. Stephen: …Where simply the rate of spread of the disease is slow enough then, and the people are not either dying or becoming cured of the disease. For example if it’s a disease with a gestation period of like three hours, but you’re sick with it for a week

5. Lauren: Yeah

6. Stephen: It could hit a town, hit everyone in the town and then hit no one else for an entire week, because everyone is sick and not going anywhere and no one is going in because they don't want that disease, so that’s the situation where the disease would be relatively the same size for a while.

In this explanation, Stephen refers to a steady state behavior in terms of a constant number of sick people and no changes to the composition of the sick population. This explanation begins with my question about how it could be possible for there to be a constant number of sick people (line 1). He then mentions some pertinent information about how long it takes someone to be cured of the disease (line 2). Then he goes on to explain that it has to do with the spreading rate of the spreading of the disease and how long someone is sick (line 4). At the end of the explanation, he mentions a hypothetical situation where the disease infects everyone at once and then no one else because everyone who is sick stays home and does not spread the disease.

In this explanation, the key steady state point is when there are a constant number of sick people who are staying home and not infecting others. Notice that the way Stephen has conceived of this steady state point is inherently temporary. Eventually people get well, new people get sick, and the system is no longer in a steady state.

This explanation is cuing several kinds of knowledge including pragmatic knowledge about viruses and the knowledge about the boundaries of viruses. He is assuming that people get well and focuses on a virus that has a short incubation period relative to the time it takes to get well. Related to these times he is cueing knowledge about an appropriate period: hours and days. Additionally, he is cueing knowledge from his everyday prior experiences about healthy people trying to avoid getting sick and sick people staying home.

The case of Stephen is one of the few during the course of the interviews in which a student came to see multiple problem contexts as exhibiting similar behaviors associated with emergence. The particular episode in which he explains viruses through steady state fits into that larger arc as immediately after line 6 he mentions that in fact it might be more appropriate to consider the system as an unstable equilibrium because “the number of people with the disease is probably almost always increasing or decreasing over time.” Thus, he is saying that the system does not exhibit motion associated with steady state, a contradiction with his previous explanation. Possibly steady state could have been helpful for him because he rejects it in favor
of a situation where the system is dynamically changing and this is associated with decentralized causality.

Beyond this case of Stephen mentioning steady state in the virus context, there were not many other cases of steady state motion in virus data perhaps because for a variety of reasons steady state does not fit with viruses. Stephen’s steady state virus explanation somehow feels unrealistic. It is unlikely that many people are infected simultaneously, and it is unlikely that they would all stay home to avoid infecting others. In a subsequent comment Stephen implies that he too views this situation as contrived, “I think that would require some real fine tuning with regards to the parameters, the time the gestation time, and the travel time for the people and stuff like that.” Potentially Stephen’s knowledge of the pragmatics of viruses, including human behavior with respect to illness and relative travel times is supporting his judgment that this situation is unrealistic. Possibly a similar set of knowledge might be influencing other students’ explanations about viruses, such that they too use their pragmatic knowledge of viruses spreading and thus steady state does not fit. For the case of Stephen, his prior knowledge about viruses greatly influenced how he conceptualized viruses through the steady state pattern. For the other students I would similarly expect that steady state does not fit with viruses as related to their knowledge of pragmatics and everyday experiences with viruses.

**Steady State in Traffic Jams**

Similar to viruses and sand dunes, steady state motion was mentioned in the traffic jam problem context, but it was uncommon. One case comes from Blake, a Ph.D. student in physics who upon answering a question about a traffic jam staying the same size initially responded with an explanation that was based on changing composition (not shown) and then generated an explanation based on steady state motion.

1. **Lauren:** I'm going to change up the story again. So, say your watching the traffic jam for a really long time and you notice that it's not really getting bigger or smaller, it's kind of staying the same size, roughly over time. What could be going on if that happened?

2.  ...

3. **Blake:** Maybe, maybe a truck flipped over in front and it's spilling all over the road and it stopped, and then the police closed the freeway at the last on ramp, so nobody is allowed on and nobody is allowed off so

4.  **Lauren:** Right

5.  **Blake:** So nothing can change, you can't leave.

Blake explains that a traffic jam might exhibit steady state motion. This explanation was generated in response to my question about traffic jams staying the same size over time. His first response used the changing composition explanatory pattern (line 2) but then he responded using the steady state explanatory pattern. He explains that if the highway is closed, potentially due to a big accident, and nobody is allowed on or off then nothing can change (lines 3 and 4). In this explanation, both the cars and the entire jam are in a steady state such that nothing is changing. No cars are leaving or joining the jam, because the highway is closed.

This explanation likely is based on pragmatic knowledge of traffic jams from everyday experiences. For instance, everyday experiences with the possibility of trucks flipping over and jams forming, as well as prior experiences about how police respond to these events, such as freeway closure if the accident is very severe. Similarly, underlying this explanation is some
prior knowledge about highways having on and off ramps, such that there are only certain places where one can leave or join the road.

Although Blake’s steady state explanation is not associated with decentralized causality, his explanations that immediately followed incorporated changing composition, which is associated with decentralized causality. Immediately after line 5 he explains that when there are traffic jams people slow down to look at the jam such that “it can be equilibrium, even though the cars themselves are moving.” This kind of equilibrium in which the macro level system appears to be the same size, and the micro level system is changing is changing composition. As was previously mentioned, this pattern is emergent.

Blake’s steady state traffic jam explanation was one of the few cases to invoke this pattern for this situation. The other possible case of steady state in traffic jams comes from the interview with Cara, an 8th grader, who discussed the possibility of all the cars being “jammed up” on the highway, resulting in no motion. Perhaps this pattern was uncommon because for a variety of reasons steady state does not fit with traffic jams, similar to the virus problem context. The situation discussed in Blake’s explanations, in which a jam happens and then the police close the road such that no one can enter or leave the highway, is not a reflection of many of our typical experiences with jams because usually when in traffic congestion we slowly crawl forward and are able to get out of the jam in a reasonable amount of time. The knowledge about traffic jams that other students cued reflected prior experience with slow forward motion; hence, steady state might not have fit with their conceptualization of traffic jams.

No Steady State in Forest Fires, Birds, Fish, or Diffusion
I hypothesize that key to students use of the steady state explanatory pattern is viewing some aspect of the phenomena as constant or unchanging and not viewing the entire phenomena as temporary. In the data corpus, there were no cases in which students activated the steady state explanatory pattern within the forest fire, bird, fish, or diffusion problem context. I hypothesize that this is due to the continual movement or temporariness associated with these processes. Forest fires exhibit temporary behaviors; a fire burns for a period and then is extinguished. Similarly, birds and fish are in continual motion, birds do not hover in the air. In addition, diffusion involves continual movement. Traffic jams might be a special case because they exhibit temporary behaviors; a jam forms and then dissipates. In the above section on traffic jams, Blake activated some knowledge about the temporary nature of traffic jams and recognized that eventually a traffic jam will dissipate. Yet, despite him activating that knowledge, he did generate an explanation based on the steady state pattern, although it was in conjunction with him explaining the phenomena through changing composition. I hypothesize that this piece of knowledge about the behavior being temporary, when applied to any of the problem contexts, such as traffic jam or forest fires, might constrain students such that they do not conceptualize the phenomena through the steady state pattern. In summary, possibly students’ particular prior knowledge about the problem contexts, if the behaviors are temporary or not, might constrain whether or not students’ activate the steady state explanatory pattern.

Steady State Summary
In the above analysis, I presented cases of students generating explanations based on the steady state explanatory pattern in the sand dune, traffic jams, and virus problem contexts. A few students mentioned the size of dunes being in a steady state where it is unchanged over time. A student also mentioned a traffic jam being in a steady state, resulting in no cars are joining or
leaving. Another student mentioned the population of people sick with a virus being in a steady state when everyone stays at home and no people are getting sick or well.

There is some evidence that steady state motion may be associated with centralized causality (Jacobson, 2001). A fundamental attribution of steady state motion is a point in time where nothing is happening, which might suggest that this pattern is potentially unhelpful in supporting students in recognition of emergence, given that a key part of emergence is the changing self-organizational nature of a system. However, in the data I find that it might be helpful in some cases because generating a steady state explanation might support students in questioning this pattern because their prior knowledge suggests that the behavior associated with the particular problem context is constantly changing. I hypothesize that this is what happened in the case of Stephen’s virus explanation. Similarly, it may have been helpful in generating subsequent emergent explanations, as in the case of Blake’s traffic jam explanation that uses changing composition, and Ravi’s sand dune explanation that uses the periodic motion explanatory pattern. Across these cases I argue that the use of the steady state pattern and the other subsequent explanatory patterns depends on the kind of problem context specific knowledge students activated.

I also presented a hypothesis for why there was no steady state explanatory pattern in the forest fire problem context, and possibly the diffusion problem context as well. In forest fires, students tended to focus on the temporary nature of forest fires, similar to that of viruses. This focus on the temporary nature of forest fires constrained them such that steady state motion was not an appropriate explanatory pattern for a forest fire because they viewed the fire as in continual motion. Similarly, in diffusion the process exhibits a continual motion. Steady state was not applicable to that context based on the ways their prior knowledge supported them in understanding the context.

**Periodic Motion**

One particular explanatory pattern seen in these seven problem contexts is through periodic motion. For the purposes of this analysis, periodic motion includes both cyclical and oscillatory behavior. Cyclical and oscillatory behavior may be distinguished by the existence, or not, of a restoring force. A mass on a string oscillates, but the seasons are cyclical as there is no force that pushes or pulls on them, returning them to a neutral position (no restoring force). For the purposes of this analysis, I lump them together and refer to the combined group as periodic motion because it is often difficult to discern the difference in this data.

I begin the analysis by discussing a case of periodic motion in the sand dune problem context, where it was mentioned quite often and focuses on dunes sizes. I then discuss the periodic motion of traffic jams where it is manifested in different ways than in the sand dunes context in that it focuses on changing density of cars in traffic. Finally, I discuss, in brief, the few cases in which periodic motion was mentioned in the virus problem context where a student focused on the process of getting sick repeatedly. In the analysis, I find that periodic motion is more common in the recurrent processes, for instance, sand dunes and traffic jams, and less common in the non-recurrent processes, for instance, forest fires, diffusion, and viruses. However, this periodic motion explanatory pattern was more common in viruses than in forest fires and diffusion. I conclude with a discussion of how students’ prior knowledge and the nature of the problem contexts, whether they are recurrent or not, influences students’ explanations.
Periodic Motion in Sand Dunes

Periodic motion was common in the sand dunes problem context. In this section I present two examples, one from the discussion with Laurel who focused on the periodic motion of dunes and another example from the conversation with Leah who focused on the periodic motion of sand particles. These few cases of periodic motion in sand dunes tended to come from the undergraduates, master-credential students, and Ph.D. students. During the interview, Laurel, a masters credential student, generated an explanation for a hypothetical periodic pattern for sand dune motion. In her explanation, she focuses on the periodic nature of dunes as they continually get bigger and smaller. She also includes in her explanation a mechanism for how the dune gets smaller, she includes a reason why the dune does not disappear, and she compares it to a rotating wave.

1. Laurel: Or I was thinking maybe it's, it's probably more like, like as the wind, you know how, I was saying how the wind was like taking the outside layer or something,
2. maybe it's like this big and then it starts doing that, and the dune gets smaller [gestures big dune getting smaller].
3. But it wouldn't get flat probably, there would still be a little, you know a little cone there
4. Lauren: Yeah
5. Laurel: And then maybe that would start collecting more [gestures collecting] and growing [gestures growing] and then the wind could take it away get smaller [gestures getting smaller] and like this.
6. 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.

In this transcript excerpt, Laurel explains that dunes might get bigger and smaller in a periodic pattern similar to waves. At first she mentions the wind taking away the outside layer of sand thus providing a mechanism for how the dune gets smaller (lines 1-2). Then she mentions that when this occurs, the dune will not get flat, there will still be some sand remaining (line 3). Due to this remaining sand, the dune will start collecting more sand and grow bigger (line 4) and the wind could take away sand again such that the dune gets smaller (line 4). She sums up the explanation saying that the dune rotates: “maybe it's more of like a wave getting bigger and then getting smaller and then it's getting bigger” (line 6).

In this selection, Laurel uses her prior knowledge to generate an explanation incorporating periodic behavior in sand dunes. Embedded throughout this explanation is some knowledge about the size of the dune being a salient. The importance of this is expected given that one of the follow-up interview questions also highlighted the changing size of dunes. First, she explains that dunes get smaller because the outside layer of sand is removed (line 1), likely, she also sees the wind moving sand as a relevant behavior. Then, she explains that the dune will not disappear, there will be a small cone of sand remaining such that it begins collecting more sand and getting bigger again (line 3). Embedded in this idea are likely several pieces of knowledge, including finding the changing size of dunes and a small cone of sand as equally important. In addition, there may be some underlying pragmatic knowledge about the dunes behavior, perhaps she does not expect a dune to disappear. Next, she mentions a mechanism for
how a dune gets bigger, it collects more sand (line 5). She also mentions that similarly the wind can remove sand thus making it smaller (line 5). Finally, she mentions the changing size of dunes like a wave, getting bigger and then smaller in a periodic manner (line 6). Notice that she is using some prior knowledge that supports her in finding the periodic nature of the dunes behavior as salient, and she connects this knowledge with the periodic motion associated with waves. As I discussed in Chapter 4, this explanation supported her final changing composition explanation as it focused on the relative rates of sand joining and leaving the dunes.

Laurel’s explanation captures the periodic nature of the dunes size rotating and she incorporates a partial mechanism for how the dune gets bigger and smaller. She mentions in lines 1 and 5 that dunes get smaller as the wind takes away sand. In addition, she mentions that dunes begin getting bigger when the small “cone” starts collecting more sand. However, there are some holes in this mechanism. She does not take into account when the dune changes from getting bigger to getting smaller. At this point in the discussion, she does not mention the practical issue of sand joining and leaving the dune simultaneously, but that issue is addressed later in the discussion. As was discussed further in Chapter 4, her explanation of dune periodic motion might have been helpful for her subsequent explanations that are associated with decentralized causality given her incorporation of a partial mechanisms for how dunes get smaller and bigger.

Comparing Laurel’s sand dune periodic motion explanation with the few other cases in the data there are similarities and differences. I find some variety in terms of what aspects of the dune exhibit the periodic motion but there is a commonality in terms of students comparing sand dunes to water waves within these explanations. As discussed previously, Laurel focused on the periodic motion of the changing size of dunes while Leah mentions the back and forth motion of sand particles as periodic. Just as Laurel compared sand dunes to waves, Leah also mentions that the sand behaves similar to water. Leah focuses on the similarity between the up and down water and sand particle motion. Leah is a Ph.D. student in physics, so it is expected that she is able to access a great deal of prior knowledge related to the movement of sand dunes.

1. Leah: I guess, like if you have waves propagating in like a material, in a fluid like water. One of the things that characterize that behavior is that the individual, particles move up and down and they don't actually move much from side-to-side. So, you have like oscillations, as the wave travels through the water, that are locally up and down.

2. I don't know if things work the same way in sand, but it seems like, at least to some extent, sand has to actually, some sand has to move from point to point.

In the above transcript excerpt Leah describes water waves propagating and the up and down motion of the molecules, as opposed to side-to-side motion (line 1). She then mentions that sand particles might move the same as water, up and down, but then adds additional information that to some extent the sand has to also move from point to point (sideways) (line 2). In this case, she is explaining sand particles motion through the periodic motion explanatory pattern.

Underlying Leah’s sand dune periodic motion explanation there is some prior knowledge about the flow of water, oscillatory motion, and how to coordinate the two problem contexts, water flowing and sand dunes. Within Leah’s conceptual limits she sees both the fluid and
particle levels as salient. She coordinates her knowledge about fluids and, specifically, how the fluid flows with how particles move and sand flows.

Comparing the Leah and Laurel data there are differences in terms of what attributes of the problem context exhibited the periodic behavior. However, both students similarly incorporated prior knowledge about sand as similar to water waves, and their explanations include a similar lack of an explicit restoring force. However, there is a big difference in terms of their application of periodic motion. Leah focused on the micro level sand particles side-to-side motion while Laurel applied it at the macro level to the dunes size. Both students incorporated prior knowledge about sand particles and dunes with respect to water waves. However, in neither case was there an explicit restoring force or underlying mechanism that causes the periodic motion. Laurel got closer as she mentions a partial mechanism for dunes to get bigger and smaller while Leah did not mention any mechanism influencing the side-to-side sand grain motion.

**Periodic Motion in Traffic Jams**

In the following explanation for periodic motion in traffic jams, the student is focusing on density waves of cars. This is different from Laurel and Leah’s explanations in the sand dune problem context. In this context, Keaton (physics Ph.D. student) is not taking about traffic jam sizes having a periodic pattern of increasing and decreasing size or individual cars moving back and forth, which would have been similar to the sand dune data. Keaton is explaining that there are density waves of cars, sometimes the cars are closer together and going slow and sometimes the cars are farther apart and going faster (line 9). This point is emphasized by the fact that he imagines a hypothetical situation in which there is a counter on the side of a highway enumerating the number of cars passing per a second. Sometimes a small number goes by (denser traffic, cars going slower) (line 6) and sometimes a big number of cars pass by per a second (less dense traffic, cars going faster) (line 7).

1. Lauren: Why again, if you have more cars, all moving?
2. Keaton: So, imagine you put so many cars on the road. They are all like bumper to bumper
3. Lauren: I see
4. Keaton: Then like everyone would be afraid to move fast at all
5. Lauren: I see
6. Keaton: so then, the actual amount of cars passing a point per a second would be very small.
7. So if you plot like the number of cars going by per a second as a function of the number of cars on the road per a foot, then, it would have a maximum somewhere.
8. Lauren: I see
9. Keaton: So, one part of the reason why, traffic jams just form spontaneously it could be like these waves.
10. Points where there are a lot of cars close together and points where they are far apart.
11. And if you're coming to a point where there is cars close together you tend to slow down, and if the cars slow down then they also get closer together.
Keaton’s explanation focuses on the periodic nature of traffic jams in terms of changing density waves. He begins by mentioning the cars being bumper to bumper (high density) (line 2) such that people would be afraid to move too fast (line 4). Then he mentions that in this case, the number of cars passing a given location in a given unit of time would be small (6) possibly because the cars are going slow. Then he abstracts the density wave idea to explain what kind of graph would appear if you plotted the number of cars passing a given point as a function of the number of cars per foot on the road (density) (line 7). This plot feels a bit unconventional; however, perhaps the main point is that sometimes a given part of the traffic jam is more or less dense than the average density and the most and least dense parts of will appear on the graph as a maximum or minimum (line 7). Next, he moves away from the graph and mentions that these jams form spontaneously just like waves (line 9). Then he reverts to the density wave idea when mentioning points in time where cars are more or less densely packed (line 10). Finally, he mentions some specifics of how one particular car might deal with this situation, when you approach a place where cars are close together you tend to slow down and when cars slow down they in turn tend to get closer together (line 11). In this last line, he mentions a runaway effect in which congestion increases and cars get slower and slower. Overall, in this excerpt he focuses on the periodic nature of traffic jams in terms of changing density waves, places where the cars are densely packed from several perspectives including an abstracted graph and perspectives of being in a car.

Embedded within this explanation are several kinds of prior knowledge, about both specifics of traffic jams, and more general knowledge from physics. He finds several aspects of the traffic jams phenomena as salient, this includes the traffic jam and passenger perspectives, the relative positions of cars being closer and farther from each other, and the vehicle speeds. He also is drawing on pragmatic knowledge of cars wanting to avoid crashes and people being afraid to move when the vehicles are bumper to bumper. In this transcript excerpt as expected, he is cueing prior knowledge, possibly from academic experiences in physics and related areas, about creating and interpreting plots.

Aspects of Keaton’s explanation are associated with decentralized causality and emergence. He connects the microscopic level (cars) with the macroscopic level (jams), which is thought to be an important part of understanding complex systems (Wilensky & Resnick, 1999). Embedded within this explanation is a sense of the self-organizational nature of this system where there are many cars on the road and traffic jams form spontaneously (lines 2 and 9), which is a key part of emergence. Finally, he is recognizing some variability in the traffic jams behavior, including where cars are bumper to bumper and people are afraid to move and where the cars are farther apart.

Similar to Keaton, other students mentioned changing densities of cars in a periodic manner. For example, Samuel, an undergraduate student, (transcript of the explanations is in the Appendix) mentions having seen an experiment (his words) in which cars are set to travel in a constant circular track. He compares it to a merry-go-round and the cars get jammed up in what he refers to as shock waves. Samuel also compares traffic to a jelly that can compress and then expand multiple times. In this sense, Samuel is focusing on a changing density in traffic, sometimes the cars are closer or farther apart, but overall he pays attention to the periodic nature of the changing density of cars. Other students also generated similar periodic motion explanations of traffic jams. For example, Kyle, a Ph.D. student, (transcript of the explanations is in the Appendix) mentioned periodic motion with a focus on the fluxuations in cars speeds resulting in this naturally occurring periodic motion. Across these cases of periodic motion being
mentioned in the traffic jam problem context, it tended to be by undergraduates and Ph.D. students.

In this section, I discussed in detail the case of Keaton who focuses on the periodic and changing density waves of cars. When generating this explanation he drew on prior knowledge from physics and his everyday experiences with traffic. His explanation may be associated with decentralized causality as it captures the self-organizational nature of traffic jams along with connecting the micro and macro levels. Similar explanations were generated by other students including Samuel and Kyle who also mentioned the periodic nature of traffic.

**Periodic Motion in Viruses**

There were only a few cases of students mentioning periodic motion in the virus problem context. In this section, I discuss the case of Ravi who mentioned a periodic motion behavior of people getting sick, recovering, and getting sick again. This explanation was embedded within a discussion of a threshold of building up resistance or immunity to the virus. In response to a question I posed regarding how, hypothetically, there could be a constant number of sick people, Ravi explains that people who are sick recover and then get sick again.

1. Lauren: What if just hypothetically, instead of, the virus, people who have it, kind of decreasing,
2. what if instead hypothetically, there is just kind of, a constant number of people who are sick with it. How could that happen?
3. Ravi: depending on, in that case, it would have to be, the virus that is able to, to maybe either, change form,
4. or, if they the human immune system is not able to stay immune to it, then the same people that originally had the cold, will recover and then get the cold again. And so, it would be this constant recovery and then, people get the cold again, it would stay like, constant that way, and that happens,
5. if the virus like mutates to form that’s, that, isn't resistant to the, the current human, immune system and could cause the cold to re-occur. So that’s possible.
6. Lauren: so, like, the, gets the virus and then get better and then it again?
7. Ravi: yes
8. Ravi: or like, they would get it maybe a slightly different form or they would get umm, well, maybe the same form, and still, like, their body has a build up immunity to it, so, umm, they can just catch it again.

Previously I had asked Ravi to consider the spread of a virus, but at the beginning of this section, in line 1, I asked him to consider a constant number of people being infected. First, he mentioned that the virus might change form (line 3) and then he mentioned that people do not stay immune; in his words “people that originally had the cold, will recover and then get the cold again”, such that the infection is constant (line 4). Building off this notion, he presented another option, the virus mutates form and people get sick again (line 5). He added more information in line 8 explaining that people could get “a slightly different form” of the virus and that the body has built immunity.

This explanation accounts for the periodic nature of viruses in terms of getting sick, recovering, and then getting sick again. Interestingly, he presents some confounding factors including the role of a faulty immune system such that you get sick again and the virus mutating
to a different form. Both of these factors could result in the apparent periodic behavior of getting sick repeatedly. Through this, Ravi raised an interesting confounding issue about what counts as periodic motion. Perhaps it is not truly periodic motion if you are getting sick with a newly mutated version of the old virus. This issue will be discussed in the following section as it has a bearing on the spread of viruses being a non-recurrent process, which is important because this problem context might not align well with the explanatory pattern of periodic motion.

Underlying this explanation is some prior knowledge based on his experiences with viruses. Ravi mentions the virus changing form and mutate. Likely he has some prior knowledge about viruses changing. Similarly, he also cues some prior knowledge about the human immune system changing as it may or may not stay immune to the virus. In these ways, his knowledge is helping him focus on variability in the system.

Notice that embedded within this explanation is a threshold point in line 8 about building up immunity. As will be discussed in a later subsection of this chapter, he is using the threshold explanatory pattern to focus on the body building up immunity to the virus. Incorporating both the threshold and periodic motion pattern into this explanation might be helpful because he is seeing several qualitatively different behaviors, which is associated with self-organization.

The case of Ravi was the only clear example of a student using periodic motion in the virus problem context. Perhaps this is a reflection of it not being truly periodic because the person is being infected with different viruses each time. Possibly this is also not an optimal problem context for periodic motion as our common experiences, and likely prior knowledge with viruses, is about getting sick once and then getting well.

No Periodic Motion in Forest Fires and Diffusion
There were no clear cases conceptualizing diffusion, forest fires, birds, or fish using the periodic motion explanatory pattern. In this section, I argue that for forest fires, periodic motion was likely excluded partly because of the implicit framing of the situation, which did not incorporate a fire being re-kindled. In comparison, for diffusion, periodic motion does not fit and hence it is not surprising that it was not incorporated into students’ explanations. Both forest fires and diffusion are non-recurrent spreading processes, similar to the spreading of viruses, and students’ prior knowledge constrained them such that they generally could not conceptualize these non-recurrent processes in a periodic manner. As previously discussed, for viruses it may not have been truly periodic because the people may be infected with different viruses each time. Possibly this is also not an optimal problem context for periodic motion as our common experiences, and likely prior knowledge with viruses, is about getting sick once and then getting well.

There are several reasons why no students mentioned the periodic nature of forest fires. This is partly due to the framing of the situation, a fire being re-kindled was never presented as an option, and no students mentioned this possibility. Many students mentioned a forest fire originating with a lightening strike and then spreading outward through the forest. This focus on the one directional spreading behavior may have constrained the students in not focusing a potential periodic nature. Additionally, some students cued knowledge about running out of fuel for the fire as a potential reason for it ceasing. Given an inherent limited supply of fuel, this kind of prior knowledge would also have a tendency to support seeing the one-directional spread of a fire. From the scientific perspective, it is fundamentally impossible to undo the burning of a tree, similar to the mixture of water and juice, and these characteristics of the phenomena may have been incorporated into some student's understandings.

Diffusion, which is also a non-recurrent process, is slightly different from forest fires. Once diffusion has occurred, there is no way to go back. Unlike a forest fire after being extinguished, we cannot rekindle diffusion. Perhaps the closest option is to start a new diffusive
process with new liquids; in this situation it could occur again and again, similar to multiple forest fires and people getting mutated version of the same virus again and again, but it would not be the exact same process.

Viruses are similar to forest fires in the sense that they can be periodic in terms of an outbreak every couple of years, but they are fundamentally a non-recurrent process. Having been infected with a virus, it is impossible to undo that event. This issue was reflected in the previous sub-section discussing the fact that Ravi mentioned the periodic nature of viruses in terms of mutating and infecting with slightly different versions of the virus. Despite my framing of the spread of viruses as a non-recurrent process, this data point is important because it shows that students can conceptualize the phenomena in ways that I did not anticipate or plan for such an event. The most likely way to conceptualize these non-recurrent processes as recurrent ones is to account for slight variations in the phenomena, such as mutations in the virus or the fire being rekindled while incorporating a periodic motion. In this section, I argued that students’ prior knowledge constrained them such that they generally do not conceptualize non-recurrent processes in terms of periodic motion. In the rare cases in which they do conceptualize them this way, it requires application of their prior knowledge in specific supportive ways that allow this specific focus, such as finding mutating viruses as relevant.

**Periodic Motion Summary**

In the above analysis, I first discussed examples of students’ explanations based on conceptualizing sand dunes and traffic jams using the periodic motion explanatory pattern. Then I presented a unique case of one student conceptualizing viruses through periodic motion. Finally, I discussed forest fires and diffusion where there were no cases of periodic motion.

In the sand dune problem context I discussed similarities and differences across explanations generated by Laurel and Leah. The central difference was that Laurel focused on the size of sand dunes getting bigger and smaller, which was relevant to her, but Leah found that individual particles periodic motion to be relevant. Both students cued some prior knowledge about water waves being relevant to the sand dune problem context and neither incorporated information about a restoring force.

In comparison, in traffic jams, Keaton focuses on the changing density of cars. This included specific knowledge about the pragmatics of traffic jams, for instance, being scared when the cars are bumper to bumper, and prior academic knowledge about creating and interpreting plots of changing density of cars.

Students conceptualize sand dunes and traffic jams through the periodic motion pattern as both are recurrent processes, but there are some interesting differences across students’ explanations of these two problem contexts. Keaton focused on a periodic motion in terms of the density of cars while Laurel focused on a periodic motion of dune size and Leah focused on a back and forth periodic motion of particles movement. These are three different kinds of applications of periodic motion to these recurrent processes. Notice that the particular version of the periodic motion pattern is sculpted specifically to work in that problem context as related to students’ specific prior knowledge. For Keaton, in traffic jams, the most relevant feature are the surrounding cars and not the size of the entire traffic jam, hence focusing on periodic motion in terms of the changing density of cars is a reasonable fit. For Leah and Laurel regarding sand dunes, the size of the dune and the sand particles motion was relevant, hence focusing on periodic motion in terms of the changing size of dunes and particles motion is a reasonable fit. The particular prior knowledge students activate about traffic jams or sand dunes influences how they explain the phenomena through periodic motion.
Sand dunes and traffic jams being recurrent processes are different from the other problem contexts discussed in this section. Viruses, forest fires, and diffusion are all non-recurrent processes. There was one case of a student using the periodic motion pattern in the virus problem context, but his account of this behavior was built around the idea of a virus mutating and people getting slightly different versions of the virus repeatedly; hence I claim that is not the same kind of periodic motion as discussed in the sand dune and traffic jam problem contexts. Building off this case I hypothesized that it might be possible for a student to construct a forest fire or diffusion explanation that similarly focuses on the periodic nature of the phenomena as the fire is re-kindled repetitively, or as different liquids are mixed repeatedly. Overall, throughout this analysis, I argued that the specific kinds of prior knowledge students activate about the problem contexts along with whether a problem context is recurrent or not influences their explanations.

**Convergence to a Limit**

Convergence to a limit is a type of equilibrium and periodic behavior in which the system converges to a specific state or behavior over time. For example, one could imagine a range of speeds of cars resulting in sometimes the averages speed being greater or lower but over time the average converges to an intermediate speed. I begin this analysis by discussing convergence to a limit in the sand dune problem context where Damien’s explanation incorporates the idea of the sizes of dunes converging over time, due to mechanisms that support big unstable dunes in become smaller, and the small stable dunes in becoming larger. Then I discuss the case of Abhi whose bird explanation focuses on the positions of birds converging to a V-shape such that when their position diverges, there is a mechanism that supports them returning to the V-shape where it is easier to fly. In the final analysis case, I discuss an excerpt from the interview with Melissa, whose diffusion explanation focused on the tendency of molecules to mix such that their concentration is spread evenly throughout the substance. Across the sand dunes, birds, and diffusion context, there were only a few students who used the convergence to a limit explanatory pattern and the cases discussed in this analysis are unique. One interesting similarity across the sand dune and bird cases was the importance of underlying mechanisms that accounted for why the behavior tended to converge in specific ways. In comparison, with the diffusion problem context, no explicit mechanism was cited and instead the students implied that this behavior was a “natural state.” I hypothesize that these mechanism for why the behaviors converge are key for this explanatory pattern and have the potential to support students in coming to understand the decentralized and emergent nature of the phenomena.

**Convergence to a Limit in Sand Dunes**

In the sand dunes problem context, there were few cases of students generating explanations that incorporated convergence to a limit, in this section I focus on the one clear case from Damien, a Ph.D. student. Over the course of an eight-minute discussion Damien generates a sand dune explanation that incorporates the idea of dune sizes converging to a limit. For him, getting to this explanation is a process that builds from explanations about how dunes get bigger and smaller. Over time his explanations shift as he moves towards a discussion of effectiveness and stability of dunes. As Damien’s convergence to a limit explanation is built over a period of time, the analysis of this explanation requires more length than many of the other previous analyses. In the case of Damien’s explanation, there is no single moment in which he clearly explains that the dune sizes converge to a limit, but by looking across these different pieces of his explanation one can see the trace of the convergence to a limit pattern. A key part of the analysis of this case
is that convergence to a limit depends on many underlying pieces of explanations. These pieces include mechanisms for how dunes get bigger and smaller, many intuitive knowledge pieces, and recognition of several kinds of variety both within the behavior of dunes and variety in terms of how Damien goes about conceiving of the phenomena. Finally, Damien’s explanations are refined over the course of the discussion, and by the end of the conversation he generates an explanation that is based on changing composition pattern and thus is emergent.

At the beginning of the discussion immediately after the initial sand dune question, Damien mentions lots of wind and sand in the desert such that the dune gets bigger due to a mechanism that I call “accumulation.” In the excerpt, he mentions that when there is a little sand dune, wind blows onto the dune and that sand is caught and the dune becomes bigger. “Sand blows onto it [gestures with hands, wind blowing onto the small dune] then it would, could, get caught instead of going over it [gestures over the small dune] so then it could [gestures getting bigger], that is some mechanism where it could get bigger and bigger.” I refer to this mechanism, for how dunes get bigger as “accumulation.” This mechanism for how dunes increase in size was seen in many cases in the data and is a key part of Damien’s explanation.

After the above explanation, Damien discussed the possibility of there being many sand dunes in the desert, not just one dune. He also mentions that a big dune could form temporarily: “different wind patterns and things like this could lead to, for a while a big sand dune forming in one place [gestures a big sand dune], but not another.” In a follow up question, I then asked for further information about why there would be a many sand dunes and then immediately after my question Damien switches from his prior discussion of accumulation of sand to a discussion regarding the effectiveness of this process. Subsequently, Damien explains that as the dune gets bigger the process to destroy it becomes more effective and the process to make it bigger become more effective.

1. Damien: There is the process to build up a bigger sand dunes, and the process to build up, small--, to destroy sand dunes. And it seems like, well yeah, maybe not.

2. But, I guess my intuition was that, as a sand dune gets bigger the process to destroy it gets more effective.

3. But, I guess the process to make it even bigger [gestures bigger] also gets more effective because it can sort of trap more sand this way.

4. So, yeah, maybe that intuition is not quite right.

First, in line 1, Damien mentions a process to build up bigger dunes and a process to destroy dunes. Then he goes on to explain that as dunes get bigger the process to destroy them gets more effective (line 2) and oppositely the process to make a big dune even bigger also gets more effective (line 3). Recognizing this potential contradiction, he then cues some uncertainty (line 4). Notice that he is accessing some intuitions about the size of dunes being connected to the effectiveness of the wind in supporting a dune getting bigger or smaller and he connects this with the mechanism of capturing sand in lines 3, which was mentioned also in line 1.

A minute later upon being prompted by a question from me which asked for further information about the capturing sand process (line 5), he reiterates the same mechanism as before in regards to how a dune gets bigger by capturing sand (line 6). This time he adds more information about when there is already a small “bump” in the desert (line 8).
Lauren: Tell me more about the capturing sand, how does that work?

Damien: I mean, well so, if there is sand in the air, right, and it's just blowing, a lot. [gestures sand blowing] It's gonna blow a lot until it hits something.

And so, if the whole terrain was totally flat [gestures with hands to imply a flat surface] it's not going to hit anything. It might fall, but it probably just keeps going.

But if there was a bump [raises hand to signal a bump] and it was blowing along it's gonna run into the bump [gestures sand running into the bump] and after that it can't go anywhere, so its sort of capturing sand grains that way.

In this excerpt, he mentions two possibilities. First, the sand blows in the air until it hits something (line 6). For example, when the sand that is suspended in the wind hits the bump of sand in the desert, this sand is captured and leads to the dune getting bigger. This mechanism is the same one mentioned previously, but it includes more details. The second possibility is that the whole terrain is flat and the sand blows along not hitting anything.

Thirty seconds later I asked him to further discuss the issue of how the process of losing sand becomes more effective for larger sand dunes. Remember this issue was discussed previously in line 2. He explains that it has to do with the amount of surface area on the dune that is exposed to the wind.

Lauren: And then, talk me through the, you mentioned how it sounds like, the bigger sand dune might also, get, make the process by which it looses sand more effective.

Damien: Right

Lauren: How does that work?

Damien: Well, so, it's, I mean, it's sort of similar, right? Because the wind is blowing on the sand dune, and so, umm, there is more area for the wind to see. [gestures implies “area”] And so that just takes away more, more sand per any given time.

This excerpt contains key aspects of the mechanism for dunes changing size as it relates to convergence to a limit. Damien is drawing on an intuitive knowledge piece about more area of the dune leading to more effective movement by the wind to take sand away, potentially a version of the more is more p-prim. In line 12, Damien explains that when the dune is larger there is more area for the wind to hit, which allows the wind to take away more sand. This in turn leads to the dune getting smaller, although that additional piece of information is unmentioned, yet implied. In other words, based on a p-prim-ish intuition, Damien is explaining that as a dune gets larger the process by which it loses sand and gets smaller might be more effective because it has more surface area from which to lose sand.

A minute later after a side discussion about how various wind patterns might influence the shape of dunes, I suggested we change up the main question from how dunes get bigger or smaller, which was the initial question, to how dunes could stay the same size. I suggested this change based on his prior explanation. Although this might appear to be a big divergence, remember that at the beginning of the discussion he mentioned the possibility of there being many sand dunes in the desert, I incorporated this idea into my questions in lines 13 and 15.
Damien goes on to explain that if the dunes are all the same size then below the peaks there is no wind because it is blocked and above the peaks there is lots of wind.

13. Lauren: The process, how, say you have an area where there is a whole bunch of sand dunes, are all approximately the same size, instead of some big and some really small,
14. Damien: right
15. Lauren: how would the processes you described before, create a bunch of sand dunes all the same size? Or could they even? I don't know.
16. Damien: If the sand dunes are roughly the same size and there is a lot of them,
17. then you can imagine that if you are like below the level of the sand dunes peaks, then wind, there should be basically no wind. Because it just blocks it.
18. But if you’re above there should be a lot of wind and so any sand dunes that like momentarily gets bigger will be cut off by the high winds above.

After my suggestion about how dunes could all stay the same size (line 15), he then explained the dynamics of dunes from two different perspectives: below and above the dune peaks. If you are below the dune peaks, then there is no wind because the dunes have blocked the wind (line 17). This explanation is based on him cueing the blocking p-prim, such that dunes block the wind from hitting. Then he explains that if you are above the dune peaks, there is lots of wind. If any one dune momentarily gets bigger, it will be cut off and become smaller (line 18). This explanation is key for the explanatory pattern of convergence to a limit as he mentioned two mechanisms that account for the behavior from two different perspectives, above and below the dune peaks. The result of application of these two mechanisms is that the dunes will likely converge to a common size.

Following the above excerpt, I asked a new question about two dunes next to each other, and over time one getting bigger and one getting smaller.

“Say I’ve got, two sand dunes next to each other. Instead of you know, before in the story you came back and one sand dune was gone and a new one appeared, say you came back and you noticed that one sand dune had gotten much bigger and one had gotten much smaller. How would, how would that work?”

The purpose of this question was to change up the dynamics of how the dunes were shifting over time. It was meant to serve as a slightly new, but clearly related context, in order for me to see if or how his understanding might change when answering this new question. As discussed in Chapter 3, this question was common across the interviews.

To answer this question Damien generates an explanation that is based on the idea of dune stability. He explains that big and thin dunes are less stable and will collapse (line 19). Shorter and fatter dunes are more stable and it is easier for them to capture sand (line 20). I then ask for further information (line 21) and he reiterates that tall and thin dunes will fall down (22) and short flat dunes are stable (23) and then explains that there are many possibilities between the most stable and unstable dunes.
19. Damien: I'm not sure. I guess, you could imagine like a sand dune forming that’s sort of unstable. That like, is too thin [gestures thin dune], so eventually all the sand sort of collapses and it flattens out [gestures sand falling down from dune].

20. And then another one getting bigger it could, I don't know, it could be formed, it could have formed in a fat shorter, fatter configuration [gestures a short and fat dune] so it's more stable and easier for it to capture more sand.

21. Lauren: I see. I see. Tell me more about this stable versus less stable idea.

22. Damien: Yeah, so if you imagine a tower of sand [gestures a tall dune] umm, there is nothing holding it together. Just a straight up tower. Just all fall down. [gestures the tall tower of sand falling down].

23. But if you have a dune that’s barely a dune, it just like flat and like, a little sand piled up. [gestures a short flat-ish dune] And there is nowhere for the sand to go, that is like the most, like it's very stable.

24. So, you can imagine all the possibilities in between and you get more and more stable or less and less stable. However, what ever shape it takes.

Embedded within this stability explanation is also key information about convergence to a limit. He provided a mechanism for why tall thin dunes get smaller and short flat dunes get bigger. These two stability mechanisms, similar to many of the prior mechanisms, such as the tall dunes being cut off by the wind mechanism in line 18, all contribute to dunes sizes converging.

Over the course of the refinement of his explanation, he never explicitly states that the dunes sizes converge to a limit. He generates a series of mechanism to account for how and why dunes sizes change. Specifically, mechanisms for why big dunes get smaller and mechanisms for why small dunes get bigger. The mechanisms for dunes getting bigger are refined from accumulation to issues of effectiveness of the process of getting bigger (lines 2 and 3) to incorporating the role of surface area into the process (line 1s2). The mechanism for dunes getting smaller incorporates the idea of the dune peaks being cut off by the wind (line 18) and issues of stability (lines 19-20, 22-23). In this section, I argued that although Damien never explicitly stated that the sizes of dunes converge, the mechanisms he discusses account for this process of the sizes of dunes converging to an intermediate size.

Damien’s explanation is based on a variety of kinds of prior knowledge about sand dunes. Much of his explanations are based on knowledge about the sizes of dunes being salient. This includes experiential knowledge about being above and below the dunes peaks and experiential knowledge about how dunes influence each other. He is also accounting for the point of view of a flat desert versus one with many dunes. Additionally, Damien activates knowledge about concepts such as stability and effectiveness. Although there was not enough data to make conclusive claims about his knowledge of these concepts, as a Ph.D. student in physics, he likely has prior academic experiences with these concepts and is applying them in this sand dune problem context. Potentially he is coordinating his prior knowledge about these concepts with the sand dunes. Activating these kinds of concepts and coordinating them across contexts is suggestive of some type of relatively sophisticated understanding.

This case of convergence to a limit is the only clear case of this explanatory pattern in the sand dune problem context in the data set. In some ways, this is unexpected because Damien’s
explanation draws on prior knowledge that was common across many students in the data set. However, it is also possible that this was the only case due to the complicated collection of underlying mechanisms that were necessary for him to generate an explanation. Remember, Damien never explicitly stated that the dunes sizes converge to a limit; it was implied throughout his explanations. Potentially finding this explanatory pattern applicable is heavily dependent on the underlying mechanisms that influence how dunes get bigger and smaller. Without those mechanisms, he might not focus on the effectiveness or the stability of dunes, which in turn might not have helped him implicitly account for convergence to a limit.

Beyond mentioning some important mechanism for how dunes change size and cueing some potentially sophisticated prior knowledge, Damien’s convergence to a limit explanation was likely helpful for him coming to recognize decentralized causality. At the end of the discussion, a couple minutes after the final transcript excerpt (line 24), he generates an explanation that incorporates changing composition, which is emergent. Potentially this occurred, as his explanations were refined over time. His initial explanation, which may or may not be centralized, was focused on the wind moving the sand in a relatively simple manner. The final explanation was more complicated as it was built on lots of pieces of prior knowledge, some of which were concepts familiar to him from previous academic experiences. There is also a great deal of high level variability within his explanations, which is potentially helpful for seeing emergence. This high-level variability includes switching perspectives (above the dune, besides the dune, and grains of sand). It also includes recognition that despite the two extremes of stability, stable and unstable dunes, there are many possibilities in between (line 24). Another kind of variability in his explanations can be seen by him mentioning many factors that influence the changing size of dunes including height, width, area, and stability.

Overall, this is a unique case because Damien’s implicit convergence to a limit sand dune explanation was rather sophisticated in terms of the underlying mechanism, in terms of his prior knowledge, and because it was likely very helpful for him in seeing emergence. Explanations of this type are rare in my data set, potentially because it requires so much underlying knowledge and is based on several underlying mechanisms.

**Convergence to a Limit in Birds**

There were few cases of convergence to a limit in the birds problem context. In this section, I discuss the one clear example of convergence to a limit, from the interview with Abhi, a 9th grader. In this excerpt, he explains that at first, the birds might scatter, but over time, they fall into formation because it is easier for them to fly in formation. He provides a mechanism for why it is easier for the birds to fly in formation when he explains that a single bird flaps its wings and causes an updraft, which in turn eases other bird’s flight.

1. Lauren: So, how do they go from right here to over here?
2. Abhi: Like I said, for a while, it's a little scattered. But after that they all fall into formation.
3. Lauren: But how does like, like for the period of time that it is kind of scattered. How do they go from that to actually being in formation?
4. Abhi: I read somewhere that, birds with, that fly in V shaped flocks. The reason that they don't fall out of formation is because this bird, when it flaps it's wings, causes an updraft that helps this bird and all the way up the V, so, if they fall out of formation, they find the difficulty of flying and so fall back into formation.
5. Lauren: I see. So, like, when they are out of formation
6. Abhi: It's a little more difficult to fly.
7. Lauren: I see, so they fall into formation because it's easier to fly?

In the discussion with Abhi, I asked him multiple times about how the flock of birds changes directions and I did this again in line 1. Abhi mentions that the birds are scattered but afterwards they “all fall into formation” (line 2). I then asked about how they go back into formation (line 3) and he responds that he read somewhere that birds do not fall out of formation because one bird flapping its wings causes an updraft that helps other birds and this behavior continues throughout the flock, the result of this process is that any bird that falls out of formation will find it more difficult to fly and therefore will fall back into formation (line 4). Key pieces of this explanation were reiterated in lines 5-8 with Abhi explaining that it is more difficult to fly out of formation and him agreeing with my statement about it being easier to fly in formation.

In this excerpt, the distribution of bird’s positions are converging to a limit in which they are in the V-shaped formation. The birds sometimes drift out of formation, but over time, they converge into the V-shaped formation because it is easier for flight. Beyond noticing that bird's positions converge, Abhi also mentions a mechanism that supports this behavior: flapping wings causing an updraft that makes it easier for other birds to fly. This mechanism could function as a restoring force, although Abhi never mentions any oscillatory or periodic aspects of the behavior. Clearly, he views the positions of the birds converging to the V-shape, but it is not clear if he expects this to happen multiple times or not.

Underlying Abhi’s explanation is some knowledge based on his prior experiences about the movement of flocks of birds. Abhi mentions that he “read somewhere” about why birds do not fall out of formation (line 4). Possibly this explanation is based on prior knowledge that comes from prior reading about flocks of birds. This prior knowledge is specific being the mechanisms for why birds tend to fly in a V-shaped formation. There is an aspect of his explanation in line 4 that appears somewhat coherent. Abhi does not appear to be searching for a mechanism to explain the phenomena; instead, he appears very comfortable and may be explaining something that he is already familiar.

Across Abhi’s entire bird discussion the above excerpt is closest to decentralized causality. Before and after this excerpt his explanations tended more towards centralized causality with a discussion of the role of a leader bird and the role of predators. This excerpt with a focus on the position of the birds converging to the V-shape with a possible restoring force captures a behavior that has the possibility to be decentralized. In addition, the existence of this mechanism is important because it connects the individual birds behavior with the entire flocks behavior.

Compared to the larger data set, this explanation from the interview with Abhi was the only clear case of convergence to a limit within the bird discussion. Abhi’s convergence to a limit explanation was based on an underlying mechanism that may have been idiosyncratic as no other students mentioned the possibility. Abhi mentioned some prior knowledge from a relevant reading, perhaps this prior knowledge was key to his explanation, and without this particular piece of prior knowledge, other students might not mention this mechanism. For Abhi, this mechanism accounts for why birds that temporarily fall out of formation would be likely to fall back into formation, because it is easier for them to fly in formation. Additionally, this
mechanism could function as a restoring force. Without this mechanism his explanation might not have worked. Perhaps if more students had access to similar prior knowledge they would have generated explanations based on this or similar mechanism and potentially they would have generated explanations that incorporate the explanatory pattern of convergence to a limit.

**Convergence to a Limit in Diffusion**

In the diffusion problem context there were a few examples of student’s explanations incorporating the pattern of convergence. For the cases that did exist, this pattern was explained in terms of molecules spreading out in an even manner. In these cases, the molecules are converging towards a point at which the concentration of the two different kinds of molecules is even throughout the substance.

In this section, I focus on the case of Melissa, a senior undergraduate student majoring in physics. Her explanation included information about the tendency of molecules to mix and when doing so, spread out evenly. Prior to this explanation, Melissa had mentioned that water and juice want to mix and she referred to the state of lowest energy and had used the word, “diffusion.” I then inquired about what she meant by the word diffusion and she went on to provide a self-acknowledged textbook definition, and then she added more details about the tendency to mix. I then asked for more information about how it happens and she explained that the molecules moved around randomly and when averaged over the group, spread out evenly.

1. Lauren: You said the word diffusion, what did you mean by that?
2. Melissa: Diffusion, the gradual movement of molecules from an area of high concentration to an area of low concentration, the textbook definition.
3. Melissa: So, the tendency of things to mix, and become, spread their concentration equally over a given area or volume. That area, given volume. If that volume isn't water, then it can move easily within water and spread evenly through out the water.
4. Lauren: I see, so how does it?
5. Melissa: And do that again with the juice, also.
6. Lauren: So, how does it do that? How does it like spread evenly?
7. Melissa: Does the molecules in, the juice or the liquid, move very freely, not as freely as a gas, but much more freely then those in the solid, so they are moving around in their natural, thus, in their natural state to move, sort of, still kind of, connected to each other, but they still have a lot of room to move, so they will, each of the individual molecules will be moving around, in a completely random way, and umm, averaged over all the molecules it will spread evenly.

In this transcript excerpt, Melissa provides an explanation for diffusion and details about the molecules spreading evenly throughout the substance. First, in line 1, I asked her to elaborate on the word “diffusion,” which she had mentioned previously. She then went on to provide a self-acknowledged textbook explanation about movement of molecules from high to low concentration (line 2). Continuing, she elaborated on this idea by mentioning the “tendency of things to mix, and become, spread their concentration equally over a given area or volume” and similarly, “spread evenly through out the water” (line 3). I then asked for more information about how this occurs (lines 4 and 6) and she compares the freer molecular movement of gasses
to solids where there is less free movement. Following that, she mentions that molecules move randomly and “the molecules it will spread evenly” (line 8).

Within Melissa’s explanation she includes the idea of a concentration and that the molecules are spreading out evenly, which is convergence to a limit. Although she mentions that the concentration converges to a point where there is an even distribution, she does not cite any specific mechanisms that cause this behavior. Several times she mentions that molecules are moving around and that this is their “natural state” (line 7). Her explanation is based on the explanatory pattern of convergence to a limit in the sense of the concentration and the molecules themselves spreading out evenly.

This explanation is based on some prior knowledge from experiences with diffusion and molecular motion. When asked about the word diffusion, Melissa mentions the “the textbook definition” in line 2. Her statement in line 2 is evidence for her drawing on some prior knowledge that she associated with prior experiences with a textbook. She is also drawing on her prior experiences in physics with use of the words “area” and “volume” in line 3, her comparison between gasses and solids in line 7, and by discussing the randomness and averages in molecular motion in line 8. From all of this evidence one gets the sense that Melissa, as a senior physics major, is drawing on her academic experiences to construct this explanation.

From her use of the phrase “diffusion” and her elaboration on this concept, one gets the impression that this explanation is likely decentralized. She has a sense of the changing concentration of molecules and of the random nature of this process, which is suggestive of decentralized causality. Notice that other common hallmarks of decentralized causality that were discussed in Chapter 4, are not present, including connecting the microscopic and macroscopic levels. However, these are only hallmarks and not necessary components of decentralized causality.

Comparing Melissa’s convergence to a limit explanation of diffusion with other student’s similar explanations, there is a commonality in terms of the recognition of the tendency for two liquids to mix. The other clearest example of convergence to a limit in the diffusion problem context comes from the interview with Abhi, a 9th grader (see the Appendix for the transcript). He discussed the tendency of water and juice to mix, with or without an external object such as a spoon stirring the substances. Similar to Melissa he saw this behavior as inevitable and viewed the spoon as speeding up the process. However, differently from Melissa, he did not use the word diffusion, nor did he explicitly discuss the random nature of the process.

Overall in the diffusion problem context there were few cases of students incorporating the explanatory pattern of convergence to a limit into their explanations and of those cases that did, the students focused on the inevitability of the molecules to spread out or mix evenly. I discussed in detail the case of Melissa who cued some prior knowledge from academic experiences and used the word diffusion when explaining this behavior. She discussed in detail the tendency of things to mix and the random nature of this process. I also briefly compared her explanation to Abhi, who also mentioned the tendency of water and juice to mix, but he did not as clearly activate the same or as much academic prior knowledge despite him having a similar academic background to Melissa.

**Convergence to a Limit Summary**

In this section, I presented three cases of convergence to a limit within the sand dune, bird, and diffusion problem contexts. I began with Damien’s sand dune explanation for how different mechanism contributes to the sizes of dunes converging. Then I discussed Abhi’s bird explanation for how birds positions tend to converge on a V-shape because it is easier for the
Periodic and Limiting Behaviors Conclusion

I found that there are four kinds of periodic and limiting behavior in my data: changing composition, steady state, periodic motion, and convergence to a limit. All four kinds of equilibrium were mentioned in the sand dune problem contexts, and occasionally some of these types of behavior were mentioned in the forest fire, traffic jams, diffusion, birds, and virus contexts. Overall, none of these kinds of equilibrium was mentioned in the fish problem context.

According to the prior literature, some kinds of periodic and limiting behaviors are thought to be associated with centralized causality while others with decentralized causality. By this I mean that generating explanations based on some of these explanatory patterns are suggestive of reasoning in either decentralized or centralized ways. Changing composition is decentralized (Resnick, 1996), while steady state motion may be associated with centralized causality (Jacobson, 2001). My results agreed with changing composition but are more nuanced about steady state. Changing composition appears to be used to conceptualize the problem contexts in cases where there is evidence of decentralized causality. Relative rates of changing agents were central to changing composition and common in the sand dune and traffic jam cases. In the forest fires problem context, where students did not conceptualize the phenomena through rate, they did not mention changing composition. I agree that explanations based on steady state can be associated with centralized causality. However, in my data, steady state was often helpful for subsequent explanations based on changing composition among other explanatory patterns. In addition, in some problem contexts, steady state may have been helpful as it was used to conceptualize a temporary and unrealistic version of the phenomena that was rejected in favor of another explanatory pattern.

Periodic motion is not widely discussed in the literature, but in my analysis I find that whether or not students conceptualize the problem contexts through the periodic motion depends on whether the particular problem context is recurrent or not. I found that for the recurrent problem contexts, sand dunes, traffic jams, fish, and birds, students discuss the periodic nature of different characteristics of the behaviors, such as the changing sizes, changing numbers of agents, and density thereby resulting in explanations that are associated with decentralized causality. For the non-recurrent problem contexts, viruses, forest fires, and diffusion, there was only one case of periodic motion and it was different from the other cases in that it was not truly periodic. In this one particular phenomenon, the virus was mutating over time such that people were getting different versions of the virus each time. From this data, I hypothesized that to generate periodic motion explanations in forest fires and diffusion, students might similarly rely on their prior knowledge to generate similar explanations that are not truly periodic.

Finally, I concluded the analysis with a discussion of the convergent to a limit explanatory pattern. This explanatory pattern was not commonly used in my data, but I
discussed it in three cases including sand dunes and birds, where it was based on mechanisms for why the behaviors converge, and diffusion where convergence was viewed as the natural state with no underlying mechanism. My goal in this section has been to illustrate some of the particular ways in which students’ prior knowledge may have constrained or supported them in conceptualizing the different problem contexts through particular explanatory pattern, changing composition, steady state, periodic motion, and convergence to a limit. In many cases, students’ explanations based on these patterns may have been productive for coming to an understanding that is associated with decentralized causality. When possible, I also presented hypotheses for why these particular patterns may have been helpful for students to come to recognize decentralized causality. In this section I focused on four patterns whose behaviors all exhibit similarities in that they some type of periodic or limiting behavior. Now I move away from that family of related behaviors and focus on students’ explanations that are based on a different explanatory pattern, threshold.

**Threshold**

The goal of this section is to discuss variations across cases in terms of threshold being a more or less accessible explanatory pattern depending on students’ prior knowledge about the problem contexts. Threshold and another closely related idea, lag effects, are characterized by an initial behavior, a change in behavior that is often dramatic, and a subsequent behavior that is different from the initial behavior.

For the purposes of this analysis, I view threshold as a process in which there is initial behavior, a change in behavior, and then a subsequent behavior. During the initial behavior, the time scale is important often because there is a gradual build up of a substance or a tension. The change in behavior is often dramatic and related to an underlying mechanism. After the change, there is a subsequent behavior that is different from the initial behavior. For the cases discussed in this analysis, threshold is often not based on agency; instead, it is often based on interactions between individual agents. For example, in traffic jams, this can be an initial process in which cars are going at a fast speed, and then there is a change, perhaps a change in the density or a change in the number of cars on the road, such that there is a change in behavior manifest by cars slowing down.

There is a variant of threshold that I refer to as lag effects. Lag effects share many similarities with threshold, it is thought of as a period of time before something occurs. With lag effects, there is an initial behavior, which takes time before there is a change in behavior. Although time is an important attribute of threshold, in the lag effects the period of time is a defining feature. For example, in the traffic jam context, students mentioned the time it takes for a jam to clear up, also thought of as the time for cars to have enough space between them such that they can speed up. In this explanation, there is an initial behavior of cars being stuck in a jam, a threshold point of a certain amount of space between cars, and a subsequent behavior of cars increasing in speed. A key piece of this explanation is that the change in behavior depends on period of time such that the cars have enough space in between them to be able to increase in speed.

Beyond discussing how threshold may be a more or less accessible explanatory pattern to conceptualize a problem contexts depending on ones prior knowledge. I also argue that recognition of threshold can be supportive of generating explanations associated with decentralized causality. Through the analysis I argue that threshold is possibly productive towards supporting students generating explanations associated with decentralized causality.
because it may also support: 1) students recognition of critical variability in the behavior of the phenomena, 2) students in connecting the micro and macro level behaviors, 3) students in recognition of the underlying mechanisms, and 4) students application of the threshold explanatory pattern in conjunction with another pattern, such as cyclical motion or mid-layers. For most of the remainder of this section, I will discuss these four hypotheses in additional detail.

There are potentially several kinds of critical variability, but I focus on those that are potentially helpful in recognizing decentralized causality. One view of variability within complex systems focuses on recognition of randomness or probability as an earmark of either centralized or decentralized causality depending on whether or not it is seen as productive (then associated with decentralized causality) or detrimental (then associated with centralized causality) (Jacobson, 2001; Resnick, 1994; 1996). In my data set, productive randomness is relevant to the case of Laurel. When discussing sand dune formation she mentions the random distribution of sand grains leading to some locations having more sand than other locations thereby allowing dunes to begin forming. In addition to randomness and probability as a type of productive variability, I also investigate cases of what I refer to as high-level variability. High-level variability is a macroscopic variability presented as qualitatively different behaviors exhibited by the system. This might include completely different behaviors; for instance, chaos, order, oscillatory motion, and exponential motion. Leah, in the case of discussing traffic jams mentions several qualitative different behaviors, jams ceasing to propagate, jams oscillating, and stoppages presents high-level variability. These two types of variability, productivity of randomness or probability and high-level variability of qualitatively different behaviors are both key attributes of decentralized causality. Hence cases of students threshold explanations incorporating them may be helpful for recognition of attributes of decentralized causality.

A second reason that threshold may be helpful is that it might support connecting the micro and macro levels. Within complex systems there is often a complicated relationship between the behaviors at different levels and certain difficulties may arise from students not connecting levels (Sengupta & Wilensky, 2009; Wilensky & Resnick, 1999). However, similar to variability, connecting levels may or may not be productive for recognition of emergence, depending on the particulars of how it is applied. There could be data in which it is assumed that the behaviors at one level are the same at another level, which is associated with centralized causality. In comparison, understanding that behaviors at each level are different can be productive for recognition of decentralized causality because it might be associated with an understanding that a qualitatively different behavior can occur at separate levels. This also may be related to high-level variability as previously discussed.

Focusing of the underlying mechanisms may also support students’ recognition of decentralized causality because the mechanism at one level may be connected to relative rates, variability, and the behavior(s) at another level, all of which can support decentralized causality. From the data, it becomes apparent that there is a tight relationship between threshold and mechanisms; however, this relationship is manifest in different ways. For example, there are cases, such as Leah’s traffic jam explanation where threshold may be supporting a search or an emphasis on a micro level mechanism. There are other cases, such as Melissa’s forest fire explanation where threshold may be supporting recognition of more intuitive p-prim-ish mechanisms.

Finally, there are cases in which threshold is used in conjunction with another explanatory pattern, such that the two explanatory patterns could be bootstrapping or scaffolding each other. For example, in the case of Sarabeth’s virus explanation, she used both threshold and
an intermediate or mid-level of a group of people building up resistance. This mid-level functions as part of the underlying mechanism within the changing threshold behavior, such that the two explanatory patterns may be mutually supporting each other.

As I have argued, four aspects of student’s threshold explanations, variability, connecting levels, recognition of the underlying mechanism, and using multiple explanatory patterns in conjunction, are potentially helpful in recognition of emergence. However, an important question still is not fully answered, exactly how does recognition of threshold support these? Next, I present this hypothesis: Threshold is a macro level behavior that initially does not obligate a connection of levels, recognition of critical variability, or recognition of underlying mechanism. Let us be reminded about the nature of threshold. It is a macro level phenomenon where there is an initial behavior, a change in behavior, and then a final behavior that is qualitatively different from the original. One possibility is that threshold only captures the macro level, but there are cases in which students’ prior knowledge suggests the existence or importance of a micro level. Perhaps the student’s prior knowledge is cued in such a way as to support the search or recognition of a micro level behavior, thereby connecting levels or even cueing an underlying mechanism. Another related possibility is that the change in behavior cues or potentially even demands an underlying mechanism. Perhaps the change in behavior is dramatic enough such that students who are able to access certain kinds of relevant prior knowledge recognize that there may be an underlying mechanism. A different kind of possibility is based on the fact that threshold is composed of two qualitatively different behaviors, the initial and the final. Perhaps recognition of the variability across these two behaviors supports further recognition of other qualitatively different behaviors.

These hypotheses about how threshold may be helpful in recognition of decentralized causality are expanded further in the analysis section with additional emphasis on the kinds of prior knowledge cued in students’ explanations. This analysis is organized to begin with problem contexts where threshold was most common, traffic jams and viruses, and in the middle I discuss problem contexts in which threshold was less common, sand dunes, forest fires, and fish. At the conclusion I discuss problem contexts in which threshold was never mentioned (birds and diffusion). This information is summarized in Table H. I also discuss the variety in terms of which attributes of the phenomena exhibit the threshold behavior. For example, some of the variety I discuss is in terms of threshold at a macro level, for instance, in the sand dune case, versus a micro level, for instance, in the traffic jam case. In some cases, for example in viruses there is a threshold of time. In other cases, for example, forest fires there is a threshold in temperature. For each problem context, where applicable, I present a case or two of a student’s explanation based on the threshold explanatory pattern. I discuss why it may have been productive for them to recognize decentralized causality and I discuss some prior knowledge that might have supported the explanations. Where applicable I then generalize beyond the single case to other cases of students conceptualizing that problem context through threshold. Through this analysis, I show that conceptualizing the problem contexts through threshold can be productive for recognition of decentralized causality, but there is a great variety across the problem contexts in terms of whether or not this conceptualization occurred and what prior knowledge was activated.

<table>
<thead>
<tr>
<th>Threshold</th>
<th>Sand dunes</th>
<th>Traffic jams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Few</td>
<td></td>
<td>Some</td>
</tr>
</tbody>
</table>

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Threshold in Traffic Jams

In my data, threshold and lag effects were often used in explanations of traffic jams. I hypothesize that these explanations were productive because they connected the macro and micro levels, incorporated information about the underlying mechanism, and highlighted critical variability in the behavior; all of which are thought to be helpful in generating explanations associated with decentralized causality. In the data, there are two kinds of thresholds cited. First a threshold point of cars slowing down, an increase in density of the jam, or an increase in the number of cars leading to a traffic jam. A second and less common kind of threshold is a jam dissipating after a certain amount of time passes, resulting in the cars are able to increase their speed as the jam dissipates.

An example of the first case in which there is a threshold point leading to a jam forming comes from the interview with Leah. Leah is a Ph.D. student in physics and she mentions a threshold point in which a certain density of cars leads to a traffic jam forming. I first discuss the Leah case as her explanations were the most clear and she mentions two or three different threshold points, suggesting that her explanations might be more sophisticated than other student’s explanations. However, as I will discuss towards the end of this section, there are several commonalities between the kinds of prior knowledge she cued and other students’ prior knowledge in similar contexts. Leah’s explanation also accounts for a nice underlying mechanism of how jams occur wherein one person breaking and influencing other cars such that the changing behavior propagates outwards. Her threshold explanation occurs at the beginning of the traffic jam discussion, immediately after I asked the initial question about how traffic jams form. She begins by reiterating my question.

1. Leah: What causes a traffic jam to form? I don't, this is a question I've often wondered about. It's seems, I mean, if you observe traffic, like, there is a lot of interesting things that happen.
2. It seems like, it seems to me that there is sort of a critical density, that is reached of cars on the road and then, like, it can't. It can't propagate anymore.
3. It seems like when there is a really high density of cars on the road, to me anyway, then you start getting oscillations. Like in the, in the speed of traffic.
4. So I guess that happens because it's like, if one person hits on their break and there is like a continuous chain of cars that are close enough following distance then they also hit there break then that sort of, wave patterns that start propagate in the traffic.
5. And I guess, like, when the density of the cars gets high enough, there is not really, one person hits their break, the chain thing happens, and like at

<table>
<thead>
<tr>
<th>Forest fires</th>
<th>Few</th>
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<tbody>
<tr>
<td>Viruses</td>
<td>Some</td>
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<tr>
<td>Diffusion</td>
<td>0</td>
</tr>
<tr>
<td>Birds</td>
<td>0</td>
</tr>
<tr>
<td>Fish</td>
<td>Few</td>
</tr>
</tbody>
</table>

Table H: Table of threshold explanatory pattern with some indications of frequency.
some point it actually stops, like, the, I don't know, like, it's, yeah. It’s a good question.

6. …

7. I guess at some point you have cars entering the road way and things and when you're at some critical density already you can't add anymore without actually having stoppages.

In line 2, Leah mentions the first threshold point, a critical density of cars on the road such that they cannot propagate anymore. In this case, by using the word propagate, she seems to be referring to cars traveling; hence, by saying “it can't propagate anymore” she seems to be saying that at this critical density the cars behavior changes because they no longer move in the way that they were before. Notice that she seems to mean “move” but she uses the word “propagate.” In physics, wave motion is described usually as propagation, not movement. Given that she is a Ph.D. student in physics, she may be sensitive to the norms of wave motion in physics, but she seems to imply that the traffic jam is stopping. Perhaps she is sensitive to norms of wave motion in physics, but only nascent competent being that perhaps she is unclear, implying that the jam is stopping but phrasing it in terms of propagation. Despite this word ambiguity, it is clear that she is referring to some kind of change although there are few details about the subsequent stopping behavior.

Next, in line 3 she mentions a potential second threshold point, a “really high density of cars on the road” when you “start getting oscillations.” In this case, she is more specific about the increase in density of cars on the road leading to oscillations in the speed of traffic. Continuing with the same threshold point in line 4 she explains the mechanism that underlies this oscillatory behavior. She mentions one person hitting their breaks and this behavior influencing following cars, leading to the propagation of a wave or oscillatory pattern. “If one person hits on their break and there is like a continuous chain of cars that are close enough following distance then they also hit there break then that sort of, wave patterns that start propagate in the traffic.” In this explanation she is both connecting the micro and macro levels, individual people hitting their breaks (micro) resulting in an oscillatory pattern in the traffic (macro), and providing an underlying mechanism for the change in behavior.

Finally, in line 5 she mentions the third threshold point. This is a new high density of cars where the slowing traffic and oscillatory behavior is not caused by one person hitting their breaks; instead, there is a chain reaction and many cars stop. This third threshold occurs a couple minutes after the previous two. In line 7, after a side discussion about the similarities and differences between traffic flows and water flowing in pipes, Leah reiterates the third threshold point by mentioning traffic reaching a critical density when more cars cannot be added to the road anymore without stoppages occurring. “At some point you have cars entering the road way and things and when you're at some critical density already you can't add anymore without actually having stoppages.”

In this explanation Leah mentions two or three critical densities where the behavior of the traffic changes: 1) A critical density such that cars cannot propagate anymore, 2) a high density where oscillations or waves in car’s speeds start, and 3) a high enough density at which point the cars stop. The first threshold point might be the same as the second thus leading to an oscillatory behavior, but based on the data I cannot be certain. The second density is the most clear because she mentions an underlying mechanism of one person hitting their breaks and this behavior influencing surrounding cars. The third threshold point appears to be separate from the first and
second because she mentions all cars coming to a stop, and in the second density point she mentions oscillatory patterns that imply cars are still moving. However, the phrase is a bit unclear in the third threshold point as to whether she is referring to one car, many cars, or the entire traffic jam stopping?

Across these two or three threshold points, there is some common prior knowledge. Underlying her statement about people hitting their breaks may be some underlying pragmatic knowledge about wanting to avoid a car crash. Based on her experiences driving cars and being in traffic jams, she might be accessing some prior knowledge about the saliency of individual’s actions. Another type of knowledge is based on her conceptual limits and emphasizes the individual car level and adjacent cars. Additionally, her prior knowledge about chain reactions and the propagation of many cars is seen as relevant to her explanation. Finally, notice that stoppages, which were mentioned in lines 2 and 7, were another aspect of the phenomena that likely she has prior experiences with and are possibly salient to her in this context.

There are several aspects of this explanation that might support her reasoning about traffic jams as a decentralized process. First, notice that embedded within these threshold points is a sense of the variety of behavior of jams, cars can propagate, there can be oscillatory or wave like motions, chain reactions, and stoppages. As previously discussed, recognition of qualitatively different kinds of behaviors can be useful for recognition of decentralized causality. Second, she mentions an underlying mechanism that might cause the behavior. This is stated in line 4 with the discussion of the formation of the wave pattern she mentions cars following closely and hitting their breaks. Notice that this micro level mechanism (line 4) is mentioned after her discussion of the macro level threshold (lines 2 and 3). Potentially for Leah with her background experiences in physics, she recognizes that threshold as a macro level behavior can be explained by a micro level mechanism. This mechanism of when and why cars slow down might be supportive to her reasoning of the decentralized nature of this behavior. Third, this explanation accounts for the behavior at different levels, which is thought to be a key part of decentralized causality. She mentions the individual interactions between cars in line 4 and several times she mentions the density of cars (lines 1, 2, 3, 5, and 7), and the entire explanation addresses the macro level phenomena of how jams form (line 1). Overall, there are aspects of Leah’s explanation that suggest some nascent sophistication and possibly some novice students could be sensitive to these things.

Comparing Leah’s potentially productive and sophisticated traffic jam explanation with other student’s traffic jam threshold explanations there are some similarities and differences. In terms of differences, Leah’s explanation was likely the only case in the traffic jam data where a student referred to multiple threshold points. It was more common for students’ explanations to include only one threshold point. Additionally, Leah’s explanation was clearer than other students’ similar explanations and she used the phrase “critical density,” which is plainly a threshold point. In comparison, Jared, whose explanations may be more typical, mentioned “too many people using the roads,” which captures a similar conceptual idea, but the language is different.

In terms of similarities across students’ traffic jam threshold explanations; there are commonalities in terms of what threshold point is being referred to and what underlying prior knowledge supports the explanations. First, many students mention threshold or lag effects based on car’s speeds, densities of cars, or numbers of cars. This applies to both traffic jams forming and dissipating. In addition, there were cases of threshold or lag effects in traffic jams among students with different academic backgrounds, including high school students,
undergraduates, and Ph.D. students. For example, Nathan (Ph.D. student) mentions a threshold point of density of cars such that cars have to slow down in order to avoid collisions. “But as soon as traffic density gets higher, rush hour, then you would reach a point where a car going slower than you would invariably come across your path over time and if you refused to slow down, then you'd collide and then you'd be forced to slow down, by physics.” Another example comes from Sarabeth (11th grader) who explains the lag time for cars to speed up and begin moving after passing through a jam. “It takes time for you to start again and then it takes time for them to see you starting.”

Second, there are similarities in terms of the prior knowledge activated within explanations based on traffic jams. This was not surprising, given that students have both a great deal of experience riding in cars and being in traffic jams, and potentially they have experiences with other similar behavior such as waiting in lines. More specifically, many students drew on similarities in terms of prior knowledge, including: 1) pragmatic knowledge of jams, cars want to avoid crashing, 2) boundaries of knowledge, such as focusing on the changing speeds of immediately surrounding cars, and not focusing on the average speed of all the cars in the jam, which is likely not relevant in this context, 3) experiential knowledge, such as experiences of riding in cars, hitting the breaks to avoid a crash, seeing other cars slow down and speed up, and 4) p-prim knowledge intuitions. For example, Jared used an intuition of “more is more” that is similar to Ohm’s p-prim in diSessa (1993) when explaining that the more cars on the road, the further likely it is that a traffic jam will form. “More cars on the road, the more likely it is that someone, like, a few people would be going slowly and then they will trigger this whole thing.”

To summarize, in my data set there are many cases of threshold and lag effects in the traffic jams problem context and the majority are within explanations of traffic jams forming, while some are within explanations for traffic jams dissipating. I discussed in detail the case of Leah who articulately mentions multiple threshold points, which influence the changing behavior of jams. In that case, the threshold explanatory pattern might have been productive for her as she incorporated information about qualitative variations in the behavior, she connected the micro and macro levels, and she took into account an underlying mechanism. There are aspects of Leah’s explanation that suggest some nascent sophistication and possibly more novice students could be sensitive to these things. In addition, there were some commonalities across many students in terms of the specific prior knowledge activated and threshold point. Similar to Leah, other students often mentioned the speed, density, or number of cars on the road as key parameters for the threshold point. Another key piece knowledge across the data is knowledge about pragmatics, for example wanting to avoid accidents. Across the seven problem contexts, traffic jams is the one in which the threshold and lag effects explanatory pattern was most common. I now turn to problem contexts in which this explanatory pattern was mentioned, but less frequently.

**Threshold in Viruses**

There are some cases of threshold being used in the virus explanations. Often, these explanations accounted for a threshold of time to be cured or lag effect between exposure to the virus and symptoms appearing. Across these explanations and different kinds of threshold, there were some commonalities in terms of the prior knowledge about disease, carriers of an illness, and the build up of immunity.

In this section, I focus on Sarabeth’s explanation because it is one of the clearest explanations in the data set and other students’ threshold explanations are ambiguous in various ways. In some cases lag effect of time to be cured or before symptoms appear are embedded
within other explanations and it is difficult to separate the threshold explanatory pattern from other patterns, for instance, changing composition. Sarabeth is a 12th grader who explained that the behavior of viruses is based on the number of people infected. In this transcript selection she is rather clear about the virus dissipating as many people have been exposed to the virus, built up resistance, and thus there is a dwindling number of people who could potentially get sick.

1. Lauren: Okay. Okay. But you know how the flu virus, you know, the flu season it like kind of like, runs a course a little bit. You know like there is a point where lots of people are getting sick and then eventually it kind of goes away a little bit. How does that happen? How does the flu eventually kind of, the particular flu epidemic eventually kind of go away?
2. Sarabeth: Well, once enough people have it, then, there is not as many people to infect cause they build up a resistance to it,
3. Lauren: I see
4. Sarabeth: Once you have it, you won't get it as bad again.
5. Lauren: Uhhh
6. Sarabeth: And, after a certain point, like a certain number of the population, has already had it, so.
7. Lauren: I see
8. Sarabeth: There is not as many people just to
9. Lauren: I see. So like people who have already had it,
10. Sarabeth: They can't get it again.
11. Lauren: I see, so it's like you get it once and then you’re done?
12. Sarabeth: Yeah
13. Lauren: So it, I think I'm hearing you say that it dies out when there is not as many new people to infect?
14. Sarabeth: I mean, it would still infect them but they wouldn't get sick.
15. Lauren: Why not?
16. Sarabeth: Cause your immune system would know how to deal with it
17. Lauren: I see, so you’re like resistant?

In this transcript excerpt, Sarabeth explains that the flu dissipates as people who have already been infected with the virus build up resistance such that they can no longer get the virus and as a result there is a dwindling number of people who could potentially get sick. At the beginning of this excerpt, I ask her about how the flu epidemic might dissipate. “How does the flu eventually kind of, the particular flu epidemic eventually kind of go away?” Sarabeth then responded in line 2, when a certain amount of people have been infected and built up resistance there are less people to infect. “Once enough people have it, then, there is not as many people to infect cause they build up a resistance to it.” In the remaining lines of this excerpt, she expands on this idea. First explaining in line 3 that once you have the flu, you cannot get it badly again. She then continues in lines 6-10 explaining that there is a threshold point of a certain amount of people in the population who have had the flu and cannot get it again. I then restated this idea in line 11. Sarabeth then expanded upon this idea of getting sick once and not again, in lines, 14-17 explaining that the flu can still infect people who already had the virus, but they do not get sick because their immune system has built up some resistance. “It would still infect them but they wouldn't get sick…. cause your immune system would know how to deal with it”. In this
selection, the key threshold point is the point in time where enough people or size of the population has already been exposed to the virus and built resistance such that the virus stops spreading and eventually dissipates.

This excerpt from the Sarabeth interview is based on her prior knowledge about viruses. This includes knowledge about the pragmatics of viruses such as the limited size of a population and only getting sick once. There are also boundaries to her knowledge based on experiences of being sick including the often temporary nature of illness. However, as this piece of information about the temporary nature of viruses was embedded within the initial interview question, it is not surprising that she accessed it during the discussion. She also accessed knowledge about what is relevant, in this case it is knowledge about viruses spreading from one person to another, the binary nature of people being sick or not, having resistance or not, and the temporary nature of being sick. Notice that the temporary nature of being sick is either based on many types of knowledge, or perhaps just one but I cannot be sure of which type. The temporary nature of being sick was acknowledged during the initial interview question, so she was keyed into it thereby making it relevant. This is also something she likely has prior experiences with and is within her accessible conceptual limits. Another important piece of knowledge in her explanation is the binary nature of being sick or not, she finds this salient and within her conceptual limits. Notice that she does not focus on the variability of sickness, not necessarily because she literally believes that viruses are binary, but more likely because within this context she finds the binary nature of being sick more relevant that the variability of sickness.

In this explanation, threshold provides a way to incorporate a mechanism for change, key prior knowledge, and the intermediate layers explanatory pattern. Before the above transcript excerpt, she focused on describing the spread of the virus without any underlying mechanisms. Then, in line 1, I asked about how the flu dissipates. She immediately mentions a threshold point of a certain amount of people being infected and building up resistance such that there are not many people remaining to infect (line 2). Possibly my question was central for her initial recognition of threshold. Throughout the remaining excerpt, she continues to mention the underlying mechanism of building up resistance. For example, in line 16 she explains that one can get infected with a virus after already having had it, but you will not get sick “cause your immune system would know how to deal with it”. The idea of resistant is important to her threshold explanation as it provides the underlying mechanism for the threshold limit, a certain amount of the population cannot get sick. As discussed above, this mechanism is based on two key pieces of prior knowledge about only getting sick once and about a limited size to the population. Also, embedded within this explanation is an intermediate level group in which a “certain number of the population” (line 6) who already had the virus and “can’t get it again” (line 10). In this data, the intermediate level is a group of people who have built up resistance to the virus. The intermediate level group is a key part of the threshold because it is connected to the mechanism of building up resistance. Overall, threshold provides a framing for this explanation because it accounts for an underlying mechanism, is based on prior knowledge about getting sick once and building up resistance, and it implies an intermediate level group based on that prior knowledge.

As I mentioned previously, the case of Sarabeth is the clearest within the data set, but there are other cases, often with more implicit or uncertain thresholds across students with varying academic backgrounds including other high school students (besides Sarabeth), undergraduates, and Ph.D. students. For example, Ravi, a Ph.D. student generates an explanation that implies a building up of resistance to a virus to achieve immunity (discussed in
the periodic motion section). An additional example comes from Stephan, another Ph.D. student, who several times mentions lag effects in terms of the time it takes to both get the disease after being infected and lag time to be cured (discussed in the steady state section). Similar to Ravi, for Stephen the lag time is a bit uncertain, possibly more implicit then explicitly mentioned.

Throughout these cases, both the clear and uncertain ones, there are some commonalities across the nature of the prior knowledge. This includes prior knowledge based on experiences with the time it takes to be cured of a virus. There is also some common prior knowledge about what is relevant, the people who serve as carriers of the disease, and a build up over time towards immunity.

Within the virus problem context, some students generated explanations that accounted for the spread of a virus through a threshold or lag effects behavior. There were a few clear cases and some uncertain ones using this pattern. One of the clearest cases comes from Sarabeth who discusses a threshold point of building up resistance to the flu such that there are a dwindling number of people who could potentially get sick. I discussed this case in detail and hypothesized that this explanation might have been helpful to her as she uses an intermediate level group to support her understanding of an underlying mechanism.

**Threshold in Sand Dunes**

There were only a few cases of sand dune threshold and in those cases it was the sand dune size that was salient for students. I saw two versions in the sand dune data: 1) the case of Lily in which she mentions that when sand dunes get too big they fall down, and 2) the case of Laurel in which she mentions that sometimes at a given location enough sand particles collect such that it attracts enough other sand such that the pile starts getting bigger again. While these two sand dune threshold cases are opposites, underlying them in some similar prior knowledge. In both cases, the sand dune size is relevant and students are drawing on prior knowledge and experiences with material goods piling up and falling down.

I shall begin with discussing the case of Lily, a high school student, who explains why sand dunes fall down when the size of the dune reaches a threshold point.

1. Lauren: So any idea, what variables, what else might influence how this happens?
2. Lily: Well, if there were people there, stepping on it, sand would move, if there was an earthquake it would move.
3. If there was so much sand, some would start to fall down the sides, but I guess there would be, the dune would still be there.
4. Lauren: So, how would, how would the sand, when or how would the sand fall down the sides?
5. Lily: Well, when wind, if you have, [drawing] your pile of sand, and more sand on it,
6. it gets to a point where it just has to, no where for the sand to go so it kind of like crumbles down there.
7. Lauren: I see, so what do you mean by, there is nowhere, nowhere else for sand to go?
8. Lily: It can't rest on it.
9. Lauren: I see, so its like
10. Lily: Or it like, is kind of like that slant think when it gets too, too steep it's gonna fall off
11. Lauren: I see.
12. Lily: Doesn't have a place to sit, or, and gravity makes it fall.

In this explanation, Lily explains that sand falls down the sides of the dune when it reaches a point where the sand can no longer stay on the dune. At first she mentions dunes getting smaller because of people stepping on it or earthquakes (line 2), but then she abandons this idea and focuses on the sand falling down the side without a direct central cause (lines 3-12). For the falling explanation, she first mentions a certain amount of sand such that it falls down the sides. “If there was so much sand, some would start to fall down the sides.” (line 3). I then asked her how this might happen and she mentions in line 6 a threshold point where the sand has nowhere to go so it needs to fall down. “It gets to a point where it just has to, no where for the sand to go so it kind of like crumbles down there.” I then asked for more information in line 7 and Lily explains in lines 8 and 10 that the sand cannot “rest” on the dune when it gets too steep so it needs to fall off. She elaborated this idea further in line 12 mentioning that gravity makes it fall. In these explanations, she mentions conditions or variables that influence when the dune hits a threshold point where the sand falls.

Underlying Lily’s explanation of sand falling down there is some intuitive knowledge about the behavior of granular materials in piles. She may be accessing a general causal intuition about piles of materials being able only to support a certain quantity before materials fall off. This might be thought of as an intuitive version of the angle of repose or a similar intuition about the behavior of material goods when piling. The critical angle of repose is the steepest angle that can form on a pile of granular materials before the materials begin to slide. While this is a technical piece of knowledge directly related to mechanics and geology, I posit that in this context it has an intuitive counterpart, which is what Lily may be cueing. For Lily, the fact that at some point the granular material falls off is obvious, it just happens and does not require further explanation.

In this explanation, the threshold point provides a reason for when and why the dune changes. In line 3, she describes the changing dune behavior without mentioning a threshold point. I then asked her in line 4 to consider the when or how aspects of the changing behavior “when or how would the sand fall down the sides?” After this point, her explanation shifts from only describing the change (line 3) to incorporating a threshold point (lines 6, 8, 10, and 12). Possible, the way the threshold explanatory pattern accomplishes this is by shifting from the more intuitive potentially p-prim based explanation in which sand falls without any further details (line 3) to the more mechanistic explanations in lines 6, 8, 10 and 12. This shift happened in conjunction with the questions I asked. She mentioned the sand crumbling down and having nowhere to go (line 6) and then I asked for some elaboration (line 7). Following this she continued with the idea of the sand not being able to rest on the pile (line 8) as well as not having a place to sit (line 12). Both of which are reasons why the sand falls. At the end of line 12, she mentions the most physics sounding reason of all, “gravity makes it fall.” In this case, threshold provides a reason for when and why the dune changes and the way this occurs is with a shift away from a more intuitive based explanation towards a more mechanistic physics explanation in conjunction with my interview question about when or how the behavior changes.

Threshold and the relevant mechanism for the changing behavior along with a possible conceptualization of a mid-level group may jointly support her in recognition of decentralized causality. The mid-levels group mentioned in this excerpt is a bit ambiguous, but one could consider the collection of sand that starts to fall (line 3) as some kind of intermediate group that has a distinct behavior from the group of sand particles that remain on the dune not moving.
Hence, she is potentially recognizing that there are qualitatively two different groups of sand particles that exhibit two different behaviors including sand falling off the dune due to gravity when the slant gets too steep, and sand remaining on the dune. This kind of variability in which there are different kinds of behaviors within a phenomenon is a key part of decentralized causality.

A second case of a student generating an explanation that accounts for the behavior of sand dunes in terms of the threshold explanatory pattern comes from the Laurel interview. The entire Laurel sand dune discussion, including her explanation for dunes beginning to form due to threshold, was discussed extensively in Chapter 4. In this section I will summarize the previous discussion briefly in order to compare it with Lily's sand dune threshold case. The excerpt below comes from the end of the interview at a point where Laurel has already rejected the centralized explanation on several occasions and made progress towards the decentralized explanation. At first, Laurel explains that she has two ideas; the initial one is the focus of this analysis as it is about an initial threshold size of a pile of sand that allows the dune to get bigger. She explains that by chance, enough sand particles land in one location such that it is sufficient sand to start catching more sand so that the pile becomes bigger.

91. Laurel: Well, I have two ideas.
92. Maybe it's by chance that like,
93. maybe some you know, some number, some vital number of sand molecules or whatever got all in one place [gestures implies sand particles all in one place] and then that was enough to start catching more [gestures implies catching more], more deliberately.
94. I don't know why
95. I'm think of it like, like they all just happen to fall, but then once it gets big enough then it actually maybe the, it's big enough to kind of start stopping other molecules, or sand, which makes its bigger. [gestures implies the sand dune getting bigger]

In this excerpt, Laurel twice explains that the dunes get bigger from random variations in the distribution of sand particles and this leads to a threshold point where the dune begins collecting more sand to get bigger. First Laurel mentions that this process begins by random variations in the distribution of sand such that one location winds up with more sand than another. “Maybe it's by chance that like some number, some vital number of sand molecules or whatever got all in one place.” Embedded in this idea is the threshold point of a “vital number” of sand particles in that one location. Subsequently she explains that after this happens, the pile can catch more sand. In the second case (line 95), this explanation is then reiterated using slightly different language. Laurel explains that sand particles fall and then at some point the pile of sand gets big enough such that it can stop other sand particles, resulting in it gaining more sand and growing larger. “They all just happen to fall, but then once it gets big enough then it’s big enough to kind of start stopping other molecules, or sand, which makes its bigger”. Again, underlying this selected version of the explanation is an initial behavior of sand particles falling in a random manner, a threshold point where the dune gets big enough to stop other sand particles, and a final behavior in which the dune grows bigger.

As was extensively discussed in Chapter 4, this explanation may have been productive for Laurel as she moved towards reasoning in a decentralized manner. More specifically, this
explanation includes an underlying mechanism for how dunes get bigger by catching or stopping other sand particles. This mechanism may be helpful in recognizing decentralized causality. There is also an element of randomness or variability in the behavior of individual sand particles; randomness is sometimes associated with decentralized causality.

Embedded within this explanation are several kinds of prior knowledge about sand dunes. This includes prior knowledge about aspects of the phenomena being relevant, including the random distributions of sand particles, the size of dunes, the particles falling in particular locations, and the ability of a dune to get bigger by accumulation of sand particles. Another kind of knowledge is mentioned in line 95; Laurel mentions that perhaps the dune is big enough to stop other sand grains. Potentially embedded within this statement is a version of the blocking p-prim. For this knowledge piece, there is a dune that blocks the sand grains, which are suspended within the wind, such that the grains of sand join once in contact with the larger pile. This knowledge piece was seen elsewhere in the sand dune data and appeared in such a way that it felt intuitive and self-explanatory.

Although the specifics of the knowledge pieces were different across Laurel and Lily’s sand dune threshold explanations, they share several similarities in terms of what phenomena they viewed as relevant and in their intuitive nature. Both students focused on a threshold of a dune’s size, based on the size of dunes being relevant. However, they differ in terms of the details. Laurel focuses on a random distribution of sand particles leading to a small pile of sand that then gets bigger as more sand accumulates. In comparison, Lily focuses on dunes getting smaller when they reach a threshold point when the sand particles fall off the dune. They are paying attention to inverse processes, dunes getting bigger and dunes getting smaller, but they are both viewing these processes in terms of the threshold pattern. Given that they focus on different processes, these two students also invoke different intuitive prior knowledge. Laurel might have cued the blocking p-prim, leading to dunes accumulating more sand and getting bigger, and she uses some intuitive knowledge about the random variations in the distribution of sand leading to a small pile beginning to form. Differently, Lily might have cued some intuitive prior knowledge about the angle of repose.

Laurel and Lily’s sand dune threshold explanations were the only two clear cases of threshold within the sand dune problem context and I am a bit surprised that there were not more similar explanations. These two cases appear to be based on important and potentially common intuitive prior knowledge about dunes. I would have expected these types of explanations to be more common across the clinical interview data, and I am a bit surprised not to see more cases of students generating explanations in the sand dune context based on the threshold explanatory pattern. Perhaps this is because the interview questions or other commonalities across the interview did not strongly activate this pattern as relevant. While I cannot be sure of the reasons, I view these two explanations as interesting, but unusual flukes rather than common explanatory pattern, despite the prior knowledge activated within Laurel and Lily’s explanations.

Threshold in Forest Fires

Similar to sand dunes, there were few cases of threshold or lag effects in the forest fire problem contexts, but these few cases tended to focus on a threshold in temperature. In my data, there were two versions of a threshold in temperature. The first was that initially the materials are not burning, but when it gets hot enough there is a certain point at which the materials combust. Secondly, for materials that are already on fire there is a certain point when it becomes harder to maintain the fire, so it is extinguished. These two versions of threshold in the forest fire problem context are inverses of each other, one is about a threshold point of a fire beginning, and the
other is a about a threshold point of a fire being extinguished. Having two inverse threshold points is similar to the sand dunes cases where their as a threshold point of dunes collapsing and a threshold point of dunes beginning to form.

In the first forest fire case, Antonio, an undergraduate majoring in physics, discusses a threshold of temperature. He mentions a point where the temperature becomes high enough so that the material substance, in this case he is talking about paper, combusts. He then compares this example of paper combusting to a leaf on fire.

1. Antonio: How does the fire spread? Lets see, fire is heat, it's a plasma of charged particles flying away from each other. Basically the atom breaks down into separate pieces, that’s is what fire is.
2. Lauren: Uhh
3. Antonio: From my understanding of it. I'm sure it's a plasma. Basically it's electrons flying apart from each other. This gas which we call 'flames.' And it's really energetic and really hot and this energy transfers from one part to another so if I have a flaming piece of paper and another flaming something, this is really hot plasma, like to light her up.
4. Lauren: Yeah
5. Antonio: The lighter flame, put it up next to it [piece of paper], this gas the plasma is going to transfer it's energy to the paper
6. Lauren: I see
7. Antonio: And then rattle these molecules around cause they will have more and more energy
8. and pretty soon they will hit the temperature where paper decides it doesn't want to be a solid white piece of thing any more and turn into that same plasma, and combust, and turn with that and spread the fire along.
9. Same way it would from one tree leaf to another tree leaf, on to the bark and on to the wood itself and then that flame will be there, and then it will excite the molecules next to it, heat up those and make those combust and just keep going.

Antonio first explains the nature of fire as a plasma of charged particles and then he focuses on an example of a piece of paper being on fire. He goes further and mentions a threshold point when the paper combusts and finally in the last line he mentions that a leaf on a tree will exhibit similar behavior to that of paper. Specifically, on line 1, Antonio asks himself how fire spreads and explains that fire is plasma of charged particles. He reiterates these ideas in line 3 explaining that this plasma is composed of electrons flying apart from each other and they are energetic, hot, and allow energy transfer. Continuing on line 5, he uses an example of putting a flame next to a piece of paper such that the plasma transfers energy to the paper. First, the molecules in the paper will move around as they gain energy (“rattle these molecules around cause they will have more and more energy”) and then it will hit a threshold temperature where the paper will combust. “They will hit the temperature where paper decides it doesn't want to be a solid white piece of thing any more and turn into that same plasma, and combust.” Finally in line 9 he explains that a leaf on a tree will behave similarly to the piece of paper with fire spreading from leaf to leaf and to the bark as the molecules in nearby leaves are excited, heat up, and combust. “Same way it would from one tree leaf to another tree leaf, on to the bark and on
to the wood itself and then that flame will be there, and then it will excite the molecules next to it, heat up those and make those combust.”

Embedded within this threshold explanation is a mechanism for how the fire spreads and there is a connection between the atomic and plasma levels. Both the mechanism and levels connecting might be productive for Antonio in recognition of the decentralized nature of the spread of fire. In both lines, 1 and 3 Antonio connects the atomic and plasma levels of fire. In line 1, he mentions that fire is composed of atoms breaking down into separate pieces and in line 3, he mentions that what we call “fire” is plasma of “electrons flying apart from each other.”

The connection between the atomic and plasma levels is discussed a couple lines later. Antonio mentions the underlying mechanism for the spread of fire includes excited and energetic molecules heating up surrounding molecules. In line 5, he describes this behavior at a macro level mentioning that if there is a flame next to a piece of paper, the plasma transfers its energy to the paper. Then in lines 7-8, he mentions the molecules rattling around because they have more energy, which in turn causes the combustion. This mechanism is then applied to the trees and leaves in line 9 where Antonio explains that the flames on the wood will excite the nearby molecules, heating them up and making them combust.

Antonio is flexibly switching between the macro (paper and leaves) and micro (atoms and molecules) levels, suggesting that this explanation is productive or even associated with decentralized causality. Both levels are mentioned often and he switches between them with no great challenge. Possibly this is a reflection of his expertise, being a senior level undergraduate student majoring in physics. Most of the mechanistic aspects of this explanation are based at the micro level, the molecules, and atoms moving around and transferring energy, but the threshold point is at the macro level, paper and leaf combustion. Perhaps this is a sophisticated threshold case because he so fluently connects a macro threshold with these important micro level mechanisms.

Underlying Antonio’s explanation is a variety of prior knowledge pieces that influence what aspects of fires he finds relevant. Notice that he finds the behavior of the fire at the molecular level to be relevant and he focuses on the movement, temperature, and energy of the molecules. He also finds it relevant to see fire as a plasma of charged particles. Given that he is a senior level physics major, finding this micro-level view of fire relevant likely is based on some prior experiences thinking and learning about the molecular view of fire, potentially some prior academic experiences with related topics. Additionally, related to his prior experiences and what he finds relevant, he uses the example of a piece of paper on fire to explain forest fires and then connects the two contexts. He may be coordinating the behavior across the paper and tree contexts, which might not be surprising. I would expect students with his academic background to coordinate the spread of fire across similar contexts such as leaves and paper burning.

While Antonio focuses on a combustion point where paper or leaves catch on fire, Melissa oppositely focuses on a threshold point where materials stop burning. Her explanation was prompted by a question I ask about how a fire eventually gets smaller (“How does that get smaller, eventually?”). Melissa, an undergraduate majoring in physics, responds that at a certain point materials become harder to burn or pass the fire along. “I think that once it reached a certain point it was, that stuff became harder to burn or harder to pass the fire on”. Then she continues to explain in more detail that fire gets to a point where the flames cannot move on, perhaps it uses up all its fuel, or perhaps it hits a natural boundary like a river.
“it can't burn the stuff, so, the flames won't you know, if it can't burn, the flames, it won't it can't move past it… it will, kind of, stop there, but then, while it's like, on, at that boundary, it will, eventually use up all it's fuel, and it will go out… if it reaches like a river or something, like, then it can't go across the water… something that is stopping it that it can't burn, it has to stop there and so once it stop there, it can go no where else, stay there or recede back in, or out”

Underlying this explanation is a threshold point of the fire stopping. She mentions several possible causes for the change in behavior: the fire hits a boundary, all the fuel is used up, it reaches a river, or something else stops the fire. The result of any one of these is that the fire recedes or goes out. Despite the multiple potential causes, Melissa is clear that eventually the fire reaches a threshold point where it will stop, for one reason or another.

Embedded within her explanation of the inevitability of a fire stopping is some prior knowledge and specifics about the nature of fire. This includes knowledge about what aspects of the fire she finds relevant, the flames, the burning fuel, and the surrounding environment, for instance, a river. This also includes some pragmatic knowledge about fire going out eventually. It is possible that underlying this explanation of fires dissipating is the dying away p-prim, but in this case, Melissa provides several causes for the fire going out, which is not done commonly when p-prim are activated given that they require no further explanation once cued.

In this explanation, Melissa first mentions the threshold point of the fire stopping and then searches for the mechanism that accounts for this threshold point. The threshold point may be supporting or otherwise encouraging her to search for a mechanism, particularly because it is at a macro level (fire ceasing to burn) and perhaps she has a sense of an underlying micro level mechanism, despite the lack of one being mentioned. Melissa is a senior-level undergraduate majoring in physics and she is very articulate and I found her comfortable and able to bring into the discussion ways of thinking about the behaviors that were related to her academic work in physics. Although she, unlike other similar students including Antonio, never explicitly mentioned the plasma nature of fire, a couple minutes later she did mention the micro level of the fuel for the fire. This occurred after I asked a follow-up question about the kinds of fuel she was thinking of. She replied “any of the carbon and like hydrocarbons basically, basic combustion formula. CH02 and C02 and like H20, any formulary hydrocarbon that could satisfy the basic combustion equation could be a source of fuel and most of those would be organic.” Based on her comfort level with this perspective on fuel, I would argue that earlier in the conversation she had some sense of an underlying micro level mechanism, despite the lack of one being mentioned. When discussing the reasons why fire stops she mentioned several more intuitive reasons including a boundary point, running out of fuel, a river, or the fire simple receding. These intuitive reasons may be p-prim-ish, for instance, the idea of a fire dying away, a boundary blocking the fire, or the fuel being used up, which are intuitive in nature and not at a micro level.

In summary, the macro level threshold point may be supporting her in searching for an underlying micro level underlying mechanism, but for unknown reasons she instead focuses on more intuitive p-prim-ish type mechanisms.

Comparing Melissa and Antonio’s threshold of forest fires explanations finds that they are quite different and this difference is likely due to what prior knowledge they found relevant during the discussion. Antonio focuses on a combustion point where paper or leaves catch on fire. Melissa oppositely focuses on a threshold point where materials stop burning. Antonio’s explanation captures both the atomic and the macro level and he connects the two through the
underlying mechanism of energetic atoms influencing surrounding atoms as the fire spreads. In comparison, Melissa’s threshold explanation focuses on the macro level only. The micro level is mentioned later when I asked for elaboration about the fuel and includes several macro levels causes for the fire receding or going out. Given that Antonio and Melissa have relatively similar academic backgrounds, this difference in explanations is likely due to differences in prior knowledge, specifically what kinds of prior knowledge they drew on as relevant during the discussion, especially the macro versus micro levels.

In general, the threshold of forest fires was only mentioned a few times in the data set and this is a bit surprising given the commonalities between the kinds of prior knowledge mentioned by Melissa and Antonio and by other students. Of the cases of the threshold explanatory pattern being used in the forest fire problem context, it includes cases from high school, undergraduate, and Ph.D. students. Many students mentioned knowledge about the conceptual limits of fires, for example, something being on fire or not being on fire, also many students mentioned experiential knowledge about fire, for example, seeing something burning or not and knowing that fire is both hot and temporary. In addition, many students cued knowledge about the phenomenon that is similar to the kinds of prior knowledge Melissa and Antonio cued in their threshold of forest fires explanations, including knowledge about temperature, types of materials (e.g. wood, paper), the characteristics of the materials (dry or wet), the existence of a molecular level, the changing size of fires, and the existence of trees/leaves/undergrowth.

I posit that explaining forest fires through threshold was not more common due to the nature of the interview question and problem context story. The phrasing of the initial story and question did not highlight a dramatic change when a fire begins and goes out; instead, it emphasized the spread and contraction of a fire, which is a more gradual process. Perhaps to explain forest fires through threshold one needs to see a dramatic change, such as combustion as described by Antonio.

In summary, I found two kinds of threshold of forest fires explanations, but overall this explanatory pattern was uncommon in the larger data set. In Antonio’s case, the threshold explanation was likely productive for his reasoning about decentralized causality as he connected the atomic and plasma levels when explaining combustion point. Comparably, Melissa focused on the macro level of a fire dissipating when it runs out of fuel or hits a boundary. Antonio and Melissa each drew on different prior knowledge, but for both of them, their knowledge shared some similarities with the larger data set. A threshold of forest fires was not common in the data set, perhaps because there was little emphasis during the discussion on a dramatic change.

**Threshold in Fish and Birds**

The fish and bird problem contexts are similar to each other, and there are few cases of threshold mentioned in the fish problem context and no cases of threshold mentioned in the bird problem context. Also, the few cases of threshold in the fish problem context were only by 8th-12th graders. The case of threshold mentioned in the fish problem context is unusual because it diverges from my planned discussion topic of how schools of fish shift position and size and instead focuses on evolutionary issues including fish building up immunity to electricity over several generations.

Erik’s fish threshold explanation describes how fish build up immunity to electricity resulting in them getting to a point where electricity can no longer cause harm. This explanation is embedded within a discussion of fish evolution. Similar to common misconceptions about “need” being thought to be a central element in evolutionary changes (Bishop & Anderson, 1990; Southerland, Abrams, Cummins, & Anzelmo, 2001), Erik’s explanations focused on fish
becoming faster, developing more camouflage, and developing immunity to predators as beneficial traits for protection. More specifically, Erik mentions “eventually the fish will build up immunity to electricity and when it get electrified it won't hurt them.” I then asked how this happened and he says: “Parents pass a trait down. The same way I learned to be immune to electricity by experiencing it a lot then my child would experience electricity and they would become more immune to it. Eventually my blood line would be totally immune to electricity.” He is focusing on a build up of immunity to electricity over generations to a point where electricity can no longer cause harm. Erik's explanation focuses on the purpose of the schools of fish, “for protection,” then focused on how they achieve this goal, and what happens when a predator such as a shark chases after individual fish. Also, this threshold explanation incorporates information about a long period time, many generations.

Underlying Erik’s fish threshold explanation is a variety of prior knowledge. This includes knowledge about pragmatics of fish wanting to avoid predators and be safe. Additionally, information about what he finds to be relevant, such as the build up of immunity to electricity and parents passing down traits to their children. In addition, agency is an important piece of this explanation because fish want to avoid predators and be safe.

As mentioned previously, Erik’s explanation of fish building up immunity to electricity was unexpected because for both the bird and fish problem contexts I anticipated the students would focus on a threshold of size of the schools or flocks, as opposed to an evolutionary threshold. A threshold of size of the flock or school, leading to it getting bigger or smaller, would have been similar to the sand dune and forest fire threshold cases. However, students did not mention a threshold in size of the flocks or schools. Possibly this is because students underlying knowledge did not support any specific mechanisms that would have accounted for the threshold points leading to a change in behavior. Remember, in the forest fire and sand dune cases students mentioned specific mechanisms accounting for the changing behavior, including intuitions about when sand particles fall off dunes and what temperature causes paper to combust. In general, I did not see students mentioning any particular mechanisms for why flocks of birds or schools of fish would change size at particular points. For example, one could hypothetically imagine students saying that at some point the flock or school became so big that it got unwieldy and had to get smaller. Alternatively, perhaps when a school or flock is forming, there is a point at which it becomes big enough that it attracts other birds or fish. These are completely plausible explanations based on mechanisms that could have accounted for a threshold point, but students did not mention them. Notice that these hypothetical explanations of thresholds of the size of flocks or schools would draw on different prior knowledge than Erik cued. Erik cued prior knowledge about safety and predators, which lead to a threshold based on agency that is different knowledge than might have been useful in a more mechanistic threshold of flock size. In summary, my hypothesis is that students rarely mentioned a threshold in flock or school size because they were not cueing prior knowledge that would have provided an underlying mechanism for the changing size of flocks or schools. Had they cued some prior knowledge that accounted for an underlying mechanism then they might have been more likely to mention threshold in those problem contexts.

Threshold in Diffusion
Throughout the data about diffusion, there were no clear cases of a student using the threshold explanatory pattern. There are potentially many reasons for this lack of data, but before I hypothesize why this pattern was uncommon I shall first discuss what an explanation based on
this explanatory pattern might have looked like, and then I will hypothesize why these explanations did not occur in my data.

If students were to generate an explanation based on threshold within diffusion, they might focus on either a threshold of water molecules or a threshold of color. At the micro-level, students might focus on a threshold of water molecules in terms of certain speeds or densities leading to a change in behavior. On the other hand, they might focus on the macro-level by paying attention to a threshold point of the mixing color such that the colors appear different. In addition, one could hypothetically mention lag effects in terms of the amount of time or build up needed for the diffusion process to begin or end.

Probably these kinds of threshold diffusion explanations did not occur in the data because of the students’ prior knowledge about diffusion. First, diffusion is a fast process. From the students perspective it happens quickly and perhaps to see threshold the process would have needed to be slower so that students could see it as involving an initial behavior and a change in behavior leading to a subsequent final behavior. Second, Newton’s law of heating (or cooling) often describes diffusion as a differential equation in which the rate of change is proportional to the difference in quantities. Graphically this differential equation describes a phenomenon that appears to be exponential. This is different from a graph of threshold, which we would expect to have a behavior described by a particular function, then a change in behavior, and then a subsequent different behavior that is different from the initial behavior, which would be a new function, which is different from the previous function. I would not expect a graph of threshold to have the type of curve that is associated with exponentials and Newton’s law of heating. Perhaps threshold is simply not an optimal explanatory pattern for diffusion. Finally, in order to see threshold at the molecular level one would likely need to activate some prior knowledge about the behavior of individual molecules. Within the data set, there is little evidence for students finding the molecular level within diffusion to be particularly salient. There are few cases of students accessing this particular piece of prior knowledge, but it was often in terms of discussing random molecular motion, not underlying mechanism that influence the macro level behavior. As a result, it is not very surprising that students did not access the threshold explanatory pattern in the diffusion problem context because of the nature of this process and their prior knowledge.

**Threshold Summary**

Threshold is one explanatory pattern that is both thought to be productive for supporting students towards reasoning about problem contexts using decentralized causality and was used in multiple problem contexts. For the purposes of this analysis, I describe threshold as an initial behavior, a dramatic change in behavior, and a subsequent behavior that is different from the initial behavior. Within this scheme, time is important because there is often a build-up during the initial behavior.

In the analysis, I documented some variety in terms of the ways in which threshold was applied to the seven problem contexts. Sometimes it was applied to the macro level (e.g. size of dunes), micro level (e.g. speed of cars), and other times it was applied to characteristics that describe the phenomena (e.g. temperature and energy of molecules). More specifically, in traffic jams students often mentioned a threshold of the car’s speeds, the density of cars, and the numbers of cars thus focusing on individual agents and their relationship to each other. Comparably, for sand dunes students mentioned a threshold of dune size, as they get bigger or smaller, which involves focusing on the macro phenomena. With viruses, students mentioned a threshold or lag effect of time to be cured of the virus, time before symptoms appear, and size of the population having been exposed to the virus. Differently, with forest fires students
mentioned a threshold of temperature when combustion occurs and a threshold point where the fire gets smaller. Finally, a very different case comes from fish where a student mentions a build up of immunity to electricity over many generations. A threshold in sand dune size could be thought of as similar to a threshold in forest fire size and these might also be similar to a certain size of a population have been exposed to a virus. From a scientific perspective, a threshold in cars speeds and atom’s temperature might be similar as temperature is a measure of speed, but given the differences in the particulars of these problem contexts, students did not necessarily see them as similar. Overall, there is a great deal of variety in terms of what particular threshold point was embedded within students ways of conceptualizing the particular problem contexts and this was influenced by their prior knowledge and the nature of the specifics of the problem context.

Within these threshold explanations, students did several things that might have been productive for understanding the decentralized nature of these processes. In the analysis I argue that threshold is possibly productive towards supporting students generating explanations associated with decentralized causality because it may also support: 1) recognition of critical variability in the behavior of the phenomena, 2) connecting the micro and macro level behaviors, 3) recognition of the underlying mechanisms, and 4) application of the threshold explanatory pattern in conjunction with another pattern, such as cyclical motion or mid-layers.

**Mid-Levels**

In this analysis, I investigate a productive explanatory pattern in which one focuses on the behavior of a complex systems by focusing on the intermediate or mid-level. The mid-level is a group of agents or particles between the macroscopic and microscopic levels. A variety of researchers (Levy & Wilensky, 2008; Fredericksen, White & Gutwill, 1999; Eylon & Ganiel, 1990; White, 1993) have documented the importance of the connection between the macroscopic and microscopic levels. Connecting levels may be productive in understanding the decentralized nature of complex systems because it might support one in seeing how the macroscopic behavior can arise from interactions at the microscopic level, which is a key part of emergence (Resnick & Wilensky, 1999).

Focusing on an intermediate level is a well-known strategy and has often been investigated in the domain of electricity. Students’ difficulties have been documented by Eylon and Ganiel (1990), who found that students had trouble connecting the macro level circuit devices and the micro level electric charge. Frederickson, White, & Gutwill (1999) found that making conceptual links between levels, such as the macroscopic and microscopic levels, is productive for students learning. White (1993a) advocates an instructional approach that focuses on an intermediate causal model via a progression of increasing complexity that support an understanding among different levels, such as macroscopic and microscopic, and iconic and symbolic.

In the domain of complex systems, Levy and Wilensky (2008) found that the mid-levels strategy could be helpful in understanding the behavior of complex systems. Levy and Wilensky (2008) documented the strategy in the context of students explaining the emergent behavior of packs of deer and students on the playground. In the data, they found two versions of this strategy, subdividing the whole into intermediate levels or aggregating individuals into intermediate levels. For example, participants mentioned an entire classroom of students being subdivided into several rows to perform calisthenics on the playground, a version of subdividing of the whole. Additionally, participants mention aggregating individuals such as sick deer...
socializing in groups thus spreading disease faster. Based on a coding scheme aimed to capture when students beliefs are associated with a “complex system” or a “clockwork” model the authors found that the strategy of subdividing the whole is related to a high complexity reasoning score and thus supportive of students’ understanding of “complex systems” principles.

In my analysis, I find that many students focus on the mid-levels in their explanations of sand dunes and few use it in the bird, fish, and virus problem context, and no data in the other problem contexts. In the sand dune problem context students use an explanatory pattern in which they focus on the layers of sand that are exposed to the wind moving sequentially. In the birds and fish problem context students, use of the mid-levels explanatory pattern often focused on sub-groups of birds or fish acting as units or engaging in behaviors separate from the other groups. In the virus problem context a few students mentioned the virus spreading to one town at a time and a few students mentioned different groups of people exhibiting different characteristics, such as being sick or being healthy.

As previously mentioned, this data had only a few cases of mid-levels. This is a bit surprising given that Levy and Wilensky found this strategy to be common to several problem contexts including the spread of viruses through packs of deer, the spreading of rumors, and children in the playground spreading out to perform calisthenics; all of which that share strong resemblances to problem contexts addressed in this study. I argue that the particular ways students conceptualize the phenomena, in this case through the mid-levels explanatory pattern in the sand dune, bird, fish, and virus problem contexts, productively influences their ability to generate explanations associated with decentralized causality. In the other two problem contexts, diffusion and forest fires, there are no versions of the mid-levels explanation that resembles the sand moving in layers nor any other versions of this explanation. The relative frequency of this explanatory pattern in each problem context is summarized in table E. Perhaps there is something about the ways students understand the forest fires and diffusion problem contexts that does not fit with the mid-levels explanatory pattern.

<table>
<thead>
<tr>
<th></th>
<th>Mid-levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand dunes</td>
<td>Many</td>
</tr>
<tr>
<td>Traffic jams</td>
<td>0</td>
</tr>
<tr>
<td>Forest fires</td>
<td>0</td>
</tr>
<tr>
<td>Viruses</td>
<td>Few</td>
</tr>
<tr>
<td>Diffusion</td>
<td>0</td>
</tr>
<tr>
<td>Birds</td>
<td>Few</td>
</tr>
<tr>
<td>Fish</td>
<td>Few</td>
</tr>
</tbody>
</table>

Table G: Table of mid-levels explanatory pattern with some indications of frequency.

**Mid-Levels in Sand Dunes**

In the sand dune data, I find evidence for the mid-levels conceptualization where layers of sand move sequentially. This explanatory pattern focuses on the top layer, the most exposed layer of sand being blown first, followed by each subsequent layer. In this way, intermediate groups are formed based on the physical location of the sand particles. I claim that it is the nature of the particular physical arrangement of the sand that scaffolds this version of the mid-levels strategy because the surface is salient and the outer most level needs to move first and the wind works on the surface because it is unable to penetrate the deeper levels.
The sand dunes version of the mid-levels conceptualization is different from how the mid-levels strategy was used in Levy and Wilensky’s paper. In that paper, students were explicitly subdividing the whole into parts or aggregating individuals into small groups. I do not see these versions of the mid-levels strategy in the sand dune data. I see no evidence that students are deliberately and consciously subdividing the entire dune into parts or aggregating individual sand particles into small groups. In this data, the mid-levels are formed based on the arrangements of sand particles.

In this analysis, I present, in detail, an example from the interview with Laurel about her mid-levels sand dune explanations. In this case, the mid-levels explanation (sequential layers mechanism) was rejected because it did not account for the variableness of the wind.

As was discussed in Chapter 4, Laurel rejects three variations of the mid-levels explanation due to a clash between her expectations of the sand moving in layers making sense and her underlying knowledge about the variableness of wind. For brevity, I will discuss one example of an explanation she generated that is based on a mid-levels pattern. Laurel mentions that the top layers of sand, which are most exposed to the wind, will be blown first then followed by the next outermost layer and this process will continue until the entire dune has moved. At the end of this selection, she mentions that the wind is not constant with the same strength and direction.

52. Laurel: 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.
53. So, then like, this top layer of sand [draws top layer of sand with a purple marker] would kind of get blown first, or whatever, or whatever, I don't know,
54. on the first on the top, it depends on where the wind is coming from.
55. 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] 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.
56. 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]
57. But then, I know that when its windy, its not like the wind is constant,
58. it's always blowing in exactly this direction at exactly the same, exactly the same, like strength.

In the above selection, Laurel generates an explanation for wind moving sand in sequential layers but then questions the underlying assumption of a constant wind. After mentioning the existence of a sand dune and the wind blowing into the side of it (line 52), she
explains that it moves in layers. The “top layer of sand would kind of get blown first” and assuming that the wind keeps blowing, then the next exposed layer of sand would get blown (lines 54-56) and this would continue until the entire dune has moved (line 57). Then Laurel explains that she knows that the wind is not constant, there is some variability in terms of strength and direction (line 58-59).

Underlying this explanation is some prior knowledge about the nature of wind and sand. Laurel is taking a viewpoint on the phenomena that focuses on the entire dune and layers of sand. She is also focusing on the process of the dune moving locations (line 57) by seeing that it has a start point (line 56) and an end point (line 54 and 57). She also finds characteristics of the wind, such as direction and strength, to be a relevant variable (lines 58-59).

As discussed in Chapter 4, she generates three versions of the mid-levels (sequential layers) explanation and then questions all of them because of her intuitions about wind and sand not being constant. In Chapter 4 I argued that although it takes time, for her rejecting these mid-levels explanations is productive because she was explicitly rejecting knowledge that is associated with centralized causality and this is one of many steps that supports her change from explanations associated with centralized causality to explanations associated with decentralized causality.

Beyond the case of Laurel, there were many other cases in my data of students generating explanations based on mid-levels. Similar to Laurel’s explanations, these other students’ explanations tended to focus on sand moving in sequential layers as the wind blows the outermost layer first, followed by the next layer until the entire dune has moved. Other students’ explanations also tended to use experiential knowledge about sand dunes and wind. One difference between Laurel’s mid-level explanation and other students’ pertains to issues of productivity towards an understanding associated with emergence. While there is some evidence that this mid-levels explanation was helpful for Laurel, for her it was associated with centralized causality and she rejected it. However, for other students, it was not necessarily rejected and sometimes it ambiguous whether it was associated with centralized or decentralized causality.

In the case of Laurel’s mid-level explanation, it was productive for her in ways that are different from how Levy and Wilensky (2008) documented the mid-levels explanation to be helpful. Levy and Wilensky (2008) found it to be helpful because it connected the microscopic and macroscopic levels because they found that students either subdivided the whole into parts or aggregated individuals into intermediate groups. In comparison, for Laurel the mid-levels conceptualization of sand dunes is useful because it highlights the variableness of the moving wind and sand that then lead to decentralized explanations. In addition, in the sand dune data, students focused on the physical arrangement of sand particles in layers. This supported a particular version of the mid-levels pattern where the top layer of sand, the most exposed layer is blown first, followed by the next layer. In this version of the mid-levels pattern, the arrangement of the sand particles is crucial; this issue is not mentioned in Levy and Wilensky (2008).

In this section I showed that students’ prior knowledge about sand dunes, specifically them finding the layers of sand to be salient, influences how they explain sand dunes through mid-levels. In the case of Laurel, this explanatory pattern may have been helpful as she rejected it because it did not highlight the appropriate variableness underlying the motion of wind and sand.

**Mid-Levels in Birds, Fish, and Viruses**

In the birds, fish, and virus problem, contexts there were few explanations that were possibly based on the mid-levels explanatory pattern. A commonality across the data was in terms of sub-
groups of individuals exhibiting behaviors that are different from the larger group. In birds and fish, this often involved a small group changing directions, turning, speeding up, or slowing down, or perhaps two groups merging. In virus, this was a bit different as it often involved groups of people who are sick or not, potentially living in different towns. Hence, in the virus, bird, and fish cases the sub-groups were formed based on social factors, personification, or other characteristics of the agents.

An example of birds moving in intermediate groups comes from the interview with Melissa, an undergraduate majoring in physics. She explains that one bird in a flock might leave when it becomes tired, and then later join a different flock of birds of the same species. “If there was like seven birds, one is tired, needs to go rest for a little bit, it could like fly north again and find the same group or, if you know, I don’t know if birds actually do this, but just join another group. Lets say the same species that’s also flying north again, cause you know, they have the same genes, more or less, they are all, probably from the same place, so, just join up with, ‘hey cousin, what’s up, lets fly together’ kind of thing.” One could consider this explanation as based on the mid-level explanatory pattern where there are many flocks of birds within a population and each flock has a unique flight pattern. Interestingly, in this explanation, Melissa connects the behavior of one individual bird who switches flocks, to the movement of the different flocks. In this case it is unknown if this explanation was helpful for Melissa. Beyond the case of Melissa’s bird mid-levels explanation, there were a few other mid-levels explanations, from either undergraduate or graduate students.

An example of fish moving in intermediate groups comes from the discussion with Antonio, an undergraduate majoring in physics. He mentions that fish like to hang out in big groups, but sometimes there are small groups, and sometimes the groups merge because they all want to hang out together. “Maybe they do like to hang out in big groups and there is one small group and another small group and the small group not moving so this one will turn around and go join this small group to be a bigger group…. and this group is going over here, doing their own thing and they notice that someone in this group sees that side, ‘hey look there is a bunch more of us over there, lets go join them.’ ” This explanation is based on the mid-levels explanatory pattern such that the fish sometimes hang out in big groups or small groups, and sometimes the small groups join. Underlying this explanation is some prior knowledge about the relationship between humans and the fish that that leads to a personification of fish such that they like to hang out with one another. Beyond the case of Antonio, there were a few other cases of mid-levels explanations in the fish problem context from all 8th graders, undergraduates, and Ph.D. students.

The mid-levels explanatory pattern was also used a few times in the virus problem context in terms of the virus spreading from town-to-town where each town could be considered a mid-level group. An example comes from the discussion with Jared, a Ph.D. student in physics. He explains that some people travel a great deal and it only takes one person to spread a virus to a town. “Some people travel a lot in their work. Or they go see a friend or something. It only takes one person to travel to another town to give someone the virus and then they can go home and there is lots of people living in towns so there is going to be lots of people traveling around to other towns, so it only takes one of them to spread the virus and then, you know then it's in the other town and it can spread.” In this case, we can think of the mid-level as being the sub-group of people that live in a particular town that may or may not be infected with the virus. Beyond the case of Jared, the mid-level explanatory pattern was used in a few other cases from explanations generated by both undergraduates and Ph.D. students.
Mid-levels Conclusion
In this analysis, I investigated the explanatory pattern of focusing on the intermediate or mid-level, such that there is a group of agents or particles exhibiting a behavior between the macroscopic and microscopic levels. Connecting levels may be productive in understanding the decentralized nature of complex systems because it may support one to see how the macroscopic behavior can arise from interactions at the microscopic level, which is a key part of emergence.

In my analysis, I find that the mid-levels explanatory pattern is common in sand dunes, and less common in bird, fish, and virus contexts. In the sand dune problem context students use a particular version of the mid-levels explanatory pattern in which they focus on the layers of sand that are exposed to the wind moving sequentially. In the birds and fish problem context, students use of the mid-levels explanatory pattern often focused on sub-groups of birds or fish acting as units or engaging in behaviors that are separate from the other groups. In the virus problem context, a few students mentioned the virus spreading to one town at a time. Often in those cases, the students connected the mid-level and the micro level by focusing on one bird, fish, or person switching between flocks, schools, or towns.

When comparing across these problem contexts, there are many cases of students using the mid-levels explanatory pattern when discussing sand dunes, and few cases in the other problem contexts. This is a bit surprising given the results presented in Levy and Wilensky (2008). Levy and Wilensky (2008) found this strategy to be common to several problem contexts, the spread of viruses through packs of deer, the spreading of rumors, and children in the playground spreading out to perform calisthenics, that share strong resemblances to problem contexts addressed in this study. Perhaps the particular ways the students conceptualize the problem contexts in this data influenced whether and how the mid-levels explanatory pattern was used. More specifically, in sand dunes, students used their prior knowledge about what aspects of the phenomena they found salient to construct mid-levels explanations that take into account the geometric arrangement of sand. In the bird, fish, and virus problem context students’ mid-level explanations were based on social factors, personification, and other characteristics of the agents. There were only a few cases of mid-levels in the fish, bird, and virus problem contexts. In comparison the mid-levels may have been quite common in similar problem contexts investigated by Levy and Wilensky (2008). Perhaps the nature of the ways that the discussion, interview questions, and problem context were framed to the student results in a situation such that the mid-levels pattern not easily fitting in with their understanding of the problem contexts. Similarly, for the problem contexts in which there was no mention of the mid-levels explanatory pattern, diffusion, and forest fires, perhaps there is something about the way students conceptualize those explanatory patterns such that mid-levels does not fit either.

Discussion and Conclusion
The purpose of this chapter is to illustrate variability in student understanding of the seven problem contexts. In order to accomplish this goal, I focused on their understanding as illuminated through six explanatory patterns, all of which are potentially helpful ways of thinking about the problem contexts as exhibiting decentralized causality. Within each pattern I discussed how often it occurred in the seven problem contexts, how it appears similar and different across the problem contexts, what kinds of prior knowledge were activated, and how it may have supported students’ understanding of decentralized causality. I argued that this variation in students’ understanding is due to the different kinds of knowledge resources activated and differences in their understanding of the nature of the problem context.
The major limitation of this analysis is that it was not easily possible to do a coding that could have enabled reliable quantifiable data about the frequency of each explanatory pattern within each problem context. This was not possible due to limitations of the data corpus, the nature of the clinical interviewing style, the fact that process of identifying each pattern is not reliable enough to warrant analysis that could produce frequency counts, and a small sample size. As was discussed in Chapter 3, the particular interviewing style used in this dissertation and analysis process were necessary as they allowed investigation into the student generated explanatory patterns and they support investigations of students’ prior knowledge. However, future work should focus on an analysis of the frequency of explanatory patterns across problem contexts while also taking into account students’ prior knowledge.

In comparison to the current analysis, much of the prior work on students’ understanding of complex systems or emergence de-emphasizes a multitude of prior knowledge resources and variations of understanding and instead focuses on the pre-determined “forms of explanation.” For example, Perkins and Grotzer (2005) present a taxonomy of causal models. Within this taxonomy, there is a range of models from less complex models towards more complex models. The causal model of emergent entities and processes is one of many within this taxonomy and it is associated with complex agency. The authors assume that different kinds of explanations are associated with these different causal models. They discuss instructional interventions for a variety of topics including, static electricity, density, and ecosystems. In other words, they focused on teaching students’ these causal models with the goal of supporting conceptual change.

From a different theoretical perspective, Chi and colleagues (Chi, et. al., 2012; Chi, 2005; Slotta & Chi, 2006) discuss students’ difficulties with understanding emergent processes resulting from a miscategorization of a particular emergent process at the ontological level. An example of this would be construing diffusion as a direct process rather than an emergent process. Within this perspective, overcoming such misconceptions involves a conceptual shift across ontological categories. Building on Chi and colleagues work, Jacobson and colleagues (Jacobson, 2001; Jacobson, et al., 2011) investigate learning about complex systems and focus on two specific ontological categories, complexity, and clockwork. Chi et al., (2012) explicitly claim that “misconceived causal explanations do not pertain to a lack of knowledge about any single level” (Chi et al., 2012, p. 12). They are instead focusing on misconceived causal explanations as due to inappropriately relying on a direct-causal schema when an emergent one is more appropriate.

Across both of these perspectives, there is a general trend in focusing on learning about emergence as involving the need to acquire so called “emergent” causal models (Perkins & Grotzer, 2005) or particular ontological models or schema (Chi, et al., 2012; Chi, 2005; Jacobson, 2001; Slotta & Chi, 2006). In this way, they de-emphasize the multitude of prior knowledge resources students bring to conceptualizing complex systems, and in the case of Chi et al., (2012), they explicitly claim that knowledge about specific levels is not the crucial factor. In addition, these studies tend to de-emphasize how different problem contexts might influence students’ understanding. Perkins and Grotzer (2005) do incorporate different problem contexts, but they do not engage in any comparison of their causal models across the problem contexts as the models are intended to be domain general. The body of work by Chi and colleagues tends to only focus on one emergent process, diffusion (Chi, 2005), but recently has focused on diffusion and natural section (Chi et al., 2012). Although in this article they do not engage in any comparing and contrasting as the ontologies or schema are intended to be domain general.
Although Jacobson and colleagues (Jacobson, 2001; Jacobson, et al., 2011) did include a variety of problem contexts in their studies, similar to the prior literature they too did not explicitly compare and contrast students’ understanding across problem contexts.

I find in this chapter that students’ understanding of particular problem contexts, whose behavior is associated with complex systems, varies across forest fires, traffic jams, sand dunes, and diffusion among others. This calls into question this general trend of de-emphasizing domain differences in students’ understanding of emergence. Additionally, I have shown the variability and importance of different kinds of prior knowledge in students’ understanding. This calls into question the general trend of de-emphasizing prior knowledge resources in students’ understanding of emergence. Below I outline some observations about the specific differences in students’ understanding across these problem contexts as related to their prior knowledge.

The central point is that I find that there is a spectrum in regards to students level of ease in seeing emergence across these seven problem contexts. Sand dunes are at one end of the spectrum as students were able to access many prior knowledge resources in their sand dune explanations and they used many explanatory patterns. At the other end of the spectrum is diffusion where students were not able to access as much intuitive knowledge and had trouble generating explanations based on these patterns, the main exception being explanations based on prior academic type knowledge. Then I conclude this section with a discussion of how these results may translate into instructional implications.

**Sand Dunes**
Overall, I find the sand dune problem context to be one in which students are able to access many kinds of prior knowledge resources that are potentially helpful in supporting them seeing the phenomena as working in a decentralized manner. Penner (2000) also interviewed students about a similar phenomenon, rocks on a talus slope, but he did not do a detailed analysis of the students’ relevant knowledge resources. In this data set, students find both the entire dune and sand particle level relevant. Also, despite some students initially being reticent, sometimes implying some unfamiliarity with dunes or being unsure about the dynamics of wind, overall they do find wind salient and often access prior knowledge about how wind moves sand particles and how that relates to the entire dune. A major source of prior knowledge supporting this might be students’ familiarity with granular materials. This knowledge comes from prior experiences playing in sand boxes, playing with dirt, or any other of the numerous related experiences with other granular materials (e.g. pouring flour or grains of rice into a bowl). My hypothesis is that despite some students reticence about answering this question the large amount of intuitive prior knowledge about granular matter supports them eventually coming to see the movement of sand dunes in a decentralized manner. Also, this is supported by another attribute of the problem context, the implausibility of the more centralized explanations. By this I mean that many of the more centralized explanations commonly mentioned about sand dunes are deemed implausible by the students, including ideas about dunes forming on trees or boulders, or dunes being caused by people walking. Overall, I find that in different ways, students’ activated many kinds of prior knowledge in this problem context that is helpful for supporting them in coming to see sand dunes as decentralized.

**Traffic Jams**
Overall I find in the traffic jam problem context that students are able to access many kinds of prior knowledge resources that are potentially helpful in supporting them coming to see the phenomena as working in a decentralized manner, but differently from sand dunes, students
sometimes focused on unique attributes of human emotions and safety. In this problem context, students tend to find the motion of individual cars and the existence of the entire traffic jam to be salient. They also tend to have many ideas about the relationship between individual cars and the entire jam. However, students have particular prior experiences. They tend to have lots of experience riding in and driving cars, but few experience seeing the entirety of a traffic jam at once, which may lead to them not finding the overall size of the jam salient. A major source of student prior knowledge about traffic jams comes from experiences riding in cars. This includes pragmatic knowledge of jams, when to slow down, when to speed up along with a strong desire to avoid accidents. Further to the point, students tended to access lots of prior knowledge about human psychology and emotions related to jams. For example, many students mentioned how they felt frustrated in jams, or annoyed at one person who was speeding or otherwise engaging in a particular behavior. There was also a trend of discussing jams in relation to people’s desires about where and when they chose to travel, such as the role of more popular destinations, and the likelihood of jams during rush hour. Not all of the specific prior knowledge relevant to traffic jams is necessarily helpful or detrimental to coming to see the decentralized nature of traffic jams, it depends. For example, the lack of finding the entire size of the traffic jam relevant may have hindered them in seeing how the collection of cars resulted in the changing size of jams, but the focus on humans emotions and safety may have supported them focusing on the underlying mechanism influencing when cars slow down and speed up, which in turn might have supported recognition of decentralized causality.

Viruses
Overall I find the virus problem context to be one in which students are able to access many kinds of prior knowledge resources that are potentially helpful in supporting them coming to see the phenomena as working in a decentralized manner. The case is different from the other problem contexts because much of this knowledge focuses not on the virus itself, but instead on the person who is infected with the virus and their associated experience. Students tended to find the process by which viruses spread from person-to-person, through coughing or shaking hands, relevant along with related issues of cleanliness. Also, many students accessed a great deal of prior knowledge about expectations of how people should behave when they are sick, issues of staying home versus going to work or school were relevant. Another relevant issue was about time when one is possibly infected with a virus, but not yet experiencing the symptoms and potentially spreading it unknowingly. In this way, students were accessing relevant prior knowledge about specific time scales involved with the spread of viruses. Some of this prior knowledge is related to the students focusing on issues about the overall population, such as the changing number of sick versus well people, and how a few sick people can travel or otherwise spread the virus to a large number of individuals. Interestingly, almost no students found the germ or molecular level to be salient, instead students almost unilaterally focused on the people infected by the virus. Overall, compared to sand dunes and traffic jams, I would hypothesize that in those two problem contexts, students might have a slightly easier time in coming to recognize the role of decentralized causality, but still in the virus problem context students were able to access many kinds of helpful prior knowledge resources.

Forest Fires
In many ways forest fires are similar to viruses given that both involve a spreading behavior, but I suspect that forest fires present more challenges for students than viruses in coming to see decentralized causality. Here I present a couple hypotheses for why this might be the case. First,
in forest fires, students accessed a great deal of prior knowledge that supported them in focusing more on centralized causality. This included ideas about physical boundaries including rivers, roads, or firebreaks influencing the spread of the fire. Also, there was an emphasis on fires starting due to human carelessness, for instance, dropping a cigarette out of a window or due to a lightning strike. Second, although there were many students who discussed the micro level, in terms of the motion of electrons, plasmas, and heat transfer, they generally did not connect this to the macro level fire in a way that captured the decentralized nature of the phenomena. Finally, there was also a strong focus on various factors that aided or inhibited the spread of the fire including factors such as hot and dry or wet and cool conditions, the relative speed of the burning materials (e.g. dead leaves burn fast and green plants burn slow), and the density of the forest. While many of these factors are important attributes of the fire, they did not particularly support the students in coming to understand the decentralized nature of forest fires. A different kind of reason why forest fires might have been more challenging for students in coming to see decentralized causality is because students tended to focus more on the process of things catching on fire and spreading than on the process of being extinguished. While there are many reasons why the process of something catching on fire might be more relevant than the process of being extinguished, one hypothesis is that if students were to focus on both process equally, perhaps that would support them in coming to see decentralized causality through the equity of the rate of things catching and ceasing to be on fire.

**Birds and Fish**

Overall, I find that birds and fish were both challenging for students to see as decentralized causality, both in similar ways to each other, and in different ways from forest fires. In this section, I am presenting my observations about birds and fish together because they are so similar, and because I suspect that any apparent differences in the data are idiosyncratic. One challenge for these two problem contexts is perhaps the question of how flocks of birds or schools of fish change directions. Across the data set, the one approach I saw that was most helpful in coming to see decentralized causality was focusing on specific mechanisms for why when birds or fish fall out of formation, they might tend to go back into formation. These mechanisms took the form of instinct or a desire to be in formation due to greater safety or ease of travel. Beyond this, students activated lots of prior knowledge about fish and birds, this includes pieces of knowledge that may have supported them in seeing the phenomena in more centralized ways, and pieces of knowledge that are more impartial to the kind of causality. For example, several students mentioned the idea of there being a leader bird or fish that influences the behavior of other animals and this is associated with centralized causality (Resnick, 1996). However, many students also mentioned other issues that were generally impartial to the kind of causality including environmental influences (wind, weather, rain), physiological needs (sleep and food), familiar relationships (desire to be with family/friends), and the role of predators. Possibly, for these two problem contexts, similar to some of the other problem contexts, students cued many kinds of related prior knowledge, only some that was supportive to coming to see decentralized causality in this context. This may be a version of the hyper-richness hypothesis, a challenge in learning being not the absence of knowledge resources but instead a plethora of relevant ways of thinking about the phenomena (diSessa, 2007b).

**Diffusion**

The diffusion in water, is challenging for students to see in terms of decentralized causality. The
few cases that students did successfully come to see as involving decentralized causality within diffusion often involved accessing a great deal of prior knowledge, likely from prior academic experiences about the underlying molecular motion and how it connects to the macro level. In the convergence to a limit sub-section, I presented the case of Melissa’s diffusion explanation as likely the best case of such an explanation. Beyond this case, I hypothesize that diffusion is a difficult problem context for students when coming to see decentralized causality.

This difficulty is not because students have a lack of knowledge about diffusion. During the interviews, students did access many kinds of prior knowledge about diffusion including all kinds of ideas about the role of automatic mixing of liquids as compared to stirring two liquids together. I also saw many students discussing differences between mixing water and juice mixing compared to water and oil. One trend centered on differences between gasses, solids, and liquids. There was some discussion about the role of balancing and consistency in the mixing and there was some discussion about relative concentrations of the two liquids. Finally, many students mentioned variables that might influence the phenomena, mainly temperature, energy, and the role of gravity.

I suspect this problem context is challenging because of a lack of familiarity and limited prior experiences with the molecular level. Compare the molecular level in this problem context to sand dunes and traffic jams, where students had an easier time and where the micro levels, which involved sand particles and individual cars, are very intuitive.

Another challenge with diffusion is that it may be seen as inevitable and hence not needing a mechanistic explanation. Potentially students might have sometimes cued a knowledge piece about diffusion being an inevitable process that always just happens and does not need an explanation. If this is the case, diffusion becomes a bigger challenge because one is then working against some kind of intuitive explanatory primitive about what phenomena need explanations.

**General Discussion**

Now that I have covered some of the specific challenges and affordances of each problem context as related to students’ prior knowledge, I next discuss these results as situated within the relevant literature on instructional implications. As was discussed in Chapter 1 students’ difficulties with complex systems and emergence have been documented extensively (e.g. Chi, 2005; Chi, Roscoe, Slotta, Roy, & Chase, 2012; Hmelo-Silver, Marathe, & Liu, 2007; Jacobson, 2001; Resnick, 1994; 1996; Slotta & Chi, 2006; Wilensky & Resnick, 1999). Many of these researchers have proposed various instructional techniques and approaches to support students in learning about these systems. As many of these researchers have observed, a main challenge for students in learning about complex systems is that often one level of the system is not easily accessible. There is one trend that focuses on providing learners with experiences to interact with these systems at multiple levels as a means of making the micro level more accessible using agent-based models (Jacobson & Wilensky, 2006). There is another trend that focuses on supporting students’ learning by helping students conceptualize these systems as an interrelated web of behaviors, functions, and structures (Hmelo-Silver, Marathe, & Liu, 2007). While I tend to agree with these approaches that are generally focused on making attributes of the system that are not easily accessible more accessible, my results are overall more nuanced. I find that a main factor distinguishing certain problem contexts from being easier or harder for students has to do with the kinds of prior knowledge resources activated. Rather than start with problem contexts that are very challenging, such as diffusion, my results would instead suggest that we start with problem contexts such as sand dune, where students are able to access many intuitive knowledge
resources at multiple levels such that coming to see decentralized causality is not an enormous challenge.
CHAPTER 6: DIVERSITY OF EMERGENT THINKING

Introduction
The purpose of this chapter is to investigate cases of students’ reasoning as exhibiting emergent thinking. As was discussed in Chapter 1, some of the existing literature on students learning of complex systems uses a common coding scheme in order to operationalize when students are exhibiting reasoning patterns that are consistent with an understanding of how complex systems behave. This coding scheme includes several elements of complex systems Resnick (1996) refers to them as guiding principles and Jacobson (2001) refers to them as beliefs associated with a complex systems mental model. I refer to them as indicators because they often function as rough indicators for emergent thinking. As mentioned in Chapter 1 and 3, this prior literature has identified many of these indicators. See Appendix C for a list of many of these indicators.

I take as a starting point for this analysis two of the many heuristics of emergent thinking; 1) small perturbations leading to large effects, and 2) different behaviors at different level. The first indicator is meant to capture the idea that an initial action in a complex system can have large consequences. The second indicator is meant to capture the idea that the behavior of the individuals at the micro level can be distinct from the behavior of the phenomena at the macro level.

In this document I first review what emergent thinking is and relevant literature about these two indicators. Then I discuss how this particular analysis fits in with the entire dissertation, particularly the ways in which this analysis is an extension of Chapter 4. The core of this chapter is the analysis of students’ generated explanations that incorporate one of these two indicators. For each indicator I present two cases of a students’ explanation incorporating that indicator in order to illustrate some variability. Thus the analysis consists of a total of four cases.

These four cases were chosen because they best exemplify how these two indicators are used within the specific problem contexts. These four cases nicely exhibit clarity of the indicators, and as will be discussed further in various ways these cases all exhibit aspects of rather sophisticated understandings. Thus these cases can be viewed as exemplary examples.

The results illustrate that students’ emergent thinking is quite specific to the problem context, and that there is variation within each of the two general heuristics. For example, for the indicator, small perturbations leading to large effects, I discuss that one student, Jared explains that a single bird may do something random, leading to the entire flock breaking apart because all of the birds get confused. Or, when one bird does something random, nothing might happen because the other birds can compensate accordingly. I compare that bird case to the case of Raj’s traffic jam explanation, which is about one person switching lanes which results in many other people slowing down as a traffic jam forms. I discuss how these two students drew on prior knowledge that is quite specific to the problem context, about birds and traffic, and how there is variation across these two cases in terms of the initial behaviors, number of possible outcomes, and overall effects. There are similar findings about the second indicator: different behaviors at different level, in terms of the specific problems contexts, diffusion and forest fires.
and the amount of variation and relevant prior knowledge across two cases.

The results have implications for our understanding about what counts as emergent thinking. I show that it is not one unified criteria. In these cases these indicators are applied differently depending on the problem context and the specific relevant prior knowledge. For these students’ emergent thinking varies a great deal across problem contexts and across these indicators of emergence.

This is important because it influences: 1) how researchers identify students’ emergent thinking, and 2) instructional activities meant to support students developing emergent thinking. If one assumes that students’ emergent thinking is not one unified thing, then likely one would need multiples ways to capture their emergent thinking that take into account this lack of unification. Similarly, another implication of assuming that students’ emergent thinking is not one unified thing is the implication that there is not only one developmental pathway towards emergent thinking. We would assume many developmental paths that depend on specifics of the problem context and relevant prior knowledge. Instructionally, one would then need to take into account these problem context differences as well as student variation in prior knowledge.

What is emergent thinking?

As discussed in Chapters 1 and 3, the literature has identified a series of what I refer to as indicators of decentralized causality that are used within a common coding scheme as a guide to help researchers identify when students’ reasoning is taking into account decentralized causality (e.g. Jacobsen, 2001; Jacobson, Kapur, So & Lee, 2011; Levy & Wilesnky, 2008; Penner, 2000; Resnick, 1994; Wilensky & Resnick, 1999). This list of indicators includes the following: small perturbations leading to large effects, different behaviors at different levels, constructive randomness, lack of a leader, and no predictability of individuals behavior. These indicators have been used within this common coding scheme in order to capture when students’ reasoning is more associated with decentralized causality. For instance, Jacobson et al., (2011) investigates students learning of complex systems using a hypermedia learning environment that included agent-based models and text-based scaffolds. Using this coding scheme for attributes of complexity the authors found that students performed higher on transfer problem solving tasks if they had enriched their ontologies about the behavior of complex systems. The prior literature has tended to use these indicators as part of a coding scheme to quantify the extent to which a student could be said to be exhibiting “emergent thinking”; but, differently, in this chapter I take them on as an analytical lens.

In this chapter I use two of these indicators, small perturbations leading to large effects, and different behaviors at different levels, as an analytical lens to investigate the underlying pieces of emergent thinking. I use these indicators in order to analyze the specifics of individual’s emergent thinking. For this analysis they function as a partial specification of a students’ reasoning, rather than joint gauges of a single mode of emergent thinking. By emergent thinking I am referring to students’ explanations as reflecting ways of understanding how the particular phenomenon works that are based on evidence for a normative understanding of complex systems.

If one conceptualizes the prior literature as using these indicators as a label to capture underlying emergent thinking, one can view this analysis as opening up these indicators and looking at what kinds of prior knowledge and specifics about the problem context contribute to this label. This prior research tends to use these indicators as literally indicators of the presence of emergent thinking as a global competence. I focus on specifically what is contained within each of these indicators with regards to the kinds of knowledge resources and understandings
that these indicators depend on. I find that these indicators involve very specific knowledge and are not necessarily global indicators of general competence. In this way the current analysis is not about labeling emergent thinking, but is instead about investigating the underlying pieces of emergent thinking. This focus on the underlying pieces of emergent thinking has the potential to be useful in helping researchers identify the variations within students’ emergent thinking and to help researchers better understanding what contributes to emergent thinking. Recognition of what contributes to emergent thinking may support future work that is focused on scaffolding students’ emergent thinking.

How does this chapter fit within the prior chapters?
This current chapter is building on the analysis and results in Chapter 4. Chapter 4 contained two cases in which students’ final more decentralized explanations were rather canonical cases of emergent thinking, because for this data set they contained commonly used indicators in identification of emergent thinking. Remember, in Chapter 4, the two students’ more decentralized explanations incorporated the indicator of different behaviors at different levels—specifically those students’ explanations incorporated the ideas of 1) sand particles joining and leaving the dune at equal rates while the size of the dune is constant, or 2) dunes moving upwind while sand particles move down wind. These are two of the most frequently distinguishing factors in determining emergence. These two cases are canonical instances of emergent thinking because, first, they are examples of the most common version of emergent thinking in this data set, and second, they share some similarities with a classic illustration of emergent thinking in which cars move forwards on a highway while traffic jams move backwards (Resnick, 1994; 1996).

In this current chapter I investigate cases of emergent thinking that incorporate one of two indicators, different behaviors at different levels, which is similar to Chapter 4, and small perturbations leading to large effects. Despite a common investigation into different behaviors at different levels across Chapter 4 and this chapter, the specifics of that indicator are quite different in the current chapter.

In Chapter 4 the examples of different behaviors at different levels focus on the directional motion of sand particles and sand dunes. In contrast, this chapter emphasizes different principles applying to different levels, specifically in the case of forest fires, the principle of conservation applying to the micro level and not to the macro level. This point is important, in Chapter 4 and in prior research (e.g. Resnick, 1996) this indicator was operationalized in terms of directional motion and in the current analysis this indicator is operationalized in terms of features of the problem context and a broad and abstract principle. Directional motion and abstract principles are two different ways to operationalize this indicator. Recognition of this indicator as being applicable to an abstract principle is novel and important because it illustrates variability in how this indicator can be substantiated. Thus this case is interesting as it presents a novel application of this indicator and as will be argued below, suggestive of sophisticated emergent reasoning.

Small Perturbations Leading to Large Effects
In this section I discuss two examples of students’ generated explanations incorporating the indicator of small perturbations leading to large effects in order to compare them and investigate prior knowledge cued in the explanations. The first example is about how one bird’s random perturbation can either lead to the flock breaking apart because all of the other birds get confused, or can lead to nothing changing because all the birds compensate. The second example is about
one car switching lanes leading to a snowball effect of many other cars needing to slow down to accommodate the car switching lanes given a desire to avoid accidents. For both cases I discuss the specific prior knowledge that influence the students’ explanations and some variation across the cases in terms of the initial behaviors, number of possible outcomes, and overall effects.

Random Perturbations in Individual Bird Behavior
In this episode I discuss an explanation about the consequences of the random initial perturbations of one bird in a flock and below I argue that it is associated with emergent thinking. This analysis illustrates that for Jared in this case, emergent thinking is specific to the problem context and the particular knowledge elements cued about individual bird behavior and personification of birds. This excerpt comes from the interview with Jared, a PhD student in physics. Before I present the data and analysis, it is pertinent to clarify the word “random.”

There are different possible meanings of randomness in the context of complex systems. These differences can be seen both in the type of randomness and in the kinds of phenomena that exhibits the random behavior. Resnick (1996) mentions random initial positions and random walks. He also discusses that people tend to incorrectly see randomness as destructive as it is annoying but in fact randomness helps create order within self-organizational systems. For example, randomness creates initial seeds from which larger patterns can grow. He treats the idea of destructive randomness as a guiding heuristic (Resnick’s language) for recognition of centralized causality or indicator of centralized causality, and constructive randomness as an indicator of decentralized causality. Chi et al., (2012) discuss three potential meanings of the word random in the context of emergent processes: 1) A single agent’s movement, which is also discussed in Jacobson (2001), for instance, a single bird’s random movement. 2) The interaction’s lack of restrictions, for example, a bird’s behavior being influenced by any other bird’s behavior as there are no restrictions. 3) The unpredictability or unexpected patterns of behavior within an emergent process, as discussed in Wilensky and Resnick (1999), for example, the unpredictability in the changing orientation and movement of the entire flock of birds. Chi et al., (2012) argued that all three kinds of randomness are important, but the first is easiest for students, the second is more difficult but not impossible, and the third kind of randomness is most difficult for students. These different meanings of randomness are important because Jared uses several different meanings of randomness in his explanation about the consequences of the random initial perturbations in bird behavior.

Within this excerpt Jared explains how the random variation in one bird’s behavior constitutes a perturbation of the system behavior. He mentions that one bird may do something random and then the other birds might also do something random as the random perturbation spreads throughout the flock.

“If one of them, well, if one of them did something random…then the ones behind them can't follow it anymore. And they have to do something random, and then the ones behind them can't follow them anymore, and have to do something random and then it goes all the way back.”

In this excerpt he is explaining that a random variation in one bird’s behavior spreads throughout the entire flock because a single bird cannot continue to follow other birds as they were before, when those other birds change their behavior and are now doing something random.

Then he goes on to mention another possibility, a bird in the middle doing something random and the birds in front continuing their existing behavior because they don’t care. “If the
one in the middle half way down does something random, then the ones in front, they may not care. The ones behind, they may, figure it out so they can keep following the ones already flying.” Jared is explaining that if a bird in the middle of the flock does something random the ones in front will not do something random, possibly because they cannot see the bird doing something random behind them. Also, the birds in back might be able to compensate and continue flying as they were before by following the ones in front.

Next, Jared combines the two possibilities, such that the flock might break up when a middle bird does something random.

“Or they [birds in the back] may get confused and also do something random, in which case, and some of them would break up. So I guess the whole thing would break up and leave the front one to start doing something random.”

In this excerpt he is explaining that when a middle bird does something random the birds in the back of the flock might get confused and thus also do something random. In this case the random variation in one birds behavior would spread throughout the entire flock resulting in the entire flock breaking apart.

Overall, in these segments Jared is explaining two possible implications of one birds random perturbation; either the flock breaks up because birds get confused and thus cannot keep following or it doesn’t break up because the birds can figure out how to compensate when one bird does something random.

To clearly understand the ways in which this explanation is evidence of emergent thinking, it is important to understand what Jared means by the word, random, as this word may or may not be evidence of emergent thinking. As mentioned previously, there are a variety of different meanings of the word randomness that could potentially be relevant to this data. I argue that Jared uses two meanings of the word random. He is referring to 1) the random motion of individual birds and 2) the unpredictability of the overall pattern. Jared refers to the random motion of an individual bird when he says, “if one of them, well, if one of them did something random…then the ones behind them can't follow it anymore. And they have to do something random.” In this excerpt he is discussing the individual birds doing something random. In this next segment, he is referring to both kinds of randomness, the random motion of individuals and the consequences of the flock breaking up. Also, notice that in this excerpt he is discussing both birds and fish.

Jared: break up
Lauren: yea, break up, how, what do you mean by that?
Jared: So, if, if, it's like the school of fish, if some of, cause the birds are following the other birds, so if like, one or some of the birds change direction, or like do something random then the whole thing will break apart

By explaining that the flock will break up, Jared means that the overall V-shape pattern will be disrupted such that it is no longer in the V-shape formation when one bird does something random. Notice that in the two above excerpts, when he mentions a bird changing directions or doing something random, he is focusing on the random motion of an individual. The second meaning of randomness was embedded in previous excerpts where be mentioned that if one bird
in the middle of the flock does something random, the birds behind that bird may or may not get confused, which thus may or may not result in the flock breaking up. In this way there is some unpredictability about what will happen after a bird in the middle does something random, the flock may or may not break up. Multiple uses of randomness, especially the latter one, are evidence of recognition of the unpredictability of the overall behavior and the self-organizational nature of the phenomena as was discussed in Chapter 1.

Jared’s explanation is based on prior knowledge about the motion of individual birds, which he finds relevant. He mentions the existence of a singular lead bird or more generally, birds following other birds. He also mentioned that there could be more than one leader bird, thus suggesting that it is a role any bird can assume not a property of only one bird.

Also, this explanation is based on several kinds of prior knowledge that are features of the problem context including the arrangement of birds and the personification of birds. A key piece of this explanation is based on Jared paying attention to the relative position of birds in the front, middle, and back. These relative positions influence his reasoning about individual birds behavior and whether or not the flock will break up. Also, many times Jared cued knowledge about the personification of birds. He explicitly mentioned or implied that the birds were confused, that birds will notice certain characteristics of other birds, and that perhaps they will not care about the behaviors of other birds. Personifying birds, applying characteristics such as confusion or caring about the behavior of other birds, is usually regarded as non-normative, but interestingly in this case Jared was cueing knowledge about birds’ instincts and desires and this knowledge was important to his overall explanation; Jared mentioned birds liking to fly in a V-shape formation.

In this explanation Jared is drawing on specific prior knowledge about how he expects birds to behave and using that knowledge to construct an explanation that is associated with emergent thinking. In his explanation there is an initial perturbation, one bird doing something random, and two possible results only one of which is dramatic, the flock either breaks up or perhaps nothing would occur. Within this explanation there are two kinds of random behaviors, an initial birds random perturbation and the unpredictability of whether or not the flock will break up, the latter of which is emergent. The explanation is based on some prior knowledge that is specific to the bird problem context, about the role of individual birds, and the relative positions of birds and the personification of birds, which includes some knowledge about birds’ instincts and desires.

This analysis illustrates that for Jared in this case study, emergent thinking is specific to the problem context and the particular knowledge elements cued. His understanding of the behavior of a flock of birds as a complex system is based in his understanding of individual birds random behavior and how that may or may not lead to the flock breaking up. This is based in knowledge about the relative position of birds and his tendency to personify birds, which in his explanation provided reasons why the flock may or may not break up, the birds may or may not get confused.

**Large Consequences of Cars Switching Lanes**

Next, in the following episode, I discuss one case of an explanation about traffic jams, which is based on the indicator of small perturbations leading to large effects. This explanation comes from an excerpt of the interview with Raj, a 10th grader. In this case, similar to the prior case, Raj’s emergent thinking is specific to Raj’s problem context as it is based on particular prior knowledge about individual cars behavior and the collective actions of many cars in a traffic jam.
In this explanation Raj explains the behavior of traffic jams in terms of how an individual switching lanes results in lots of other people needing to slow down.

“But, if I want to switch lanes, the guy in that lane has to stop or pass, and then the guy before him, after him, has to stop, and so you stop one person and that just snowballs down, cause as soon as one person stops everyone behind him has to stop.”

He is explaining that one person switching lanes results in many other people subsequently needing to slow down such that there is snowball effect.

In this explanation he has a sense that the behavior is not only about one person merging into a new lane; the overall effect is a result of many people’s collective behavior. “The more that you merge over, the more people that you’re stopping; but it’s not like it’s just one person doing it, it’s the culmination of all the people, just merging in and out of lanes.” Raj is explaining that switching lanes has large consequences for a traffic jam forming; both because an individual’s actions has large consequences on others actions and because the collective actions of many people all merging in and out of lanes has large consequences.

Within this explanation there is some prior knowledge about the pragmatics of traffic jams and possibly an intuition about the amount of people on the road influencing the jam. This explanation is based on prior knowledge about the pragmatics of trying to avoid accidents. Possibly Raj is using an intuition about more people on the road resulting in people needing to go even slower which results in a jam. Although not stated, presumably this is because when there are more people on the road there are smaller gaps between cars, which means there are smaller buffers between cars which results in everyone needing to slow down to avoid accidents. Possibly this intuition about more people on the road resulting in everyone needing to go slower is a version of Ohm’s p-prim. Ohm’s p-prim focuses on the relationship between an agent, some resistance, and a result. Often this p-prims takes the form of more effort implying more results.

In Raj’s explanation there is a car that is trying to move lanes, the resistance would be that all the other cars that influence the agent’s ability to merge, and finally, cars are or are not able to merge and a traffic jam forms. The more resistance that the individual car experiences due to all the other cars, the harder it becomes to merge in and out of lanes and thus all motorists slow down further. In this case we cannot be certain about if Raj is applying this p-prim, but it is a possibility.

Overall, this explanation is about an initial perturbation in which one or many cars switch lanes resulting in a jam forming due to the collective actions of all the individuals reacting to each other. This explanation is quite specific to the problem context; it depends on prior knowledge about cars needing to slow down to allow another car to switch lanes given people’s desire to avoid accidents and an intuition about the more people that are on the road, the greater the jam. This explanation incorporates some emergent thinking about the relationship between and individual’s actions and the collective actions of a group. The emergent thinking exhibited here is embedded within some specific prior knowledge about the nature of cars behaviors and traffic jams.

**Individual Variation Versus Problem Context Variation**

One could argue that this analysis illustrates variations across individuals instead of variations across problem contexts. This is less likely because the specific prior knowledge activated in each problem context was common across many individuals and some of the prior knowledge
elements in one context are not easily applicable to another problem context. First, as was discussed elsewhere, in the theoretical framework in Chapter 2 and the analysis in Chapter 6, many of these knowledge elements, such as personification of birds and fish, or finding the merging aspect of traffic jams relevant, were common to many individuals within the data set. Second, the knowledge elements students cued in each problem context were often specific to that problem context, and when they did coordinate a knowledge element across problem contexts it has been noted. Jared did not discuss cars doing something random and then getting confused resulting in jam breaking up, he never used the word random when discussing traffic jam and a traffic jam breaking up is not the same thing as a flock of birds breaking up. There was no discussion of the causal results of an initial perturbation. Inversely, Raj did not discuss the idea of an initial perturbation of birds leading to larger effects, but he did discuss two flocks of birds merging together as I had specifically asked about this issue. He focuses on two flocks merging in an orderly manner, “each flock can merge into just lines, and eventually this flock can become a line of all the birds here, into a V. That would just involve these V's narrowing and eventually merging together, so that they are just one straight line.” In Raj’s bird explanation there was no sense of the snowball effect, an initial perturbation leading to larger results, or the resistance provided individuals, all of which were key parts of his traffic jam explanation. Thus the knowledge elements Jared cued in the bird context were unique to the problem context and unlike the knowledge elements he cued when discussing traffic jams. Similarly, for Raj the knowledge elements he cued in the traffic jam problem context where unique to that context and unlike the knowledge he cued in the bird context.

Comparing Random Bird Perturbation and Cars Switching Lanes Explanations
Both of these previously discussed explanations are based on the indicators of small actions having large effects but otherwise they are quite different in terms of prior knowledge and the specifics of the behavior. I argue that there is quite a bit of variation across contexts. In the bird case the explanation emphasizes one bird’s random perturbation resulting in the flock breaking up or not. In the traffic jam case the explanation emphasizes one car or the collective behavior of many cars switching lanes, resulting in all drivers moving slower as a jam forms. Irrespective of the general similarities in these two explanations, they are quite different in terms of the kinds of prior knowledge the two students cued in their explanations, and in terms of the particular initial behaviors, number of possible outcomes, and overall effects. For birds the initial behavior was doing some random action, which was different from other birds, in traffic jams the initial behavior was switching lanes. In birds their were two possible outcomes, the flock breaking up or not, and in traffic jam there was only one outcome, everyone slowing down and a jam forming. Finally, the overall effect was different. For birds the overall effect was a flock breaking up and then reforming or the flock not breaking up, for traffic jams the overall effect was everyone slowing down and stopping given the snowballing behavior. These comparison cases are important because the causal result of the different perturbations is quite different. Hence, I have argued that despite these two explanations both relying on the same indicator of emergence, I find that emergent thinking is quite specific to the problem context, and there is lots of variation within this indicator of small actions having large effects.

In summary, in this section I presented two cases of students’ explanations based on the indicator of emergence, small actions having large effects. I argue that in each case, that students’ reasoning about the specific problem context, birds or traffic jams, as an example of emergent thinking was specific to the problem context and the particular knowledge elements cued. For
these two cases of students using a common indicator of emergent thinking, their reasoning as exhibiting emergent thinking is not the same.

**Different Behaviors at Different Levels**

Next, I discuss two examples of students’ generated explanations incorporating the indicator of *different behaviors at different levels*; one of these explanations is about forest fires, the other is about diffusion. In the first case the student explains that in forest fires, at the micro level there is conservation of energy, but at the macro level there is not conservation of fire as a fire spread from one tree to another tree without influencing the first tree’s amount of fire. The second example focuses on the relative processes influencing diffusion. The student explains that there are three competing processes that apply not to different physical levels, but to different features of the behavior possibly at the same level: falling due to gravity, swirling, and diffusion. He views these three competing processes as dealing with different aspects of the phenomena: diffusion acts on individual molecules behavior resulting in random motion, gravity deals with the molecules weight resulting in them moving towards the bottom of the cup, and swirling which results in mixing. One contribution of this analysis is to expand this indicator from physical levels to other dimensions of features of the behavior. Although both of these cases incorporate a common indicator as based on fairly abstract principles, they are quite different in terms of the students’ prior knowledge that influences their explanations and the specific relevant principles. Thus I argue that these two examples of emergent thinking are quite specific to the problem context and the particular knowledge elements cued despite the common indicator of emergent thinking.

**Forest Fires Conserved at the Micro Level and not Conserved at the Macro Level**

Blake, a Ph.D. student in physics explains the behavior of forest fires in terms of energy being conserved at the micro level and fire not being conserved at the macro level. In this case, Blake’s emergent thinking about the forest fires is based on particular prior knowledge about molecular energy, the behavior of fire, and how fire spreads through physical contact. He discusses molecular energy and photons in that context of conservation of energy. First he discusses the energy and heat of photons as related to the trees being on fire and producing its own heat:

“most of the energy is in the infrared region, which is heat // Lauren: Right // and so, it's shooting off all of these photons, which we can't see. But that they carry energy and so it's, you know, one of these photons flies over to that tree. And hits one of those trees electrons and then that electrons goes. And if enough of that happens the whole tree will catch on fire. And then it will be producing it's own heat. You know, and so everything starts producing it's own heat. The overall amount of heat is going to build and it's going to radiate more. So, radiation is that of the protons flying off.”

In this explanation he is discussing fire at the micro level in terms of the behavior of photons. Then he connects it to the tree level with regards to the trees catching on fire and then producing their own heat.

Next he compares sand dunes to forest fires recognizing that they are similar in some regards but conservation applies to sand and not fire. He compares forest fires and sand dunes. I ask how they both work and he replies by blowing air (“just by blowing the air”). He is
explaining that for both there is blowing air, which causes the spread of the fire or the movement of sand dunes. ("Well, pretty much the same thing, at least, so the, the forest fire spreading is like very similar to this sand dune moving over here // "). He continues by providing a reason for why they are not the same thing. ("Except it [forest fire] doesn't have to move, because it's not a limited amount of sand. You know. Before the amount of sand was conserved, the wind doesn't make more sand.") Unlike sand dunes where there is a limited amount of sand, there is not a limited amount of fire. Then he continues to explain fire and energy for forest fires.

“But now that’s it’s fire, all it is, is like energy, and energy is everywhere. I mean a tree burns. So, it must be full of energy and // Lauren: Right // I mean, energy is conserved, but not. Not worth thinking about it in this case. Cause we’re thinking of things burning, where as, and that’s how we’re measuring energy. But we could also measure the chemical energy of the tree // Lauren: Right // So in the grand scheme it’s conserved. // Lauren: Right. // But, for us, we're like, you know it’s getting hotter”

This section is a bit hard to follow, but after mentioning conservation of sand, he explains that energy is everywhere. Since he mentions energy being conserved, clearly he is aware of the idea of conservation of energy. But then after mentioning energy conservation he says “but not.” This idea is expanded further. He mentions that energy conservation is not worth thinking about in this case because we’re thinking of things burning and getting hotter and hotter. He again mentions energy conservation in the “grand scheme” but he states that in this case energy conservation is not relevant because we’re focused on things burning and getting hotter and hotter. Notice that in this excerpt he is not as focused on the photon level, but instead focused on the tree and the overall effect, increase in heat. This is different from earlier when he was discussing fire at the micro level in terms of the behavior of photons as related to the trees. In this excerpt he recognizes that there is conservation of energy, but he is saying that it is not applicable because we’re focused on trees burning and becoming hotter and hotter.

This idea is expanded four minutes later when he discusses that when a tree is on fire the fire will spread from tree to tree such that in this process the amount of fire on the first tree is not reduced. “Cause, because like when, when one tree is on fire, and there is some wind. And the fire hits at the other tree, then the other tree catches on fire, that doesn't put the first tree out. So it’s able to grow, just by two things meeting.” He explains that as a fire spreads from tree to tree the amount of fire increases. Also, he compares this to viruses as he claims they work the same as forest fires. In this section he is elaborates upon the same mechanism as in the prior section. Clearly he is aware of conservation of energy in the grand scheme, but he explains that it is not relevant because at the tree level fire spreads from tree to tree and during this process the amount of fire that the original tree has is not reduced when its fire spreads. Remember, this is different from sand dunes in which the amount of sand is conserved.

Four minutes later after we had switched to discussing viruses, he mentions forest fires again while explaining how the spread of a virus is similar to the spread of a forest fire. In this explanation he draws on a similar mechanism in that both spread by physical contact. He also recognizes that for both there is not conservation in the amount of virus or the amount of fire. The act of spreading a fire or a virus does not reduce the original trees amount of fire or the person’s amount of a sickness.
“Again so, similar to the a forest fire spreads. If I am sick and then I coughed in my hand, and then when I shake your hand, you’re gonna have some of my sickness. You know, a little bit of it came off my spit on my hand and my spit has all this stuff in it that gets you sick. You know. But, just by coughing that spit out. That’s gross, but, just by coughing in my hand I didn't make myself un-sick. // Lauren: Right // Cause, I have you know, plenty of this disease, to go around.”

Blake is explaining that at the macro level the fire can spread from tree to tree without the amount of the fire being reduced; in fact it grows. He views viruses as working similarly. As the virus spreads from person to person the amount of virus also grows. In both of these problem contexts he does not see conservation in the amount of fire or the amount of a virus at this macro level.

Comparing Blake’s understanding of the micro photon level and the macro fire level, we can see that he is applying different ideas or assumptions. Clearly he is aware of conservation of energy. He recognizes that conservation applies to energy at the micro level. At the macro level it is more complicated. He says that conservation is not relevant to the macro level spread of fire or viruses as both spread by physical contact and the process of them spreading does not reduce the initial trees amount of fire or the persons amount of virus. There is also evidence that Blake is aware of this difference. Remember he says, “so in the grand scheme it’s [energy] conserved but, for us, we’re like, you know it’s getting hotter.” Thus he recognizes that from one perspective there is energy conservation, but we feel the fire getting hotter over time.

In these excerpts about fire behavior at the two different levels Blake accesses some different prior knowledge. In the excerpt about the energy of fires at the micro level, Blake accesses prior knowledge about the photon and electron level. Given his academic background he likely has prior experiences, in academic contexts, about these topics, along with similar kinds of prior knowledge, also from academic contexts, about the principle of energy conservation. In the excerpt about fire behavior at the macro level he showed an understanding that fire is not conserved and potentially can grow without bounds. He mentions conservation of energy, but says that it is not relevant. Overall he has a subtle sense of when conservation is more or less relevant to the different aspects of the phenomena that he is explaining. Interestingly, he cues some prior knowledge that coordinates this spreading of fire by physical contact between trees as similar to the spreading of a virus through physical contact. This knowledge could come from prior experiences with fire and viruses, such as experiences with fire spreading as one lit object touches another non-lit object. This would result in both objects being equally lit without any diminishing of the first tree on fire, and a similar experience with viruses spreading.

In conclusion, in this segment we see Blake generating explanations about forest fire behavior that incorporate the indicator of different behavior at different levels. In this case the specific “behavior” that we see Blake applying to the different levels is not actually a behavior, instead he is applying a principle. Also, rather than explaining that this principle applies to some levels and not other levels, he is making a more nuanced argument. He clearly views conservation of energy as applicable to the micro photon level but for the macro level his argument is more nuanced. He is saying that there is conservation of energy but it’s not applicable because we focus on the burning tree getting hotter and hotter as fire grows without bounds. These sets of explanations are an example of emergent thinking as he recognizes these important differences at the two levels and he is connecting the behaviors at the micro and macro levels. Within this explanation he is accessing specific prior knowledge from his prior academic
experiences about the relevant principles of conservation of energy and some more intuitive knowledge about the spreading of fire through physical contact. Thus this example of emergent thinking is quite specific to the problem context; particularly the nature of how fire spreads and his prior knowledge.

**Three Competing Process in Diffusion**

In this final case I discuss an explanation how there are three things occurring within the diffusion in water: diffusion, swirling that results in mixing, and falling, due to gravity, each of which acts on a different aspects of the system not a different physical level. These data also comes from the interview with Jared, a Ph.D. student in physics. First I discuss his understanding of diffusion, which results from the random motion of individual molecules. Then I discuss his combined understanding of diffusion, swirling, and falling due to gravity, which each act on a different aspect of the system. In this case we see Jared applied several fairly abstract principles to different attributes of diffusion. In doing this he cues knowledge that is particular to diffusion.

First Jared provides an explanation of diffusion in the system.

“So, diffusion is, when, like, the individual molecules, because of the fact that they are all just bouncing around randomly off each other, and moving randomly by, because of this bouncing. They start to, to move from // they start in one place and they end up in another place”

He views that diffusion involves the random motion of molecules bouncing around. A couple lines later he reiterates this idea and adds a comment about diffusion not being a concerted flow.

“So. It's not. It's not like a concerted flow in one direction // it's just, they start here and they end up in some random place // that means that if they all started at the juice together. Water molecules together. If they all end up in some random place, then they are mixed and that’s, that’s what diffusion is.”

Jared is explaining that diffusion emerges from the random motion of individual molecules and that it is different from a concerted or direct flow.

Then two minutes later he explains that there are three things going on: diffusion, swirling that results in mixing, and falling due to gravity and each of them acts on a different part of the system. Although he begins by mentioning two influences, in fact his explanation accounts for three influences.

1. Lauren: Can you think of anything else that, influences how the, the water and the orange juice mix?
   [pause]
2. Jared: Sure, there is gravity, has an effect. Cause the orange juice probably has,
3. 
4. Lauren: Yeah
5. Jared: with mixing, which is that, there is this diffusion which, other than,
6. if you ignore the fact that when you pour it in there is all this flows that make everything swirl around // cause eventually that will, die down.
7. But, then, there is diffusion, which is making the things move to some new random point. And that makes them mix.
8. There is also gravity that makes the heavier things, be on the bottom. Preferentially.
9. Jared: So, that’s why if you mix water and oil, you can't keep them mixed, because, well, that’s not the only reason why, I guess. But, gas, but, I mean, the oil is less dense. So, for that reason, it, more likely to be on top //
10. Lauren: Right
11. Jared: and, there is also, some diffusion,
12. but, in that case the gravity beats the diffusion, that’s probably also has to do with, surface tension.
13. But, I, the orange juice, if the orange juice molecules are heavier, or if they fit together, if the orange juice is denser than water, then, it prefers to be lower down. But, probably, so, I guess, it depends on what actual molecules are in the orange juice. Some of them might be heavy enough that they don't, that gravity beats diffusion and they end up at the bottom. Definitely if there are bits of orange, they end up sinking to the bottom. //

In this excerpt Jared is explaining that there are three competing processes: there is gravity which makes things preferentially fall to the bottom, there is diffusion, which makes things move to some new random position, and there is a swirling, which is a type of flowing making things mix. In line 1, I asked Jared if he could think of anything else that might influence the behavior that we had already been discussing for five minutes. Then he mentions, for the first time, gravity having an effect (line 2) and he mentions two things happening (line 3). The first of these two things is diffusion (line 5). Next he mentions that when you pour the two liquids together there is a swirling motion that is a type of flow that results in mixing (line 6). At that point he reverts back to discussing diffusion, which makes things move to new positions and mix (line 7) and mentions the third process, gravity, which makes heavier things preferentially fall (line 8). He continues to explain that gravity is one reason why water and oil cannot mix; the oil is less dense and more likely to be on top (line 9). At that moment he mentions that there is diffusion in addition acting in that case (line 11), and the gravity beats the diffusion resulting in the two not mixing (line 12). However, in the case of orange juice, if the orange juice molecules are heavier then they will prefer to be lower, and perhaps the bits of orange within the juice will also be heavy and sink to the bottom (line 13). In summary, in this excerpt Jared explains three competing processes acting on different parts of this system, gravity which results in things preferentially falling to the bottom, diffusion which makes things move to a new random position, and swirling which is a type of flowing that makes things mix.

Notice that these processes act on different features of the system but not necessarily different levels. Diffusion acts on individual molecules. Swirling acts on a flowing liquid. Gravity acts on heavy things making them preferentially fall. For gravity it does not seem to matter if this is a liquid like oil or a molecule, he mentions gravity acting on both. Thus different physical levels are not the central feature distinguishing these three processes: instead it is that they act on different features of the system that may or may not be at the same physical level: molecules, flowing liquids, and heavy items.
Underlying these explanations is some prior knowledge likely from academic experiences about diffusion. All of his explanations draw heavily on academic experiences with diffusion, based on his discussion of the random motion of molecules bouncing around. When discussing gravity making heavy things fall to the bottom, he may be also drawing on academic prior knowledge along with experiences that suggest that gravity is relevant to this problem context. He also mentioned the mixing of oil and water. The fact that oil and water do not mix is a common example of two liquids that do not experience diffusion. Given that the non-mixing of water and oil is a commonly used example, for him it might be tightly related to his other knowledge about diffusion.

In summary, in these excerpts Jared’s explanations exhibit some emergent thinking by recognizing that there are three aspects that act on different features of the same system that may or may not be at the same physical level. He explains that there is diffusion, swirling that results in mixing, and falling due to gravity. Each of these acts on different features of the system. Diffusion involves the random motion of molecules bouncing around. Gravity causes heavier items to sink to the bottom. Swirling is a type of flow that results in mixing. Thus we see him applying these fairly abstract principles to different features of the system. His ability to do this was based on him cuing prior knowledge about the random motion of molecules and seeing gravity as relevant in this problem context. Overall this is an example of emergent thinking, but rather than him recognizing different behavior at different levels, he is using a more general version of this indicator, such as different behaviors applying to different features of the system, where the relevant features may or may not be physical levels. Also, his application of this indicator is quite specific to the particular problem context as it is based upon his particular prior knowledge and understanding of the system.

Comparing Forest Fires and Diffusion through Different Behaviors at Different Levels

Both the forest fires explanation and this diffusion explanation contain the indicator, different behaviors acting on different levels; however there are some differences that are particular to the specific problem context and particular prior knowledge. Remember in the prior literature (e.g. Resnick, 1996) the idea of different behaviors acting on different levels applied to directional motion, for instance, in a traffic jam cars move forward while the jam moves backwards. In Chapter 4 this indicator was applied to sand dunes moving upwind while the sand particles move downwind. In neither of the cases presented in this chapter is this indicator applied to directional motion. In both of these cases the students are focusing on rather abstract principles applying to these two levels, conservation in the forest fire case, and diffusion, swirling motion, and gravity in the diffusion case. Thus I argued that in these cases recognition of this indicator is specific to the particular problem context (forest fires and diffusion), based on the specific prior knowledge cued by that student, and is a rather sophisticated version of this indicator as these relatively abstract principles are more abstract than directional motion. Overall this analysis suggests that for these students this indicator of emergence, different behaviors acting on different levels, is not a single entity, it varies depending on the problem context and the particular prior knowledge cued within its application.

Discussion and Conclusion

The results illustrate that emergent thinking is quite specific to the problem context, and there is variation within each general indicator. I discussed two indicators of decentralized causality, small perturbations leading to large effect and different behaviors at different levels. For each
indicator I presented two data analyses in order to illustrate both how the specific problem context and the relevant prior knowledge cued influenced the students’ reasoning, in order to illustrate the variation with each indicator.

If one conceptualizes the prior literature as using these indicators as a label to capture underlying emergent thinking, one can view this analysis as opening up these indicators and looking at what kinds of prior knowledge and specifics about the problem context contribute to this label. I focus on specifically what is contained within each of these indicators with regards to the kinds of knowledge resources and understandings that these indicators depend on. In this way the current analysis is not about labeling emergent thinking, but is instead about investigating what contributes to the underlying pieces of emergent thinking and how they vary across problem contexts. These results suggest that these indicators are not a single entity; they need to be applied differently depending on the problem context and the relevant prior knowledge that is cued. This suggests that for these students’ emergent thinking is not one unified entity—it varies a great deal across problem contexts.

These results are important because they influence how researchers should identify and conceptualize students’ emergent thinking, and instructional activities meant to support students’ developing emergent thinking. Viewing students’ emergent thinking as not one unified entity suggests that researchers need multiples ways to capture the variability within emergent thinking and account for this lack of unification. Similarly, another implication is that we would expect not only one developmental pathway towards emergent thinking but many pathways and these pathways would need to take into account specifics of the problem context and relevant prior knowledge. Instructionally, one would then need to take into account these problem context differences and variation in prior knowledge.
CHAPTER 7: DISCUSSION AND IMPLICATIONS

Introduction
This dissertation is about students’ competencies with understanding the behavior of complex systems in the context of generating scientific explanations. In order to illustrate their competencies, the analysis focused on both students’ prior knowledge and the various kinds of explanatory patterns that students used in these explanations. These two analysis foci were combined in various ways throughout the three analysis chapters in order to capture: 1) shifts within individuals’ explanations from being more prototypically centralized to being more prototypically decentralized; 2) variation across many students’ explanations in terms of the seven problem contexts with regards to the students’ prior knowledge; 3) diversity of what counts as emergent thinking with regards to the specific problem contexts and the relevant prior knowledge. In this chapter I sequentially discuss each of the analysis chapters. I summarize each chapter, and then I discuss the major conclusions. After that I discuss some limitations of the analysis, and I conclude each section with a discussion of future work and instructional implications. At the end of this chapter there is a section summarizing the key implications of the whole dissertation.

Lines of Continuity between Centralized and Decentralized Causality

Summary
In Chapter 4 I investigate the moment-by-moment shifts taken by individual students as their explanations become less and less prototypically centralized and then become more and more prototypically decentralized. One perspective on this chapter can view it as capturing students’ generating a progression of increasingly sophisticated transitional explanations that demonstrate this shift in reasoning. The first two-thirds of the chapter focus on Laurel and the latter one-third of the chapter focuses on the case of Keaton. For Laurel, to understand how her explanations and understanding shift, I identify two transitional explanations, sand-stickiness and sequential layers. I trace lines of continuity as she relinquishes various pieces of these two explanations that are more centralized, and she adds various pieces that are more decentralized. I also do an analysis of the moves, by both her and myself, that supported these shifts. Specifically, I focus on the interviewee-initiated moves that support her shifting understanding, including major shifts in what phenomena is being explained, and small critical changes in topic. For example, there is a major shift from explaining how a dune moves locations at the beginning of the discussion to explaining how a dune gets bigger or smaller at the end. I argue that this major shift along with several related smaller shifts are crucial for her shifting understanding. I also do an analysis of the small nudges I do as the interviewer that subtly shift her explanations and understanding. For comparison purposes I also present the case of Keaton, whose explanations also shifted from being less and less prototypically centralized to becoming more and more prototypically decentralized. His overall shift was similar to Laurel’s overall shift; however, his transitional
explanations are different as he wrestles with the relative direction of the wind motion as compared to the direction of the sand grain movement and the direction of dune movement.

Conclusions
First, the analysis in this chapter illustrates the lines of continuity between these two ways of understanding and illustrates how change can occur. This is different from some of the prior work on students’ learning about complex systems that has tended to emphasize the divisions between centralized and decentralized causality (e.g. Jacobson, 2001). The analysis shows that both students’ understandings and explanations shifted towards decentralized causality and I document a series of moves, by both the students and myself, that supported these shifts. One important thing to note is that both students were able to revise their explanations based on their prior knowledge resources, and their final explanations are aligned with decentralized causality—these results are different from the hypothesis presented in Chi, et al., (2012) about students’ misconceived causal explanations not necessarily pertaining to a lack of knowledge.

Second, this chapter illustrates that although these two students traverse similar paths given a shift from explanations that are less prototypically centralized to more prototypically decentralized, their intermediate explanations are quite different. Thus there are at least two specific paths and possibly many paths that can be associated with the common shift. Noting that there are potentially many paths and these paths incorporate specific transitional explanations is important because it shows that this shift may not be as difficult as some have presumed. In addition, these results about helpful transitional explanations may lead to instructional implications.

Finally, this chapter makes a methodological contribution, highlighting the tension between the phenomena a researcher intends to be explained—in this case sand dunes moving—and the students choice of what to explain—in this case Laurel explained how sand dunes get bigger and smaller. I argue that for Laurel, the latter was a key feature for her shifting understanding. Allowing students some flexibility in deciding what to explain or productively directing students’ attention to certain phenomena within the same problem context is a potentially important methodological piece of supporting students’ reasoning about complex systems.

Limitations
A central question someone might ask about this chapter is whether the results are unique to sand dunes or only these two students, and how these results apply to other problem contexts and other students. A natural question arises about whether this common shift might be seen in other problem contexts or if there is something idiosyncratic about sand dunes. Possible this could only happen in sand dunes because students’ are able to access so much intuitive prior knowledge about sand dunes. At the time Laurel was a masters-credential student in mathematics education, Keaton was a Ph.D. student in physics. Neither of them had explicit expertise in complex systems, but they both have expertise in related disciplines. One might question if perhaps this shift is unique to students with this level of expertise and unlikely with high school students. These questions should be addressed in future work.

Future Work and Instructional Implications
Future work from this chapter should focus on applying these findings about the intermediate transitional explanations and the results of the other factors influencing the shift, including my nudges, and the students’ questions, to research and instruction. For research, a next direction
from this chapter focuses on theoretical implications of the transition. Additional work is needed to understand if this progression is unusual or difficult in certain problem contexts due to limitations of students’ intuitive prior knowledge. Also, additional work is needed into a better understanding of the things I did as the interviewer and the things that Laurel did to self-scaffold herself. This additional work has applications for what teachers could do in instruction.

If this transition is difficult or unusual, a natural question arises about whether these challenges can be ameliorated by instruction, computational simulations, or models. Perhaps students could be scaffolded by being presented with some transitional explanations. Being presented with these transitional explanations could help students’ progression towards reasoning about complex systems in ways that are prototypically decentralized. One could critique this approach in that students might be exposed to transitional explanations that are non-normative, but this critique is mitigated given that these students would be starting from a non-normative explanation and being exposed to transitional explanations that have been shown to be helpful for others. Another possibility is that perhaps students could be scaffolded by specific discursive prompts that are similar to the rhetorical questions Laurel asked herself. During the interview Laurel asked herself some rhetorical questions that proved crucial for her shifting understandings, perhaps these or similar questions could be asked by a teacher trying to help provoke similar shifts.

**Variation in Students’ Understanding and Explanations of Emergence across Seven Problem Contexts**

**Summary**

The central goal in Chapter 5 was to investigate similarities and differences across many students’ explanations and understanding in terms of their prior knowledge. The analysis focused on how the nature of a specific domain influences students’ reasoning about phenomena whose behavior is associated with complex systems, specifically, variation across students’ understanding in the context of generating scientific explanations about the seven problem contexts. I focused on student generated scientific explanations that captured the behavior of the phenomenon through six patterns: *changing composition, convergence to a limit, steady state, periodic motion, threshold,* and *mid-levels*. The first of these patterns is emergent, and in various ways the latter five are possibly helpful in students’ developing decentralized explanations.

For each explanatory pattern, I investigate its use across all of the problem contexts and I discuss the kinds of prior knowledge activated. I find that one explanatory pattern, *convergence to a limit*, is often mentioned when students’ prior knowledge supports their ability to focus on an underlying mechanism, for example, the way birds converge to a V-shape preferring to fly in formation because it is easier to fly that way. However, when explaining other problem contexts through convergence to a limit, students did not necessarily use mechanisms. For example in diffusion in water, students suggested that mixing is a natural state of the phenomena with no explicit mechanism needed.

Another explanatory pattern, *mid-levels*, is often mentioned when students cue prior knowledge about the arrangement of agents, for example in the case of sand dunes, the fact that the top-layer of sand is moved first because it is most exposed to the wind, or in birds and fish, the way a small groups of fish or a small group of birds separate or join the larger group because they want to be near friends or are tired. I find that the *mid-level* explanatory pattern is not
mentioned in some of the other problem contexts, for example diffusion in water, in which the students do not see the specific arrangement of individual molecules as relevant.

Conclusion
The results illustrate a variety of students’ understandings across the seven problem contexts in terms of prior knowledge. These results call into question a general trend of de-emphasizing domain differences in students’ understandings of emergence. I find that students’ understandings vary widely across the seven problem contexts with regards to the particular prior knowledge used and the specific explanatory patterns used. Thus, these results call into question a trend within prior research (e.g. Jacobson, 2001; Perkins & Grotzer, 2005) of de-emphasizing the multitude of prior knowledge resources that influence students’ understandings of emergence.

I find that a main factor distinguishing certain problem contexts as easier or harder for students has to do with a spectrum of the kinds of prior knowledge resources activated. For example, at one end of the spectrum are sand dunes where students are able to access a wide range of intuitive resources that are applicable at multiple levels. Coming to see the decentralized nature of the phenomena in the sand dune case is not an enormous challenge. In contrast, at the other end of the spectrum is diffusion where students encounter many challenges, for instance, a lack of intuitive knowledge about the molecular level of water.

Another contribution centers on the mini-theory of students’ epistemological resources. Although there are a handful of other mini-theories within the KiP family of theoretical perspectives, this mini-theory focuses on students’ prior knowledge and how that knowledge influences the explanations they generate about particular complex systems, for instance, the movement of sand dunes. This mini-theory is based on a catalogue of the kinds of prior knowledge students activate when explaining how a series of complex systems work. One contribution of this mini-theory are some new additions about relevant kinds of prior knowledge, for instance knowledge about pragmatics. Another contribution is to show that some p-prims, which were originally documented in Newtonian Mechanics apply to complex systems too.

Limitations
One limitation of this analysis is that it was not possible to do a coding that would have enabled quantifiable data about the frequency of each explanatory pattern within each problem context. This was not possible due to limitations of the data corpus, the nature of the clinical interviewing style, the fact that process of identifying each pattern is not reliable enough to warrant analysis that could produce frequency counts, and a small sample size. The particular interviewing style used in this dissertation and analysis process were necessary as they allowed investigation into the student generated explanatory patterns and they support investigations of students’ prior knowledge. This analyses of the explanatory patterns and students’ prior knowledge might not of necessarily been possible with a different kind of data corpus that could have supported quantification.

A second limitation is that within the analysis students with different academic backgrounds were generally treated similarity. Remember, in the data corpus there are students with a range of academic backgrounds from 8th-12th graders, undergraduates majoring in physics, masters-credential students in mathematics education, and physics and astronomy Ph.D. students. Although none of these students have expertise in complex systems, they do have different academic backgrounds and this difference can influence the results. Students with varied academic backgrounds were included in the dissertation in order to maximize the possibility of
seeing a range of prior knowledge activated. I could have, but generally did not, incorporate these varied academic backgrounds as a dimension of the analysis. Thus the analysis cannot address questions about the various ways students with different academic backgrounds reason and generated explanations about complex systems.

Finally, a third limitation is based on the relationship between students’ explanations that incorporate these patterns and their understanding of decentralized causality. For some patterns, for instance, changing composition, it is clear that this pattern is emergent. For other patterns, for instance, convergence to a limit, I found that it was potentially helpful for coming to understand decentralized causality because it focused students on the underlying mechanism which in turn might have helped the students understanding. However, for other patterns, such as periodic motion and steady state, the relationship between that explanatory pattern and students’ understanding of decentralized causality is more tenuous. In Chapter 5 I presented some hypotheses, but not all cases of these explanatory patterns are decentralized and more research is needed to understand when and how these explanatory patterns are related to an understanding of the decentralized behaviors.

**Future Work and Instructional Implications**

Future work from this chapter should continue to look at the general characteristics of situations that foster productive development with an eye towards research and instruction. Remember one result of this chapter is that students’ appear to have fewer difficulties within sand dunes as compared to diffusion. Future work should continue to build a more detailed argument for why sand dunes might be easier and what about sand dunes contributes to their being easier than other problem contexts, for instance, diffusion which appear more difficult. What other problem contexts share key characteristics with sand dunes suggesting students ease? What other problem contexts share key characteristics with diffusion suggesting students will have difficulties? Once these characteristics are identified they can then be applied to future research focused on helping guide researchers and teachers in predicting which new problem contexts will be more or less difficult for students and building instruction that takes this into account. These results suggest that when teaching a difficult concept like decentralized causality the problem context matters. There should be additional research into what contexts are optimal and identification of characteristics of contexts that influences students’ level of ease.

**Diversity of Emergent Thinking**

**Summary**

In the final analysis chapter I build from the previous results and investigate the diversity of emergent thinking. I document the span of emergent thinking across four cases and the associated prior knowledge within those cases. I focus on two indicators of decentralized causality: *small perturbations leading to large effects, and different behaviors at different level,* and I focus on two cases that implicate each indicator thus this analysis consists of four cases. Prior research tends to use these indicators as a label or literally an indicator for the presence of emergent thinking as a global competence (e.g. Jacobsen, 2001; Jacobson, Kapur, So & Lee, 2011; Levy & Wilesnky, 2008; Wilensky & Resnick, 1999). In contrast I see that these indicators involve very specific knowledge and are not necessarily global indicators of general competence. In this analysis I open up these indicators and look at what kinds of prior knowledge and how the specifics about the problem context contribute to the appearance of the indicator. Thus this analysis is not about grading the level of emergent thinking, but is instead
about investigating the underlying pieces of emergent thinking. For these first two cases about small perturbations leading to large effects, I discuss the specific prior knowledge that influence the students’ explanations and some variation across the cases in terms of the, initial behaviors, number of possible outcomes, and overall effects. For the latter two cases about different behaviors at different levels I find that students use indicator in terms of the relevant behavior being a fairly abstract principle (e.g. energy conservation). These two cases are quite different in terms of the specific prior knowledge that influences the students’ explanations and the specific behaviors that students viewed as relevant at each level; this is in contrast to the prior literature that focused on differences in directional motion at the micro and macro levels (e.g. Resnick, 1996).

Conclusion
This chapter supports the point of view that for these students’ emergent thinking is not a single unified entity—it is diverse and varies across problem contexts and across kinds of prior knowledge. I argue that these two indicators of emergent thinking are quite specific to the problem context and the particular knowledge pieces cued despite the common indicator of emergent thinking.

Limitations
The analysis presented in Chapter 6 is limited in scope; only four cases are presented of students’ reasoning about four problem contexts (birds, traffic jams, forest fires, and diffusion) in terms of two indicators. Similar to the prior chapters, there are limitations based on the students’ academic backgrounds, this analysis focuses on three students, two of whom are Ph.D. students in physics. There are also limitations in that this analysis does not address issues of comparing emergent thinking across students with different academic backgrounds.

Future Work and Instructional Implications
Results of this chapter have implications for future work that focuses on detecting students’ emergent thinking, and the results have instructional implications. A common assumption when trying to detect students’ emergent thinking is that codes are transferable across problem contexts. The results of this chapter suggest otherwise. Given the variation across problem contexts for these two indicators, implications of the analysis suggest that more emphasis should be placed on problem context variation within coding schemes when detecting students’ emergent thinking. This analysis suggests that emergent thinking is not a unified thing for these students; implications suggest that multiple instructional approaches are needed. These results also suggest that there would not be a single developmental pathway towards emergent thinking, instead we would expect many pathways. These pathways would need to take into account specifics of the problem context and relevant prior knowledge. Instructionally, one would then need to take into account these problem context differences and variation in prior knowledge.

Summary of Contributions
This dissertation uses the Knowledge in Pieces epistemological perspective on conceptual change in order to build a mini-theory about the role of prior knowledge within students’ explanations for how complex systems work; complex systems is an area which Knowledge in Pieces has not previously been extensively applied to. Using the theoretical machinery supplied by this mini-theory I illustrate students’ specific competencies with learning about complex systems in the context of generating scientific explanations as based on their prior knowledge.
resources. Although there is future to be done, this dissertation is a first step in illustrating the importance of students’ prior knowledge and specifically problem context variation in their developing scientific explanations. Implications suggests that future work should continue to emphasize students’ prior knowledge and problem context variation within their developing scientific explanations.
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Appendixes

Appendix A. Sample list of possible knowledge resources activated by one student when explaining the behavior of forest fires

Ravi

- Fire spreads through contact with other trees
- If one burning piece of a tree touches another piece of a tree, then the fire spreads
- Domino effect in which the tree passes the fire to the next tree, and the fire spreads
- Near the edge of the forest the trees are less dense, they won't be touching as much and so the fire will die down. Nothing else to burn. The fire shrinks.
- Fires need fuel and fuel comes from the tree.
- After the tree burns it becomes ash, and so the fire has no more fuel and can't subsist.
- Fire can start on a hot day, lots of sun and dry. Fire can start from heat, no moisture. Fire can start from a human source, maybe a cigarette.
- On a hot day the sun's light can ignite a fire by heating up the wood so that it catches fire. The sunlight can be magnified by many things, e.g. water droplets acting as a lens
- Heat of the fire from friction
- Rubbing two sticks together makes friction.
- A tree falling onto another tree might create enough friction.

Appendix B. Categories of forest fires knowledge resources that were common across many students explanations.

- Creation/existence of a physical boundary
- Fires start due to environmental factors
- Hot/Dry conditions are more flammable and Wet/cold conditions are less flammable. Speed of burning
- Molecular/Electron Level
- People/animal begin the fire, increase the spread of the fire
- How distance(s) influences the spread of fires
- Fires Getting Smaller
- Role of the wind
- Running out of fuel, used up.
Appendix C. A selection of possible indicators of centralized and decentralized causality

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Centralized or Decentralized</th>
<th>In existing coding schemes?</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Equilibration</td>
<td>Decentralized</td>
<td>Goldstein (1999), Levy &amp; Wilesnky (2008), Jacobsen (2001)</td>
<td>A process by which the system (or a behavior) gradually stabilizes. One way that the system may stabilize is through the presence of an attractor, but not necessarily.</td>
</tr>
<tr>
<td>No process at an equilibrium point</td>
<td>Centralized</td>
<td>Jacobsen (2001)</td>
<td>No equilibrium process</td>
</tr>
<tr>
<td>Focusing on the macroscopic level only</td>
<td>Centralized</td>
<td>Hmelo-Silver &amp; Azevedo (2006)</td>
<td>An explanation that focuses on the macroscopic movement only and ignores any microscopic movements or variations.</td>
</tr>
<tr>
<td>Environment as acted upon</td>
<td>Centralized</td>
<td>Resnick (1994)</td>
<td>TBD</td>
</tr>
<tr>
<td>Linear changing behavior</td>
<td>Centralized</td>
<td>Yes</td>
<td>The behavior changes in a linear manner.</td>
</tr>
<tr>
<td>Threshold</td>
<td>Decentralized</td>
<td>Resnick (1994)</td>
<td>A behavior may gradually change and then there is a tipping point at which the behavior dramatically changes.</td>
</tr>
<tr>
<td>Composition (dynamic equilibrium)</td>
<td>Decentralized</td>
<td>Yes</td>
<td>The phenomenon is comprised of a collection of particles that is constantly changing as some particles leave and some particles join.</td>
</tr>
<tr>
<td>Environment as interacted with</td>
<td>Decentralized</td>
<td>Resnick (1994)</td>
<td>The environment as something to be interacted with, rather than acted upon. This can result in a feedback loop and be related to the self-organization characteristic.</td>
</tr>
<tr>
<td>Lack of a Leader</td>
<td>Decentralized</td>
<td>Resnick (1994), Levy &amp; Wilensky (2008)</td>
<td>No leader, no director, or no central causal mechanism coordinating the actions of the group. Cues of this characteristic can include language about all particles moving together, changing speed for no reason, or other similar language that implies no leader.</td>
</tr>
<tr>
<td>Leader as a coordinator</td>
<td>Centralized</td>
<td>Resnick (1994), Levy &amp; Wilensky (2008)</td>
<td>A leader, director or central causal mechanism coordinates or directs the movements of the members of the group.</td>
</tr>
<tr>
<td>Seeding</td>
<td>Centralized</td>
<td>Penner (2000)</td>
<td>Needing a seed to begin movement. This is related to the leader characteristic.</td>
</tr>
<tr>
<td>Levels confusion</td>
<td>Centralized</td>
<td>Wilensky &amp; Resnick (1999), Resnick (1994), Penner (2000)</td>
<td>Expect the phenomenon at one level to act the same way at another level.</td>
</tr>
<tr>
<td>Levels</td>
<td>Decentralized</td>
<td>Wilensky &amp; Resnick (1999), Resnick (1994), Penner (2000)</td>
<td>Different perspective levels or different grain sizes (e.g. macro and micro) acting differently (in terms of rules, patterns and behaviors) resulting in different motions or different behaviors at these different levels.</td>
</tr>
<tr>
<td>Randomness of many as constructive</td>
<td>Decentralized</td>
<td>Resnick (1994)</td>
<td>Randomness implies a lack of predictability. This plays an important role in self-organization, feedback loops, and seeding. Creating order.</td>
</tr>
<tr>
<td>Randomness of many as destructive</td>
<td>Centralized</td>
<td>Resnick (1994)</td>
<td>For example, randomness leads to things being “all over the place.”</td>
</tr>
<tr>
<td>No predictability of individual behaviors</td>
<td>Decentralized</td>
<td>Levy &amp; Wilesnky (2008), Jacobson (2001)</td>
<td>Individual actions or behaviors are unpredictable. This is related to randomness.</td>
</tr>
<tr>
<td>Removal of a few components will not influence the system</td>
<td>Centralized</td>
<td>Penner (2000), Resnick (1994)</td>
<td>Assuming that the central causal mechanism will not be influenced by the removal of a few components.</td>
</tr>
<tr>
<td>Removal of components will influence the system</td>
<td>Decentralized</td>
<td>Penner (2000), Resnick (1994)</td>
<td>For de-centralized processes, removing a few components or particles will influence the overall pattern. Maybe related to Threshold.</td>
</tr>
<tr>
<td>Negative feedback</td>
<td>Centralized</td>
<td>Resnick (1994)</td>
<td>Negative feedback leading to an “in control situations,” being constructive. A response to a perturbation that decreases the magnitude of the perturbation.</td>
</tr>
<tr>
<td>Negative Feedback</td>
<td>Decentralized</td>
<td>Resnick (1994)</td>
<td>A response to a perturbation that decreases the magnitude of the perturbation. Negative feedback leading to an “out of control situation.” Being destructive.</td>
</tr>
<tr>
<td>Positive feedback</td>
<td>Centralized</td>
<td>Resnick (1994)</td>
<td>A response to a perturbation that increases the magnitude of the perturbation. Destructive: positive feedback leading to out of control situations. Closely related to local perturbations.</td>
</tr>
</tbody>
</table>
Appendix D. Sample of two indicators hypothetically applied to all seven problem contexts

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Levels confusion</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Code</td>
<td>Centralized</td>
<td>Decentralized</td>
</tr>
<tr>
<td>Description</td>
<td>Expect the phenomenon at one level to act the same way at another level.</td>
<td>Different perspective acting differently (in terms of rules, patterns and behaviors) resulting in different behaviors at different levels.</td>
</tr>
<tr>
<td>Sand Dune</td>
<td>Sand particles and dunes moving in the same direction</td>
<td>Dunes moving one direction and sand particles moving another direction</td>
</tr>
<tr>
<td>Traffic Jam</td>
<td>Jams and cars moving forward</td>
<td>Jams moving backwards, cars moving forwards</td>
</tr>
<tr>
<td>Birds</td>
<td>individual birds and the entire flock of birds are all moving in the same direction.</td>
<td>some birds are moving to the left, but the entire flock is moving up.</td>
</tr>
<tr>
<td>Fish</td>
<td>all the individual fish and the entire school are moving left</td>
<td>some fish are moving to the left, but the entire school is moving up.</td>
</tr>
<tr>
<td>Virus</td>
<td>Everyone gets infected with the virus at once.</td>
<td>Some individuals are getting sick, some are getting better, but the outbreak of the epidemic is getting worse (or better)</td>
</tr>
<tr>
<td>Forest fires</td>
<td>All trees catch on fire at the same time.</td>
<td>Some trees are catching fire, some have burnt to a crisp, but the overall fire is winding down (or getting worse)</td>
</tr>
</tbody>
</table>
## Appendix E. Sample lists of each instance of the convergence to a limit explanatory pattern

<table>
<thead>
<tr>
<th>Student Name</th>
<th>Academic Background</th>
<th>Problem Context</th>
<th>Summary</th>
<th>Kind of equilibrium</th>
<th>Coded As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abhi</td>
<td>9th</td>
<td>Birds</td>
<td>for a while the birds are scattered, then they fall into formation. If they fall out of formation, it is more difficult to fly and then they fall back into formation because it's easier to fly.</td>
<td>converging to a limit</td>
<td>Convergence to a Limit</td>
</tr>
<tr>
<td>Abhi</td>
<td>9th</td>
<td>Diffusion</td>
<td>If you stirred the liquid with a spoon, it would be a more even mixture, the consistency would be more even. It could do it naturally over time, but a spoon would make it faster.</td>
<td>converging to a limit</td>
<td>Convergence to a Limit</td>
</tr>
<tr>
<td>Melissa</td>
<td>undergrad</td>
<td>Diffusion</td>
<td>&quot;Ahh, diffusion, the gradual movement of molecules from an area of high concentration to an area of low concentration, the textbook definition. So, the tendency of things to mix, and become, ahh, spread their concentration equally over a given area or volume.&quot; This sounds like converging to a limit</td>
<td>processes of coming to an equilibrium at a macro level.</td>
<td>Convergence to a Limit</td>
</tr>
<tr>
<td>Damien</td>
<td>grad student</td>
<td>Sand Dunes</td>
<td>a sense of there not being one sand dune in the desert in isolation and instead there being many small sand dunes. For a while a big dune could form in one place. &quot;should be that way.&quot; There is a process to destroy big sand dunes. Then questions the prior intuitions.</td>
<td>The size of the dunes oscillation around and/or converging to a limit</td>
<td>Convergence to a Limit</td>
</tr>
<tr>
<td>Damien</td>
<td>grad student</td>
<td>Sand Dunes</td>
<td>I asked about a bunch of sand dunes that are all the same size. Below the sand dune peaks, no wind. Above the sand dune peaks, there is lots of wind. Sand dune that momentary get bigger get cut off by the high winds. This is a mechanism to make dunes all similar sizes. Damien: an stable too thin sand dune could form, if another one gets bigger, could capture more sand. Lauren: tell me more about stable vs. less stable. Damien: A tower of sand can fall down. Small dune, little pile, is very stable. Many possibilities in between.</td>
<td>This is all about the mechanisms and process that create the size of the dunes oscillation around and/or converging to a limit.</td>
<td>Convergence to a Limit</td>
</tr>
<tr>
<td>Keaton</td>
<td>grad student</td>
<td>Traffic Jam</td>
<td>Limiting behavior, more cars on the road, eventually they have to slow down.</td>
<td>Cars speeds converging to a limit?</td>
<td>Convergence to a Limit</td>
</tr>
</tbody>
</table>
Appendix F. Transcript of Laurel’s Complete Sand Dune Discussion

1 Lauren Wanna move onto another topic?
2 Laurel Ok.
3 Lauren So, a little story. Imagine that you have, you live in a house in a desert. And one day you go out of your house, and you walk, half a mile south, and there is a sand dune.
4 Laurel umm
5 Lauren And so, you don't go back a couple months, and then you go back a couple months later, and
6 Laurel Go back home or go back to the sand?
7 Lauren Sorry, you go back to the sand dune a couple months later. And, after not having been there for a couple months, and suddenly you notice that the sand dune has moved about 50 feet, and you notice this because you know, there was some type of marker there. How does that happen? [00:39:07.24]
8 Laurel Does it happen? [Laughing] So I guess, is this a hypothetical thing that never happens?
9 Lauren [in audible "ummm"]
10 Laurel I feel like it's umm, it's one of those puzzle game where you have to like ask, you know those, where someone tells a story and you have to ask all the questions to find out. But. Like, so
11 Lauren I'm not trying to tell
12 Laurel It does like, matter if it’s half a mile south?
13 Lauren No
14 Laurel Or it doesn't?
15 Lauren no it doesn't matter that it's half a mile south
16 Lauren and it doesn't matter exactly how many months it is.
17 Lauren okay, that’s what I was wondering. okay.
18 Lauren No, this isn't meant to be a trick question. Or a puzzle.
19 Laurel or a calculation or something?
20 Lauren No, it's not a math problem. Not a numerical problem. [00:39:44.14]
21 Laurel Yea. Okay, okay, so you, so you leave your house, and then you, you know you walk and then you find the sand dune, and then, which is. A sand dune which is a like a 0 mound or hill made out of sand? Okay. And then you go home and then you come back later and it moved. [00:40:02.28]
22 Laurel I mean it's probably windy there.
23 Laurel But then, I don't know how,
24 Laurel I guess it depends on how big the sand dune is, could the?
Laurel: Cause I don't think the wind would blow the whole sand dune all at once.

Lauren: uhh

Laurel: But it could blow all the little, [pause] all the little, all the the little sand molecules, like whatever

Lauren: umm

Laurel: like little by little.

Laurel: But I don't know how they would all end up in the same place either;

Laurel: why wouldn't it just be flat?

Laurel: Like, cause If the wind was just blowing the sand around then it would just blow it around everywhere,

Laurel: you'd think,

Laurel: but then, I don't know why

Laurel: they would all concentrate in a form, like a big pile. You know. If the wind is blowing it. But

Lauren: So, say the wind is just blowing the sand everywhere,

Lauren: uhh

Lauren: what would you see? What would happen?

Lauren: [pause]

Laurel: Well, I mean, the sand would probably be going in a direction, right? I mean the wind.

Laurel: Well then you see the sand going in a particular direction.

Laurel: I guess you would see, like

Laurel: a lot of sand in the air [laugh & waves arms up and out].

Laurel: It would probably, I mean look like, from our perspective

Laurel: it would look like a cloud, right?

Laurel: Or something of all this sand, like all this sand, like, what was it called, the dust bowls, or whatever? So, but, I kind of imagine it like

Laurel: cause sometimes when the wind blows, it seems like things are kind of like whirl pooling everywhere [moving hand to mimic whirlpool motion]

Laurel: but then, but then then 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]

Laurel: maybe that's why, it all goes in the same direction, when the wind is blowing in a certain strength or something

Laurel: And then, it blows it all, kind of in the same area and makes them somehow reformulates [moves hands in a circular motion] that sand into like a new sand dune. I don't know.
Lauren: How would the wind reformulate the sand into a new sand dune? [moves hands in cyclical motions similar to Laurel's gesture].

Laurel: 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.

Laurel: So, then like, this top layer of sand [draws top layer of sand with a purple marker] would kind of get blown first, or whatever, or whatever, I don't know, [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 sand dune].

Laurel: 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] 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.

Laurel: 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]

Laurel: But then, I know that when it’s windy, it’s not like the wind is constant, it's always blowing in exactly this direction at exactly the same, exactly the same, like strength.

Laurel: because if it were that would make sense right?

Laurel: because then the purple would fly over here [gesture implies sand particles motion from as illustrated on the drawing] and the green would fly over here [gesture implies sand particles motion from as illustrated on the drawing] and then whatever, it would go in layers, some kind of layers or a stream like that.

Laurel: But sometimes it would be, not blowing as hard so then the sand wouldn’t go as far,

Laurel: or sometimes it would kind of change directions and then it would blow it into a different direction.

Laurel: I keep thinking about, I don't know if it was a joke or a story or something about like,

Laurel: you know if a bird comes and then takes one grain of sand and then dumps it. And then one grain of sand and dumps it, like, cause if that happened, then obviously, if you keep dumping them on top of each other it would be like, you know, when you dump whole bunch of sand and it makes like a cone shape [gestures implies dumping sand and it falling into a cone shape].
That would make sense.

But, I don't know how the wind, cause the wind the wind, cause the wind like that linearly, or like with just one piece of sand going over. So.

I don't know. [pause] So then would the, originally where there was a sand dune, it would just be flat or something? Or? Just shorter, and then there would be another sand dune.

I guess I was just assuming that, all the things from this sand dune would make the new sand dune,

but maybe it's like, 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.

I don't know. [pause] So then would the, originally where there was a sand dune, it would just be flat or something? Or? Just shorter, and then there would be another sand dune.

I don't know. [pause] So then would the, originally where there was a sand dune, it would just be flat or something? Or? Just shorter, and then there would be another sand dune.

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, maybe.

I don't know.

So, usually we don't see sand dunes isolated, usually you see lots of sand dunes.

and so, in that kind of case, where you know, there is a whole bunch of sand dunes, how does you know, one, you know, kind of, if you see one sand dune at one place at one point in time and you go back and it's not there and there is a new sand dune someplace else. How does that happen if there is, you know?

So there is just a lot of them and yea, you know, [gesture implies many sand dunes] okay.

yea, okay, I was thinking, of it as like the same sand dune. [gesture emphasizes direct movement of one sand dune]

But, maybe it's? Or, the same little hill.

Umm, yea, I've been to some sand dunes before, so I think I know like, but,

I guess, since the sand is like kind of loose [gesture implies loose sand], right? It's not like it's glued together or compacted or something [holds hands together].

Then when the wind comes, the sand will just freely, like the outside layer of sand will start, can just fly other places [gestures implies sand flying away] and then maybe that keeps happening as the wind keeps coming, then next, you know, the other layers of sand just keep, you know, disappearing or not disappearing but like, being taken off of that, and then it's like disappeared around [waving hand in and outward fashion to imply sand layers leaving the dune].

and then, maybe it's kind of by chance or something that like.
Cause I can imagine if there was a little pile of sand that somehow forms somewhere 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?

It would kind of join in [gesture implies sand hitting and stopping at the dune] in a way, with that like, little pile [holds hands together to emphasize a small pile of sand] and then it would start get bigger and bigger [gesture implies little pile getting bigger] and then more sand would, kind of [gesture implies sand joining the pile] I don't know if it would be like,

you know, it's flying along then hits it and then it stops there [gestures implies sand flying around and hitting something] and it then forming a bigger sand dune [gesture implies big dune].

and then if the wind blows that, then maybe it would dissipate too.

If that happened then. I guess I don't know it would originally start, other then, like.

Well, I have two ideas.

Maybe it's by chance that like, maybe some you know, some number, some vital number of sand molecules or whatever got all in one place [gestures implies sand particles all in one place] and then that was enough to start catching more [gestures implies catching more], more deliberately.

I don't know why

I'm thinking of it like. Like they all just happen to fall, but then once it gets big enough then it actually maybe the, it's big enough to kind of start stopping other molecules, or sand, which makes its bigger [gestures implies the sand dune getting bigger].

Or I was thinking maybe it's, it's probably more like, like as the wind, you know how, I was saying how the wind was like taking the outside layer or something, maybe it's like this big and then it starts doing that, and the dune gets smaller [gestures implies that a big dune gets smaller].

But it wouldn't get flat [gesture implies a flat area] probably,

there would still be a little, you know a little cone there [gesture implies a small cone] yea

and then maybe that would start collecting more [gestures implies the small cone is collecting sand] and growing [gestures implies the dune is getting bigger] and then the wind could take it away get smaller [gestures implies the
dune gets smaller] and like this.

102 Laurel So, maybe it's not like, 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 again and again] possibly. [00:48:56.16]

103 Lauren you mentioned at one point that it would like, the sand would stick to it. How does that work?

104 Lauren How does that work?

105 Laurel Yea. Well, I know that at the beginning I said that like, because it's not stuck together so then the outside layer can like, fly away right [gesture implies sand flying off the dune].

106 Laurel So then, umm, but then when the sand is blowing, like, if there is already like, part of a hill, or something

107 Lauren yea [00:49:23.04]

108 Laurel then. Well, I guess the way I was thinking or it,

109 Laurel lets say there was an individual piece of sand and it’s being blown by the wind this way, and then there is already a sand pile, and then if it [non-verbal hitting noise] hits it it’s not going to be able to keep going, so it would like, it would kind of collect there. [00:49:39.29]

110 Laurel But then I guess since it wouldn't like, [pause], sorry it wouldn't like, I guess, that’s what I mean by

111 Laurel it sticks, it would stop moving so then it would join the little pile there,

112 Laurel and then, but then the wind could come and it’s not stuck there so it could be blown away [gesture implies sand blowing away from the dune]. [00:49:58.13]

113 Laurel So then, maybe it depends on like, cause if things are being, like joining in and some things are being blown away, I'm thinking that if that’s happening equally then it's just never going to change. Right? [00:50:14.27]

114 Laurel Gona be the same size.

115 Laurel But then, the fact that you said, like, if it seems like the hill you saw before is gone and now it’s in a different place,

116 Laurel that makes me think that it doesn't happen completely equally, that like, you know, like two things of sand fly away and two come like that. [00:50:34.24]

117 Laurel But maybe it’s more like at some points more is being added then is being taken away, and then at other points the wind somehow is taking more, more sand away than is joining that little pile I guess that’s it. [00:50:55.07]
Appendix G. Transcript of Keaton’s Complete Sand Dune Discussion

1 Lauren So, imagine you live in the desert, pretend you have a house in the desert, and one day you take a little walk outside of your house. And, you walk for maybe a mile or half a mile, and you get to some area in the desert where there is a whole bunch of sand dunes together. And, you notice next to one of the sand dunes there is some type of permanent marker, like a flagpole or something permanent. // Keaton: okay // And you go home and you come back like 6 months later, or a couple month later, after not having been there. And the marker, the flag pole is still in the same place, but there use to be a sand dune next to the flag pole, and there is no longer a sand dune, and you notice a new sand dunes has appeared maybe 50 or one-hundred feet away. How does that happen? How does a sand dune apparently move? [00:33:22.15]

2 Keaton Well, it's all because of the wind, right?

3 Keaton So, you have these little pieces of sand and they are blowing all over the place [gesture implies sand blowing all over the place]

4 Keaton and if you have like there is a dune [gestures implies a dune in front of him]

5 Keaton the wind is blowing here. [gestures wind blowing into the windward side]

6 Keaton Like. At the front of it [points to windward side],

7 Keaton the wind is hitting all the sand, going all over the place

8 Keaton and then, at the sides [points at side so the dune] the,

9 Keaton the sand, if the wind is always blowing this direction [gestures wind going in the windward direction] so more likely,

10 Keaton it's more likely for the sand to go this way [points in the direction of the wind towards the lee side of the dune]

11 Keaton than that way [points in the direction opposite the direction of the wind].

12 Keaton Cause the winds blowing it.

13 Keaton So, like, all the sand moves from one side to the other side [gestures to show moving from the windwards side to the leeward side] and then,

14 Keaton on the lee side of the dune, the, like, it's protected from the wind, so it builds up there [points to lee side of the dune],

15 Keaton it's not blowing around by the wind so much. And so it's basically, like, the, yea, [00:34:08.22]

16 Keaton it's only blowing the surface of the dune, not the inside.

17 Keaton But eventually as more and more of the sand disappears here, like, more the inside gets exposed so it's like constantly going like this [gestures in a cyclical motion] kind of. It's coming out one side, and like building up on the other side so the dune just moves in the direction of the wind. [00:34:30.00]
Lauren: How does the wind like, how does the wind make the sand come up from one side?

Keaton: All these little grains of sand that are not connected and not stuck in place. So they are pretty small so the wind can just blow them around, so, yea, like, if there are grains of sand at the top they get blown off to the ley side, and if it's on, you know,

I guess if it's, if the grain of sand is right where the wind is hitting it, it doesn't tend to go anywhere.

[00:35:00.14]

Keaton: But like, if it's on one side or the other, you know, the wind will just blow it around the dune. Like it's all coming this way and all the sand is moving up and over and around the dune to the lee side in all these different directions, to the lee side.

Lauren: I see, okay.

[00:35:15.20]

Lauren: So, imagine, instead of a sand dunes moving, you notice that, one sand dune, two sand dunes next to each other, over the six months, one had gotten smaller over the six months and one had gotten bigger. Like how might a sand dune get bigger or smaller?

[00:35:31.06]

Keaton: Hmm, that's a good question. So if the wind is stronger in a certain place for some reason, then it will blow more of the sand away from the dune. So, like, if,

let me think, if one were like shielding the other one. Say the wind is blowing this way, then this will be protected from the wind by this one, slightly.

And so, like sand will get blown off of this one into that one. And this will get bigger and this will get smaller. I think that's right.

[00:36:04.18]

Lauren: So, tell me about this, how would, the dune getting bigger? So there is sand somehow being blown onto it? Or?

Keaton: Well, let me think, so. So the wind is blowing around the dunes, so there is going to be like, if the wind is hitting this side there will be a lot of here, there is not gonna be wind between the two dunes, as much.
So sand will tend to build up in here and it's like, especially on this side of the dune. Cause like, this dune, this side of this dune is getting blown by the wind all the time. There is much less wind here. So it builds up. Sand is building up on the ley side of all the dunes, but this dune is protected. It's also building up on the windward side. So, maybe make sense. It would grow in both directions, instead of growing in one direction and shrinking in the other. I don't know if that really happens, but it makes sense to me.

Lauren Okay. Okay.

Keaton I don't know [gestures]. Do dunes move that way or do they move the opposite direction?

Keaton Cause like the sand all around the desert, right? So wind is getting, so the sand is getting blown this way, onto the dune [points at windward side] and then here it might be getting blown off of the dune [points at the leeward side].

Keaton So I might be totally wrong and the dunes actually move like into the wind [points in direction of the wind flow]. I don't know which is the right answer.

Keaton Cause, like, there is way more sand in the whole desert than there is than sand just in that dune. So, it could be that sand is always getting blown toward this side of the dune [points at windward side], and getting blown away from this side [points at leeward side]. So it moves into the wind. I'm not sure which is the real case.

Lauren L: So, talk me through, how does the wind blow sand in each of these cases?

Keaton It blows it around. Like, if there was a big flat desert //

Lauren yeah //

Keaton and the wind was blowing across the surface, and if pieces of sand are on the surface, you know, the wind hits it and it gets blown. [gestures in the direction of the wind]

Lauren So in that case, there is some sand, the wind is hitting the sand, and the sand is moving? [gestures to imply sand moving in the direction of the wind]

Keaton Yeah

Keaton Let me, does that make sense, yeah?

Keaton The sand is all moving this way [points with right hand to the left side] but it could be possible that the dune is moving the other way [points with left hand towards the right] cause like it keeps getting made of different sand. Right?

Keaton Just cause the sand grains are going one way [points with right hand towards left], doesn't mean the dune has to go that way.
So, it could be that all the sand in the desert is getting blown onto this windward side of the dune and getting blown away from the leeward side, and it actually moves this way [gestures with right hand towards the right].

Yeah, I think that’s probably, more likely, now that I think about it. Okay.

What would happen if you had wind going, say, a whole bunch of different directions?

Okay, so if it were going all directions, equally likely, then obviously the dune wouldn't move any particular direction. I guess the question is just like, would it get larger or smaller?

I guess there must be some equilibrium size. Or, would it be? Yeah, cause dunes exist right.

If winds caused them all to get smaller than they wouldn't exist. But, why would there be an equilibrium size? A really huge dune, and I don't know, why aren't there any huge dunes? I don't know.

So, before you were explaining it with just wind going in one direction, say you had a situation where like wind went like one direction in the morning or one direction in the afternoon?

Okay.

Or, like rather than think about a whole bunch of different directions, lets just think about two directions.

okay, okay, yes, lets say it alternatives.

yeah, sure.

Then, then, would it get stretched out this way [pens hands apart] I think it would get stretched out, cause it,

if the wind is blowing from the left [points to left with right hand], as often as from the right [points to the right with left hand]. But it's not blowing the other direction [points straight ahead, to signify that it is not left or right], then a grain of sand, it's gona be, move left and right a lot [moves right hand left and right], but not move in the other direction as much [moves right hand forwards and backwards]. So if all the sand is moving this way [moves both hands left and right], it seems like all the sand dunes would get stretched out as much and these lines [pulls hands apart].

But then again, at the beach, the wind is always blowing toward land [points with right hand in left direction] or toward the ocean [points with right hand to the right], but the dunes seem to be, like, parallel to the beach [pulls hands apart] instead of perpendicular.

So I don't know why that is. I never really thought about it.

Let me think. Maybe thats wrong. Maybe the dunes, like, go perpendicular to the wind, but why would that happen? I don't know.
Lauren: Where have you? Are you thinking of some particular dunes?

Keaton: Well, yea, at the beach in Florida, where I'm from. I remember like, I think, I remember the dunes, here's the beach [holds left arm straight in front], the dunes, the wind at the beach is always going this way or this way [points with right hand in left and right direction, perpendicular to the direction that the left arm is pointing].

Keaton: but the dunes are more spread out in this direction. [gestures to imply parallel to left arm/beach]

Keaton: That contradicts what I said earlier. I don't know, it's complicated. [gestures while NOT speaking] [00:42:15.02]

Keaton: Yeah, maybe what I said before about //

Lauren: Yeah? //

Keaton: like the sand, move in the direction of the wind [back and forth hand motion in a sweeping direction with left hand], so that the dunes spread out that way [both hands moving outwards], is wrong.

Keaton: Because like, in the way the grains of sand move [motions with left hand], could have nothing to do with the way the dune as a whole moves [motions with right hand].

Lauren: Right.

Keaton: So

Lauren: Tell me more about that, like why, how does that work? [00:42:37.20]

Keaton: Well, you know like, like, as, before with the traffic jam, like you have these cars and like the cars could be moving all this way [points to his left], but it could be a wave of cars moving that way [points to his right] because // Lauren: Right//

Keaton: more cars are getting into the jam on this side [points to the right] than are leaving on this side[points to the left].

Keaton: So, even through the cars are moving this way [points to the left]the wave can be moving this way [points to the right].

Keaton: Dunes could work the same way. Right. Cause, right, a dune, it's not like all these grains of sand are in the dune, and they will always be part of the dune. Cause like, the dune a month from now is going to be made up of all different sand than the dune now. So. Like this ephermal things.

Lauren: You said a dune a month from now will have different grains of sand?

Keaton: Right.

Lauren: I see

Keaton: All the grains of sand can be blown away [gestures to his right] and more of the sand comes [gestures from his left], it gradually gets replaced by more sand and you know. It's like the same dune, even though it's made of all different sand.

Lauren: And you're defining the sand dune because it's?
Keaton: It's like continuous, right? As you look at it over time, it's not like the dune disappears and then reappears //

Lauren: Right. Right.

Keaton: It's always there, right. You know, like your body, you eat food, and so eventually after some years, like, all the molecules in your body have been replaced by molecules of food you ate but you're still the same person.

[00:43:51.24]

Lauren: Right. Right. I see.

Lauren: Yeah. Yeah. When you have a dune and there is sand over a month say, such that at the end it has new grains of sand and there is some sand leaving and some sand coming?

Keaton: Yeah.

Lauren: How does it work when you have, tell me more, it sounds like there is two different things going on?

Keaton: Yeah.

Lauren: How does that work?

[00:44:19.17]

Keaton: So, yeah, I think that what I said in the beginning, moving the direction of the wind, that's totally wrong.

I think it moves in the opposite direction of the wind because, like, the reason that a grain of sand would stick onto the dune, is blown toward the dune, and then it's like, cause if the wind is blowing across than it's going to blow the sand like away. If the wind is blowing toward it, then the sand is not going to go anywhere, on average.

So yeah. It seems like, if the wind is blowing sand toward the dune it's going to accumulate there. And if the wind is blowing away from the dune the sand is gona, you know, come off the dune and blow down wind. Right?

[00:44:58.24]

Lauren: So how does the wind blowing towards the dune and away from the dune, influence whether or not the dune gets bigger? Or smaller? Or stay the same?

Keaton: All right, so, if the wind is stronger on the windward side [points to windward side of his dune] than it is on the leeward side [points to leeward side], than it means that its gona grow faster [emphasizes the windward side growing] than it shrinks [points to leeward side]. So it will get bigger.

Keaton: So lets go back to the two dunes, the wind is blowing this way, then the wind is going to be stronger over here, so this dune is going to increase and this dune like the wind is weaker here and stronger here, so, it's gona decrease. The opposite of what I said before.

Lauren: I see.

Keaton: Totally wrong //

Lauren: It's okay

Laughter
Lauren: And how might a dune stay the same size in this?

Keaton: Well, lots of reasons like, if the wind is just like blowing in all different directions. If you had the two here and the wind is blowing this way as often as this way and there is symmetry, and like neither one is gone get larger or smaller. Than the other one.
Appendix H: Additional Explanations that were mentioned in Chapter 5.

Sarabeth’s Traffic Jam Threshold Explanation

1. Sarabeth: Some one slows down and then slows down a little bit more
2. Lauren: Uhh
3. Sarabeth: and then people slow down even more.
4. Lauren: Umm
5. Sarabeth: I guess, and then, just makes it hard to start up cause then when you slow down, it causes the other person behind you to slow, react to your slowing down and then slow down themselves.
7. Lauren: So like if I stopped the person behind me has to react to me stopping and they have to slow down. And then stop
8. Sarabeth: and then it takes time for you to start again and then it takes time for them to see you starting and then
9. Lauren: any other ideas about what causes traffic jam?
10. Sarabeth: Well, there is usually some traffic jams during rush hour when everyone is trying to get home, and there is an accident and people slow down to watch what is going on. I guess like rush hour if there is a lot of people trying to go into the same small space, cause if there is like five lanes of traffic and like two coming in and then there is more people trying to get on and everyone has to slow down.
11. Lauren: I see. Why is that?
12. Sarabeth: Well if, you know how its a one car goes here and one car goes there
13. Lauren: Uhh
14. Sarabeth: This car has to slow down to let this car come in
15. Lauren: I see
16. Sarabeth: slow down now
17. Lauren: I see

Jared’s Traffic Jam Threshold Explanation

1. Jared: And the more cars on the road, the more likely it is that someone, like, a few people would be going slowly and then they will trigger this whole thing.
2. Lauren: Oh, I see
3. Jared: But, it's not necessarily, you know, there is this many cars making journey's so the're will be a traffic jam. But, the more cars there are, the more likely it is to start, so, there is lots of cars, it is very likely that there will be a traffic jam.
4. Lauren: I see
5. Jared: Sometimes there is just too many people using the roads and they're just isn't enough space and then it's back to back, and then, umm, yeah, is that okay?
6. Lauren: Yeah
Nathan’s Traffic Jam Threshold Explanation

1. Nathan: but, again in principle people could go exactly one speed until it, until it gets them, but most drivers don't make decisions that way.
2. Lauren: so, if people were to do that then, say, if everyone went at the same speed, or one speed constantly. Would then traffic jams not form?
3. Nathan: Probably, it sort of depends on the density. If there are few enough cars on the road then you can imagine that there is enough space that between cars on the highway going at 55 mph such that, anyone could join and regardless of what speed they were actually going, it would be very unlikely that before they reach 55 they were hit by a car coming behind them. But as soon as traffic density gets higher, rush hour. Then you would reach a point where a car going slower than you would invariably come across your path over time and if you refused to slow down, then you'd collide and then you'd be forced to slow down, by physics. Umm. So, I guess if you put a certain density of cars on the road and you, you insist that some of the cars have to be going slower before they reach the cruising speed then, it is impossible to maintain
4. Lauren: Yeah
5. Nathan: the same speed throughout the highway.

Melissa’s Forest Fire Threshold Explanation

1. Lauren: So, say you’re watching this forest fire for a while and you notice that over time it actually, gets bigger and then, eventually it gets a little bit smaller. How does that happen? How does that get smaller, eventually?
2. Melissa: I think that once it reached a certain point it was, that stuff became harder to burn
3. Lauren: Uhh
4. Melissa: Or harder to pass the fire on.
5. Lauren: Oh, I see
6. Melissa: So, if it's like, it can't burn the stuff, so, the flames won't you know, if it can't burn, the flames, it won't it can't move past it, so you just can't see something, so you know, it's like, I'm going to skip over you and go somewhere else, so if it meets them and it can't burn, then that's the natural boundary, so, it will, kind of, stop there, but then, while it's like, on, at that boundary, it will, eventually use up all it's fuel, and it will go out, and so, as it keeps using up more and more fuel, the boundary is going to like,
7. Lauren: Oh, I see
8. Melissa: recede, like all this fuel is gone.
9. Lauren: What kind of natural boundaries are you thinking of?
10. Melissa: I don't know if it's something like that just be burned, or like, if it reaches like a river or something, like, then it can't go across the water, so like something that it just can't like, not just like a cement wall.
11. Lauren: Right
12. Melissa: A cement wall could do it also,
13. Lauren: Right
14. Melissa: but like something that is stopping it that it can't burn, it has to stop there and so once it stop there, it can go no where else, stay there or recede back in, or out.
Abhi’s Convergence to a Limit Diffusion Explanation

1. Lauren: Can you think of anything else that would influence umm, how the water and the juice molecules mix together?
2. Abhi: If you stirred it with the spoon, then it might be a more even mixture.
3. Lauren: Oh. How would that work?
4. Abhi: The consistencies could be different. The waters and the juices.
5. Lauren: So, like, if I put a spoon into the coffee and stirred it
6. Abhi: Yeah
7. Lauren: Like, wouldn't that, like the consistency before I stirred it, or the consistency after I stirred it?
8. Abhi: After you stirred it, cause, so, for example, you might have all the juice molecules down here. Before stirring it. And the water molecules all up here. But, once you've stirred it, it would all be together.
9. Lauren: I see
10. Abhi: this
11. Lauren: So, would you need us, would you need like a spoon to stir it to make it go faster?
12. Abhi: It could go from this to this over time, but a spoon would make it faster.
13. Lauren: Oh, so how would it, if it just like happened without a spoon, like over time, how would it go from here to here?
14. Abhi: The water molecules might sort of drip into the juice molecules. So, that’s, so it might happen.
15. Lauren: So, like, this water is green and flat... okay, so like, a couple black water molecules would move over?
17. Lauren: I see. Umm, and, is that all that happens, or? What happens after that?
18. Abhi: Well, the, you, green juice molecules might move up.
19. Lauren: And then, how does it get to the rest?
20. Abhi: A few green juice molecules are really move up and a few black ones moved down and, so, that’s, so you have a more even mixture.

Samuel’s Traffic Jam Periodic Motion Explanation

1. Samuel: There is also this kind of interesting experiment I saw somewhere, they just had a, a bunch of cars driving around in a circle, in theory they should also just, like a merry go-round, go, right, but they found out in time like, the cars would eventually get jammed like, this car, like eventually it would look like this, all the cars like that. Kind of an interesting,
2. Lauren: How, why did that happen?
3. Samuel: So, I guess, the first car would slow down a little bit cause it might be, too close to the car in front and that would cause the other car, the back car to slow down too. Because he would get closer, but, yeah, eventually, I think it was called like, like a shock wave effect, when they were observing this thing.
4. Lauren: How does the shock wave, work?
5. Samuel: Let me see. So, if you have like, I guess like some jelly or something, if you hit it [gestures] the jelly would compress here, [moves hands]
6. Lauren: Oh, I see.
7. Samuel: Umm
8. Lauren: Okay, so like the cars are
9. Samuel: The cars, maybe I can draw a better picture [drawing], so cars here would be close together, so, this car would speed up, umm, hmm,

10. Lauren: So is it like the cars will sometimes be compressed and sometimes not be compressed?

11. Samuel: Right, right, so I guess that’s kind of like the stop and go of traffic, really annoying.

Kyle’s Traffic Jam Periodic Motion Explanation

1. Kyle: So, I think there are, traffic formation is, due primarily to the inability of a person to accurately control the following distance.

2. So, my sort of thoughts on this, I haven't done any real research on this. as you, lets say you have a long chain of cars, all equal distance apart from one another.

3. and you, you put real people driving those cars and you say maintain the same speed. Fluxciations about those speeds, umm, will not propagate with infinite speed through the, through the chain.

4. So if you take a, if you have a bunch of cars all moving together, consider a frame in which they are stationary. And, cars can move forward or back and they are trying to maintain the distance between these cars. And they are also trying to maintain the same speed.

5. But, there is fluxciations, because people are inattentive and bad drivers. And, so, you know, and this is just for people who have been given the instructions to stay in the same, but this person may slow down a bit, which will cause this person to slow down and this person to slow down. So the, the idea of a wave formation is very, fairly straight forward, right, now for instance in order to make this simpler, put everybody on a rink, right, umm, that wave will keep propagating through the system in both directions, and at times, umm, that wave will, there will be constructive interference due to this, because if you have a person in front of you who, umm, like slows down a little bit, it will take you a little bit of time before you can slow down again, so then, umm, as you, in that time that person gets closer, then the person behind you, and now you're going a little bit slower, the person behind you has to do the same thing and they get closer to you and then if you have a fluxciation you get closer to this person and then gaps begin opening up elsewhere and, people start getting closer and closer together. And, so you sort of have this spontaneous traffic jam.

6. and, interesting the wave speed either, the typical highway speed is about 30 mph traffic is probably backwards at about 30 mph. Umm, which, you can see this happening fairly easily. If you watch a highway.

7. I think the reason for that is that people tend to, tend to follow to closely when they are driving so, in high traffic densities you leave about, umm, when your going very, very slowly, you leave like a car length between two people, sometimes less, but when people are going faster they should leave more car lengths, but generally they only leave one or two or, lets say they leave two or three car lengths, but then when they are umm, if the traffic jam forms that will decrease down to a third of the distance, so if they are going 80 mph a third of that is like 27 or 36 or something. So they will, the speed of propagation depends, very critically on how fast they are moving and how much that distance is changing. So, traffic jams are horrible horrible things.
# Appendix I: Transcription Norms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>//</td>
<td>Interruption</td>
</tr>
<tr>
<td>…</td>
<td>Excerpt deleted</td>
</tr>
<tr>
<td>[pause]</td>
<td>Pause of any noticeable length</td>
</tr>
<tr>
<td>[explanatory text]</td>
<td>Explanatory text. Often used to describe a gesture.</td>
</tr>
</tbody>
</table>