Some Assembly Required: How Scientific Explanations Are Constructed During Clinical Interviews

Bruce L. Sherin[1] Moshe Krakowski,[2] Victor R. Lee[3]

[1]*School of Education and Social Policy, Northwestern University, Evanston, Illinois*
[2]*Azrieli Graduate School of Jewish Education and Administration, Yeshiva University, New York, New York*
[3]*Department of Instructional Technology and Learning Sciences, Utah State University, Logan, Utah*

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Abstract: This article is concerned with *commonsense science knowledge*, the informally gained knowledge of the natural world that students possess prior to formal instruction in a scientific discipline. Although commonsense science has been the focus of substantial study for more than two decades, there are still profound disagreements about its nature and origin, and its role in science learning. What is the reason that it has been so difficult to reach consensus? We believe that the problems run deep; there are difficulties both with how the field has framed questions and the way that it has gone about seeking answers. In order to make progress, we believe it will be helpful to focus on one type of research instrument—the clinical interview—that is employed in the study of commonsense science. More specifically, we argue that we should seek to understand and model, on a moment-by-moment basis, student reasoning as it occurs in the interviews employed to study commonsense science. To illustrate and support this claim, we draw on a corpus of interviews with middle school students in which the students were asked questions pertaining to the seasons and climate phenomena. Our analysis of this corpus is based on what we call the *mode-node* framework. In this framework, student reasoning is seen as drawing on a set of knowledge elements we call *nodes*, and this set produces temporary explanatory structures we call *dynamic mental constructs*. Furthermore, the analysis of our corpus seeks to highlight certain patterns of student reasoning that occur during interviews, patterns in what we call *conceptual dynamics*. These include patterns in which students can be seen to search through available knowledge (nodes), in which they assemble nodes into an explanation, and in which they converge on and shift among alternative explanations. © 2011 Wiley Periodicals, Inc. J Res Sci Teach 49: 166–198, 2012
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In the literature on the cognitive foundations of education, studies of science learning have figured prominently. A pivotal moment occurred in the early 1980s, with the publication of multiple studies documenting the misconceptions of physics students, and the resistance of these misconceptions to instruction (Clement, 1982, 1984; Halloun & Hestenes, 1985a, 1985b; Viennot, 1979). Over the following decades, a similar story has been repeated across a vast range of scientific subject matter. Although the nature of misconceptions may differ substantially across scientific disciplines, students nonetheless seem to exhibit misconceptions, and these misconceptions demonstrate resistance to instruction.[1]

Correspondence to: B. Sherin; E-mail: bsherin@northwestern.edu
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Furthermore, the reason for these difficulties is clear, at least in its broad outline. Students enter science instruction already possessing a substantial body of knowledge about the natural world. This ''commonsense'' science knowledge is the source of misconceptions, and it is also the reason for their resilience. The learning of science must involve the transformation of this existing knowledge to a form that can support more scientific understanding (e.g., Sherin, 2006).

This transformation process, whereby commonsense science knowledge is restructured, has been called *conceptual change* (e.g., Demastes, Good, & Peebles, 1996; diSessa & Sherin, 1998; Posner, Strike, Hewson, & Gertzog, 1982). Research on conceptual change in science is fundamentally concerned with two questions: (1) What knowledge of the natural world do students have prior to formal instruction? (2) How does this knowledge change as children develop and scientific expertise is acquired?

Given the centrality of these questions to cognitive research in education—even beyond researchers who focus on science learning—one might expect that the field would have reached consensus on answers. However, although over two decades have passed since the first spate of misconceptions publications, there are still profound disagreements. At the root of the debates is a general lack of agreement on an answer to the first question; the field has not reached consensus on some fundamental attributes of the nature of students' prior knowledge of the natural world (e.g., diSessa, 1993; diSessa, Gillespie, & Esterly, 2004; Ioannides & Vosniadou, 2002; Samarapungavan & Wiers, 1997; Smith, diSessa, & Roschelle, 1993; Vosniadou & Brewer, 1992). It is generally accepted that students *do* have a great deal of knowledge of the natural world, and that this knowledge is relevant for the learning of formal science. In addition, it is widely agreed that this knowledge consists of much more than a small number of propositions; prior knowledge is probably best thought of as consisting of some sort of conceptual system. What is at issue, however, are some gross properties of this conceptual system. Most notable in this regard is the question of coherence: Some researchers argue that commonsense science knowledge consists of relatively coherent theories or models. The work of Vosniadou and colleagues is a prominent—though highly nuanced—instance of this view (e.g., Samarapungavan & Wiers, 1997; Vosniadou & Brewer, 1992). But this view also appears in a number of other prominent forms (e.g., Carey, 1985; McCloskey, 1983). On the other side of the debate is the belief that commonsense science knowledge is fragmented. The work of diSessa is the most prominently cited instance of this alternative view (diSessa, 1993).

What is the reason that it has been so difficult to reach consensus in an area of research that has received such substantial attention? We believe that the problems run deep; there are difficulties both with how the field has framed questions and the way that it has gone about seeking answers. Thus, the purpose of this article is not to argue for one specific answer to the question of coherence; rather, our primary goal will be to argue that we need a new way of thinking about this question. We will argue that the coherence question needs to be re-crafted and given less scope, and we will attempt to point the direction toward a new empirical program that can help.

We see two types of problems with how questions of coherence have been framed and answered. The first type of problem is relatively easy to explain. At the most general level, we believe that we can actually be quite certain about the answer to the coherence question; sometimes students *do* possess coherent models of the natural world, and sometimes they *do not*. No researchers would contend that students never possess and exhibit such coherent models. Similarly, no one would claim that students possess and exhibit coherent models of *all* natural phenomena. It is likely that even a practicing scientist would appear inconsistent under the right conditions. Thus, in sum, the answer to the coherence question will depend on what population you are studying, and what subject matter you ask them about.

The second type of problem is a bit more subtle. In short, the issue is that the answer to questions of coherence seem to depend in a complicated manner on how ideas are elicited from participants. In order to explain more fully, we look closely at research that has been conducted in response to the seminal article *Mental models of the earth: A study of conceptual change in childhood*, by Vosniadou and Brewer (1992).

In their original research, Vosniadou and Brewer set out to study how young children understand the shape of the earth. To do so, they interviewed children ranging from 6 through 10 years of age. In these interviews, Vosniadou and Brewer asked questions of a variety of types. For example, they asked, simply, "what is the shape of the earth?" They also asked questions that required students to apply their understanding of the shape of the earth. For example, they asked "If you walked and walked for many days in a straight line, where would you end up?" In addition, they asked students to draw and discuss pictures.

Vosniadou and Brewer's results were clear, and in some respects surprising. They concluded that most of the students they interviewed answered questions as if they were applying a consistent model of the shape of the earth. Furthermore, these students could be assigned to one of six models that they identified, most of which were non-canonical. For example, some answered questions in a manner consistent with a model of the earth as flat, like a pancake, and others answered questions in a manner consistent with a model in which the earth is a hollow sphere, with humans living inside.

Recently, there have been a number of attempts to verify Vosniadou and Brewer's results (e.g., Nobes et al., 2003; Schoultz, Säljö, & Wyndhamn, 2001; Siegal, Butterworth, & Newcombe, 2004). In many cases, these attempts have yielded results that are at odds with the conclusions of Vosniadou and Brewer. Generally speaking, it has been found that, on the one hand, children can give answers that are more scientifically accurate than Vosniadou and Brewer's interviewees. On the other hand, these new studies have found that children seem to answer in a manner that is not coherent—individual children did not seem to be applying a single model. Thus, the patterns of answers given by children differ in detail, as well as in their general character, from those observed by Vosniadou and Brewer.

However, the reason for this discrepancy is not a mystery. It turns out that the newer studies conducted interviews in a manner that differed substantially from the techniques employed by Vosniadou and Brewer. As we indicated above, Vosniadou and Brewer employed a relatively open style of questioning, sometimes requiring students to draw inferences from their mental model. In contrast, the more recent studies have tended to employ a forced-choice method, in which students are asked to select from one of a number of possible answers. Second, the more recent research has made use of props in the form of three-dimensional models. For example, in some cases students have been shown models that represent possible shapes of the earth and asked to choose among them (Nobes et al., 2003; Siegal et al., 2004).

There seems to be relatively wide agreement that these methodological differences are the source of the discrepancies among research studies. In fact, researchers on both sides have conducted head-to-head comparative studies of different methods that confirm this interpretation (Siegal et al., 2004; Vosniadou, Skopeliti, & Ikospentaki, 2004, 2005). Thus, the discrepancies are not due to a failure of research teams to replicate each others' results. Rather, the core issue has to do with the relative merits of alternative ways of posing questions to students.[2]

This point has been made forcefully by Blown and Bryce (2006, 2010) and Bryce and Blown (2006). These researchers conducted a series of studies in which they looked longitudinally at the astronomy-related knowledge of a large number of participants in New Zealand and China. Generally speaking, they come down on the "coherence" side of the debate. But they also argue that the image that we get of commonsense science knowledge depends critically on the way questions are posed. To explain this point, they argue, in Bryce and Blown (2006), that it is helpful to think of children's ''conceptual structures'' as having three layers: *initial-intuitive concepts*, *traditional cultural-specific concepts*, and *scientific concepts*. They argue that, depending on how questions are posed, our interviews will preferentially reveal one or more of these layers. Thus, our interviews must be ''tuned'' to the layer that we wish to study. For example, they argue that if we wish to study the intuitive conceptual layer, then the use of concrete models (such as globes) must be avoided.

The Way Forward

Given the preceding observations, what is the right way for us, as a field, to proceed? We believe that the response to the first problem we discussed is relatively easy to state. Namely, we must not expect any universal answer to the coherence question. Rather, any answers we obtain will be at least somewhat specific to population and subject matter. But the second problem poses more of a challenge. It seems that, even for specific populations and specific subject matter, different methods yield different results. Given that observation, what is the right way forward?

Like Bryce and Blown, we believe that the first step is to acknowledge that the view of commonsense science that we uncover will depend critically on the methods we employ. But we also want to push a bit farther. First, we want to allow for the possibility that students' conceptual systems might be complex in such a way that Blown and Bryce's three ''layers'' would not constitute a sufficient description. Some researchers have argued—and we think Bryce and Blown would agree—that ''intuitive'' knowledge is ultimately integrated in expert scientific understanding (e.g., Sherin, 2006). Thus, there might not be distinct layers. Second, We realize that it mightnot be sufficient to think of any empirical method as ''tuned'' to the study of a part of commonsense science. Instead, we should recognize that no methodology provides unproblematic access to any part of commonsense science knowledge. Each type of interview provides a complex window into the commonsense science knowledge of students. Our analyses must be sensitive to this fact; we must know how to ''see through'' the data produced by interviews to the underlying student knowledge that generates responses. To do that, we need a better understanding of student reasoning processes in the circumstances we study; we must understand and model student reasoning as it occurs in the interviews we employ to study commonsense science.

This new stance holds the potential for escaping the debates that have occupied research on commonsense science knowledge for the last two decades. For example, rather than asking general questions about the coherence of commonsense science knowledge, we can move toward asking why, and under what conditions, students exhibit coherence in the interviews we conduct.

To be clear, we are not proposing a fundamental break with cognitivist tradition. Some researchers have taken the methodological dependence of student responses as suggesting a problem with the very idea that knowledge, in the form of mental representations, should be the output of our research (e.g., Halldén, Haglund, & Strömdahl, 2007; Halldén & Strömdahl, 2002; Roth & Middleton, 2006; Schoultz et al., 2001). In contrast, like diSessa (2007) and Vosniadou et al. (2005) we believe there are good warrants for continuing to understand our interviews as tools for uncovering commonsense science knowledge.

To further convey what we have in mind, consider the simple cartoon shown in Figure 1, which consists of four separate panes. In each pane, the student is seated on the left and the interviewer on the right, and the shapes in the student's head represent the relevant knowledge resources that the student possesses. In the first pane, the interviewer poses a question. In the second pane, the student gives a first answer, drawing on a highlighted subset of knowledge resources. The knowledge resources that are drawn upon, and the answer that the student

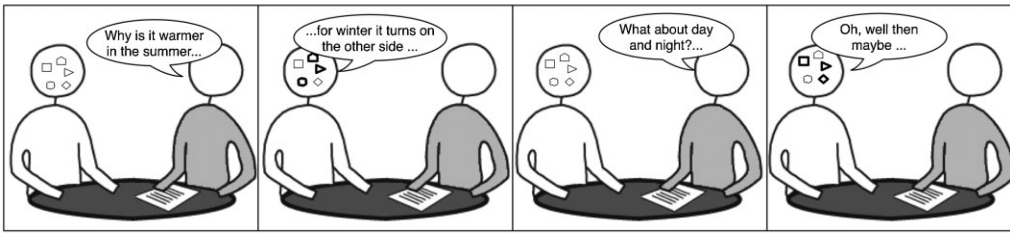

Figure 1. An interview interaction.

generates, depend on features of the interview context, including, for example, where the interview is conducted, who is asking the questions, and the history of the interview to that point. Next, in the third pane, the interviewer asks a follow-up question and finally, in the fourth pane, the student gives a new answer, drawing on a different subset of the relevant knowledge resources.

As analysts, our task is to draw conclusions about the knowledge resources the student possesses—the shapes inside the student's head. But, in order to make that determination, we have access only to the visible attributes of the interaction, including (but not restricted to) the various answers given by the student over the course of the interview. Working backward from these answers to the knowledge that generated them requires that we have some understanding of how a student generates answers from knowledge resources during an interview. More generally, we must be aware that, as an interview progresses, a sort of conceptual change will occur—an interviewee's thinking will change and drift, as they draw on and recombine various conceptual resources. Blown and Bryce (2006) refer to short timescale changes of this sort as "crystallization." However, we prefer the slightly more neutral term *conceptual dynamics*, since we do not assume that the short timescale will necessarily converge on any natural endpoint.

The purpose of this article is to begin a program of inquiry into the conceptual dynamics that occur over the course of minutes in interviews focused on science phenomena. Of course, what happens at any moment—what a student chooses to say—depends on many aspects of the interaction, including what knowledge the student possesses, what has happened to that point in the interview, and even subtle facial expressions of the interviewer. Thus, in the ideal case, our analysis of student reasoning would be embedded in a more expansive model of the interviewing interaction; it would include, for example, some treatment of the knowledge of the interviewer, and the conversational interaction between interviewer and student. Clearly, we cannot make a systematic study of all of these factors in a single journal article. In this manuscript, we will only be systematic in addressing the knowledge possessed and applied by the student.

Thus, in sum, this article will not attempt to provide an answer, pro or con, to the coherence question. Rather, we propose a new empirical program, focused on moment-by-moment conceptual dynamics in interviews, and a new set of research questions that go along with this program.

First Example

We now present a first example episode, selected to illustrate the sort of conceptual dynamics that are our focus. In our work, we have looked at students' reasoning about a range of science topics. In this manuscript, we will focus only on student reasoning about the Earth's seasons. This first episode is from an interview with an eighth grade student named Leslie.[3] In this brief episode, the interviewer asks Leslie "why is it warmer in the summer and colder in the winter?" Throughout this manuscript, we will present many examples in which students wrestle with this question. Here we consider just the first few moments of Leslie's attempt to provide an answer. Note, in this first response, how Leslie considers multiple possibilities as she tries to construct an answer.

00:00[4]	Interv.	First thing I want to know here is why is it warmer in the summer and colder in the winter?
00:07	Leslie	Um::: well, um, you know times savings? // you know? Like in the summer, when you have –
00:11	Interv.	// mm-hmm
00:13	Interv.	– Daylight Savings time?
00:15	Leslie	Yeah, daylight savings time. Um, in the summer we have more time, like, with, like, daylight and that's why it gets warmer. And like just with the circulation of the earth and like the axis that it's on just has to do with like summer and winter.
00:30	Leslie	And it depends on where we are on the earth. Like if you look at, umm, India, it's like toward the equator, you know? And so it's like always hot. And like if you go up north then it gets colder because there's just, like, I can't really say less sun, but it kind of has to do with that and there's just a lot of snow and, like ice cause it's colder up there.

In this episode, Leslie begins, in her first utterance, with a mention of "times savings," which the interviewer interprets, apparently correctly, as a reference to daylight savings time. Then, at time 00:15, Leslie fills in the sketch of an explanation: in the summer, the days are longer, and hence we receive more daylight, which makes our temperature higher.

But clearly there is more going on in these first few moments than is captured by this sketch of an explanation. First, there are elements of Leslie's answer that do not play any clear role in this explanation. For example, in her utterance at 00:15, she mentions "the circulation [sic] of the earth" and "the axis that it's on," which she says "has to do with like summer and winter." All of these statements might have been intended as elaborations of her length-of-day explanation. But she never made the connection explicit, and she did not make clear why these particular points deserved mention.

Second, Leslie actually seems to be making more than one argument. She begins by giving a length-of-day explanation in 00:15. But, in the latter part of her final utterance (which we have split off for convenient reference), Leslie appears to strike out in a new direction. She says that, in some manner, "it depends on where you are on the earth." She then elaborates on this point by stating that, in India, it's always hot, since it's near to the equator, and that it's colder "up north." It is unclear why, at this point, she has chosen to strike out in this new direction. From the point of view of the accepted scientific explanation, climate variation with latitude is not directly relevant to an explanation of the seasons. From this brief statement, we cannot tell whether Leslie, herself, believes it to be relevant, or whether she is just listing some additional material, that she knows is not directly relevant.

Finally, there is a little bit of a mystery in the last part of her final utterance. Leslie starts to say that it is colder "up north" because there is less sun. But then she appears to correct herself, saying that she "can't really say less sun," and instead attributes the lower temperatures to snow and ice. What is unclear, at this point, is why she has "corrected" herself in this way.

The point of the first example is to make the case that it is possible to see Leslie's thinking as it unfolds, and that it is possible to make inferences about the knowledge she is drawing on. It is clearly not the case that Leslie listens to the question and immediately knows what answer she wants to give. Instead, she seems to be working out her explanation as she speaks. Furthermore, though there is much that is puzzling about Leslie's responses, there is also a great deal that is visible. We can see some of the information that Leslie is weighing as she constructs her explanation, and we can see explanations that she considers and ultimately discards.

This is the core message of this manuscript; the conceptual dynamics in interviews of this sort are messy, but they are not impossible to fathom. Our goal is primarily to convince the reader of the reasonableness and potential fruitfulness of a focus on conceptual dynamics during interviews. We will attempt to show that there *are* real conceptual dynamics that occur over the seconds to minutes that elapse in a clinical interview, and that these dynamics are visible enough that we can make them an object of study. Furthermore, we expect that there will be a complex relationship between the knowledge students possess, and the manner in which a given interview unfolds. However, we believe that this relationship is not so complex that we cannot make it an object of study. This is the new program of research we are proposing; it is the program that we believe can help us to move beyond questions of coherence, and debates about the appropriate way to pose questions.

In what follows, we begin with the background needed to understand the remainder of the article. This includes a description of the data corpus we will draw upon, and the theoretical framework that we applied in our analysis. The next section describes the application of the framework to the data corpus. There we use our framework to describe patterns in conceptual dynamics in interviews. That section is the core of the article and it includes numerous examples. Finally, we summarize our conclusions and discuss prospects for future work.

Background

Data Corpus and Subject Matter

As part of a larger project, we assembled a corpus of videotapes of interviews with middle-school students on a variety of subject matter areas. For the purposes of this article, we draw on a small subset of that corpus in which students were asked about climate and season phenomena. In all, we have 54 interviews in which students were asked these questions. In assembling this corpus, we have been somewhat opportunistic. We conducted our seasons interview across a variety of school and research contexts. However, in all cases, the students were interviewed while in seventh grade, eighth grade, or in the summer immediately following eighth grade. Of the 54 interviews, 18 were conducted following a researcher-designed curriculum on global climate change (in which the seasons were not specifically discussed). Including these interviews would not substantively change our discussion. Nonetheless, in the sections that follow, we will not draw any examples from these 18 interviews.

Of the 54 interviews, 35 were conducted by the first author of this manuscript (Sherin). The remaining 19 interviews were conducted by graduate students who first watched videos of Sherin conducting the interview.

These interviews have been subjected to iterative review and coding by a team of researchers. Because of the wide variety of contexts in which our interviews were conducted, and the wide range of natural variability, we will not make any claims regarding the frequency with which various types of events occurred. Our goal here must remain more modest: to introduce a vocabulary for describing conceptual dynamics that can be evaluated and expanded upon by others.

Although our protocol allowed for some degree of improvisation by the interviewers, all of the interviews followed the same general skeleton. The interview segments always began with the interviewer posing the question ‘‘Why is it warmer in the summer and colder in the winter?’’ Then, after asking as many follow-up questions as were needed for clarification, the interviewer would ask the student to draw a picture to help with their explanation. Following this, the interviewer would again probe for elaboration in light of the picture that the student drew. In addition, we prepared a set of standard challenges that could be employed by interviewers when appropriate. For example, if a student's model did not explain why, at a given time, different parts of the Earth will experience different seasons, the interviewer had the option of asking: "Have you ever heard that when it's summer here it can be winter someplace else?" Following these questions about the seasons, the interviewer would then ask a series of questions about climate differences that exist on the earth: "Can you explain why it's warmer in Florida and colder in Alaska?"

There are a number of reasons that the subject area we are focusing on, season and climate variation, is well-suited for our presentation in this article. First, just about everyone has some knowledge of the seasons. All of the students we interviewed had some direct experience of the seasons. And many individuals have been exposed to some formal or informal science instruction that bears on the seasons. (Compare, for contrast, what the average person knows about quantum electrodynamics or cystic fibrosis.)

Second—and more interestingly—even with all of this familiarity, it is still very challenging for most people to correctly and adequately explain the seasons. The explanation of the seasons accepted by scientists is actually quite subtle, and is known to pose difficulties even for scientifically literate adults. Key to the explanation is the fact that the earth's axis is tilted with respect to the plane of its orbit, with the axis always pointing in the same direction throughout the orbital movement. For this reason, as the earth orbits, the northern hemisphere is sometimes inclined toward the sun, and sometimes away. When it is inclined toward the sun, locations in the Northern Hemisphere receive sunlight that strikes more *directly* than when it is pointed away.

Prior conceptions in this area have been moderately well-studied across a range of ages and contexts (e.g., Atwood & Atwood, 1996; Lee, 2010; Lelliott & Rollnick, 2010; Newman & Morrison, 1993; Sadler, 1987; Trumper, 2001). Looking across these studies, one finds significant variation in the prominence of different explanations of the seasons. It is clear that few people, even university students, can give a fully correct explanation of the seasons (Trumper, 2000, 2001). But the alternative models described, and the reported frequencies with which these models were observed, vary greatly across studies. We cite a single example that illustrates the complexity. Atwood and Atwood (1996) administered a written instrument to 39 preservice elementary teachers. In their analysis, they identified 16 distinct alternative conceptions of the seasons, only four of which were given by more than one student.

Although there is no simple consensus across research studies, there are some themes that emerge repeatedly. In their systematic review of astronomy education research, Lelliott and Rollnick (2010) examined 27 articles that focus on conceptions of the seasons. They note, for example, that almost all of these articles identified what they call the "distance theory," in which the seasons are explained by the earth moving closer and farther from the sun (Atwood & Atwood, 1996; Bailey & Slater, 2003; Sadler, 1987, 1998; Trumper, 2000, 2001). Other explanations that have been reported to appear with some frequency include explanations based on the earth's rotation (Atwood & Atwood, 1996), and explanations in which the earth somehow flips so that one pole, then the other, faces the sun (Atwood & Atwood, 1996; Trumper, 2000, 2001).

Our Language for Describing Knowledge

Moving forward with our analysis of conceptual dynamics in interviews requires that we have a language for describing the knowledge possessed by students and how that knowledge is assembled into explanations. Our own perspective is most in-line with scholars who argue that commonsense science is not coherent, or what has been called the *knowledge-in-pieces* perspective (diSessa, 1988, 1993; Sherin, 2001, 2006). For our purposes, we have explored the use of a relatively simple framework we call the *mode-node* framework. It is simple because it introduces only a small number of types of theoretical entities, and makes relatively few assumptions about the nature of those entities. The hope is that this simplification can make our task tractable, while still allowing us to gain some insight into the conceptual dynamics that are our focus. The framework has three primary theoretical constructs. We first introduce these constructs briefly, then elaborate in the paragraphs that follow.

Node. We think of knowledge as consisting of a large number of elements we call *nodes*. We intend our notion of node to encompass mental elements of many different types at multiple levels of abstraction. This includes, for example explicitly held propositional knowledge, as well as lower-level tacit knowledge, such as diSessa's p-prims (diSessa, 1993). However, we make the (dramatic) simplification of treating all instances of these diverse kinds of elements as a ''node'' within our analysis. Our group has attempted to exhaustively list and categorize the nodes needed to model student reasoning in our seasons interviews. Not surprisingly, this has proven to be difficult (Lee, Krakowski, Sherin, Bang, & Dam, 2006). Although we will present some analyses at the level of nodes, explaining the rationale for an analysis at this level is not the purpose of the present article.

Mode. Our second construct is a *mode*. A mode is an interconnected subset of nodes within a conceptual ecology that tends to be triggered in response to a particular class of cognitive tasks. Any node may participate in more than one mode. When the mode is triggered, a subset of nodes is selected, and each of these nodes is assigned an initial level of activation, with a pattern of weighted interconnections among the selected nodes. Furthermore, once the mode is triggered, *modal reasoning* can occur within the mental context provided by the triggered mode.

Dynamic Mental Construct. The *dynamic mental construct* (DMC) is the product of the modal reasoning. For example, in the case when a student is asked to explain the seasons, the DMC includes the current state of the explanation they have constructed. We use the word ''dynamic'' to highlight two features of this construct. First, the DMC is dynamic in the sense that it is a temporary mental state. In contrast, modes and nodes can be thought of as features of long-term memory. Second, we use the word ''dynamic'' to highlight the fact that the DMC might change rapidly from one moment to the next. The first explanation given by a student is not *the* explanation. At any given point in the interview we can identify and map out the nodes in a DMC and how they are connected to one another to form an explanation, assuming that there is an explanation at that point.

We now elaborate on our description of these three constructs in order to more fully explain them, and to show how they are different and similar to other constructs that appear in the research literature. To begin, we note that a DMC is a different *type* of entity than a mode or node. Modes and nodes are intended to capture attributes of an individual's *knowledge* and they are presumed to be relatively permanent features of long-term memory (though they might or might not be activated at any moment during an interview). In contrast, a DMC corresponds to a temporary mental state, something that has been constructed in the moment. We believe that this is a relatively simple distinction, but it is one that is sometimes lost in discussions of commonsense science.

In research on reading comprehension, this distinction has been made with great clarity. Researchers have emphasized the fact that readers bring a significant body of knowledge to the task of comprehending a specific text. For example, they know a great deal about the world (e.g., that it has restaurants and volcanoes), and they possess knowledge about the nature of particular genres of text. It is also recognized that, when reading a particular text, the reader constructs a working understanding of that text (e.g., Just & Carpenter, 1987). This working understanding must be entirely constructed in the moment (unless the reader had prior knowledge of the text), but it is constructed in a manner that depends heavily on the knowledge that the reader brings to the text. This constructed understanding is sometimes referred to as the reader's *mental model* of the text (e.g., McNamara, Miller, & Bransford, 1991).

It is also recognized that this working understanding—this mental model—will change and evolve as a text is read. Consider the following example drawn from Just and Carpenter (1987).

> John was on his way to school. He was terribly worried about the mathematics lesson. He thought he might not be able to control the class again today. He thought it was unfair of the instructor to make him supervise the class for a second time. After all, it was not a normal part of a janitor's duties.

Understanding this passage requires that a reader bring to bear a significant pool of knowledge—knowledge about such things as children, schools, and janitors. This pool of knowledge is like our modes and nodes. As we read this story, we construct a working understanding. This working understanding will grow as the text is read, and might shift in unanticipated ways. For example, as you read this story, you might first have assumed that John was a student walking to school. But, in the end, you had to yield to the more bizarre interpretation that a janitor would be leading a mathematics class. This "working understanding" is analogous to one of our DMCs. Note that it is "dynamic" in two ways: (1) It is constructed in-the-moment, and might change rapidly, and (2) it is constructed only for-the-moment, and will no longer exist when the task is complete.

Above we have linked our notion of DMC to that of a *mental model* as it is employed in research on reading comprehension. But it is worth taking the time to contrast our DMC with the notion of "mental model," as it has been employed in the literature on commonsense science. In some parts of the research literature, authors have explicitly made the choice to treat mental models as dynamic constructions. To cite a prominent example, Vosniadou and Brewer (1992) considered mental models to be constructions that are constrained and determined in part by what they call "core presuppositions." We choose to introduce different terminology in part because we wish to emphasize further the dynamic nature of the mental constructions that students assemble in clinical interviews. As we will show below, these can change into an entirely different form in a matter of seconds. Furthermore, as we hope will become evident below, not all DMCs deserve to be called "models." They are working mental states, which might include only partly formed explanations, as well as knowledge that is not even incorporated into a working model of the seasons.

There is one intermediate case that deserves some attention. We restrict our use of "dynamic mental construct" to temporarily constructed mental states. However, there will be cases in which the DMC is highly constrained by the mode that is activated. Consider, for example, a situation in which we ask an astronomer to explain the seasons. The astronomer might have, as part of their memory, many of the elements of an explanation. Nonetheless, there is still a DMC, just one that is highly determined by the active mode.

In summary, the three theoretical constructs listed above provide a simple basis for understanding the conceptual dynamics of clinical interviews. In very crude terms, we can understand a portion of a clinical interview as involving the following:

(1) The interviewer asks a question. This, together with other attributes of the current context, engender the triggering of a specific mode, consisting of a particular collection of interconnected nodes.

(2) Various types of conceptual dynamics act against the backdrop of the mode. These processes, in a sense, have their own inertia and can continue without any immediate intervention from the interviewer. They can lead to possibilities being discarded, and additional nodes from the mode being incorporated into the current DMC. Along the way, multiple DMCs may be constructed and considered.
(3) The interviewer can intervene, for example, by asking a new question, asking for elaboration, or pointing out a flaw or inconsistency. This could cause the student to construct a new DMC, or it could shift the student to another mode.

To illustrate the use of the framework, we return to the brief episode presented in the introduction, in which Leslie first tried to explain the seasons. Recall that Leslie responded in her first two utterances by mentioning a collection of partially related information including ''times savings'' and ''the circulation of the earth.''

00:07	Leslie	Um::: well, um, you know times savings? // you know? Like in the summer, when you have –
00:11	Interv.	// mm-hmm
00:13	Interv.	– Daylight Savings time?
00:15	Leslie	Yeah, daylight savings time. Um, in the summer we have more time, like, with, like, daylight and that's why it gets warmer. And like just with the circulation of the earth and like the axis that it's on just has to do with like summer and winter.

In terms of our framework, we understand this in terms of the triggering of a *mode*. Leslie's initial responses then skimmed the surface of this mode, selecting nodes for verbalization. These nodes include the notion that the SUN IS A SOURCE of heat, which is initially paired with the nodes DAYLIGHT SAVINGS and DAYS ARE LONGER IN SUMMER AND SHORTER IN THE WINTER.[5] Other nodes are mentioned briefly but do not appear to go anywhere, at least initially. For example, we understand Leslie's mention of the ''circulation of the earth'' as simply expressing the idea that the EARTH MOVES in some manner that is not clearly specified.

Furthermore, some of these nodes are organized into Leslie's first *dynamic mental construct* (*DMC*). In particular, SUN IS A SOURCE and DAYS ARE LONGER IN SUMMER AND SHORTER IN THE WINTER are at the core of her explanation. We also believe that her understanding here is fleshed out with low-level tacit knowledge that is at the level of diSessa's p-prims (1993), something to the effect that MORE EFFORT/INPUT LEADS TO A GREATER RESULT.

We understand all of Leslie's subsequent reasoning as occurring within the same mode that was initially activated. As the interview proceeded beyond Leslie's second utterance at 00:15, modal reasoning within this mode led to the construction of a new DMC. The transition to this new DMC seemed to take off from Leslie's statement that ''it depends on where you are on the earth,'' which we understand as reflecting a node associated with the idea that DIFFERENT SEASONS CAN BE ASSOCIATED WITH DIFFERENT LOCATIONS.

00:30	Leslie	And it depends on where we are on the earth. Like if you look at, umm, India, it's like toward the equator, you know? And so it's like always hot. And like if you go up north then it gets colder because there's just, like, I can't really say less sun, but it kind of has to do with that and there's just a lot of snow and, like ice cause it's colder up there.

Leslie's focus on the DIFFERENT SEASONS node seems to have led her to focus on other nodes having to do with the climate in varying locales, and to a new DMC assembled to explain climate variation (i.e., more snow and ice are associated with a colder climate).

We cannot be sure precisely why this brief stretch of interview played out as it did. For example, we cannot be sure why Leslie ended by constructing the beginnings of an explanation of climate variation rather than the seasons. Also, there is much in our proposed analysis that is uncertain. For example, for many reasons, we cannot be very certain about the particular nodes that underlie Leslie's utterance. Nonetheless, we believe that, at least in broad strokes, our framework allows us to understand what transpired here in terms of conceptual dynamics. For example, it seems possible that the transition to talking about climate was triggered by her attention to the idea that different locations can experience different seasons at the same time.

It is worth contrasting our analysis with other possible types of analysis of this same episode. For example, suppose that a researcher wanted to conduct an analysis in which Leslie was coded as possessing or exhibiting a single model. What are their choices? We can imagine a number of possibilities. Most simply, this researcher might say that there is one explanation of the seasons here—Leslie's length-of-day explanation—plus, perhaps, an explanation of climate differences (snow and ice at the poles make it cold). We could also imagine this hypothetical researcher saying that Leslie is still in the process of constructing her model of the seasons, and we have to wait to see what she says as the interview continues. Indeed, Leslie ultimately settled on an explanation of the seasons based on the idea that the side of the earth facing the sun experiences summer and, as the earth rotates, this side eventually faces away from the sun, and experiences winter. It might be that *this* is the model that should be assigned to Leslie.

These alternative analyses are not necessarily unreasonable, and we can imagine research contexts in which each might be an appropriate kind of analysis. But each of these alternatives ignores aspects of the interview with Leslie that do not *need* to be ignored. We do not need to look only at Leslie's final model; it is also possible—and sometimes important—to examine how she got there. We can look at the knowledge that she drew upon, and the processes that led her to assemble the knowledge in the way that she did. Our point is that the more inclusive, real-time analysis of Leslie's reasoning is tractable, and it provides a more complete picture of Leslie's knowledge. It also allows us to better understand why Leslie constructed her explanation given the particular conditions of this interview.

Common DMCs

There is one final preliminary step before proceeding to a more systematic discussion of conceptual dynamics in our interviews. As suggested by the brief excerpts from our interview with Leslie, the explanations given by students could, at times, shift rapidly as an interview unfolded. And the explanations given could be variable and idiosyncratic. Nevertheless, there were some types of explanations—momentarily stable DMCs—that appeared repeatedly across students. Although these DMCs might appear in only a fleeting manner, they nonetheless constitute useful reference points, looking both within and across students. The identification of DMCs is the part of our analysis that is most akin to the type of mental model identification that often appears in studies of commonsense science knowledge.

Tilt-Based DMCs. As we stated above, the standard scientific explanation of the seasons depends integrally on the fact that the axis of the earth is tilted relative to its orbital plane. In the following example, Mark responds to the initial seasons question by immediately giving a tilt-based explanation:

00:00	Interv.	First question I'd like to ask you is why is it warmer in the summer and colder in the winter?
00:06	Mark	Well, part because um the earth's axis, um, revolution around uh the sun. It- it hits an angle, say::: cause it goes around <gestures in broad circle with one hand> and it's the earth's axis, and sometimes the earth, cause is like this is the sun and this is the earth and it's like slanted this way <tilts flat hand> so it like takes longer for it to reach <gestures with pen showing movement of rays toward slanted hand> and the sun's UV rays aren't as strong when it's like, and it's also at an angle, cause it like slants.

In this explanation, we see some evidence that Mark knows that the EARTH ORBITS THE SUN and that the EARTH IS TILTED. His explanation also implies that the SUN IS THE SOURCE of heat. In these respects, his explanation is in line with the standard scientific explanation.

However, there are at least a couple of ways in which Mark's explanation falls short, or is at least incomplete. First, he does not explain how it is that the Earth moves so as to produce a changing tilt. Second, as we explained earlier, the tilt of the earth affects climate because areas that receive more direct sunlight are warmer (DIRECT IS STRONGER, INDIRECT IS WEAKER). However, it does not seem that this is what Mark intends. He says "it's like slanted this way so it takes longer for it to reach." This suggests that he is thinking that the tilt of the earth causes some parts of the earth to be closer to the sun (because that part of the earth is inclined toward the sun), and perhaps because of the DYING AWAY (diSessa, 1993) of the sun's rays as they travel to the earth. The very end of Mark's utterance might, however, belie this interpretation. He says "it's also at an angle, it slants." This might indicate that he *is* thinking in terms of how directly the light strikes the earth, but it is hard to tell from this brief response.

The tilt-based DMCs constructed by students came closest to the accepted scientific explanation. But, as was the case with Mark, these DMCs were not always fully aligned with the accepted explanation. Some, like Mark's DMC, implied that tilt affected temperature by making some parts of the earth closer to the sun. And, again like Mark, some did not specify the manner in which the earth moved so as to vary its tilt. Similar explanations have been reported in the literature on students' conceptions of the seasons (e.g., Atwood & Atwood, 1996; Lelliott & Rollnick, 2010; Sadler, 1998).

DMCs Based on the Earth Moving Closer and Farther From the Sun. A number of DMCs are based around the notion that, in one way or another, the earth is closer to the sun in the summer, and farther from the sun in winter. As we discussed earlier, this type of explanation has been highlighted in the literature on student conceptions of the seasons (Atwood & Atwood, 1996; Bailey & Slater, 2003; Sadler, 1987, 1998; Trumper, 2000, 2001). In our data, a clear example can be found in our interview with Angela. When Angela was asked to explain the seasons, she immediately explained that the earth orbits the sun in such a manner that it is closer in the summer and farther away in the winter. The implication, of course, is that being closer to the sun makes the Earth warmer.

00:00	Interv.	I want to know why it's warmer in the summer and colder in the winter.
00:05	Angela	That's because like the sun is in the center and the earth moves around the sun and the earth is at one point, like in the winter, it's on- it's like farther away from the sun and towards the summer it's closer, it's near, towards the sun.

Kelly's initial DMC was also of this precise form:

00:00	Interv.	. . . why is it warmer in the summer and colder in the winter?
00:07	Kelly	Because, because the earth is, at summer, the earth is more um close to the sun and in the winter it is far to the sun, because the earth's orbit is not a exact circle.

The standard closer-farther explanation presumes that the earth orbits the sun—it revolves around it—in such a manner that the earth is sometimes closer and sometimes farther. Angela and Kelly both made drawings that depicted this clearly. (Kelly's drawing is shown in Figure 2.) However, in some cases, we saw students construct DMCs that were similar—they were based on the notion that the entire earth moves closer and farther from the sun—but the students did not specify how this movement was accomplished. For example, William initially gave the following brief explanation:

00:00	Interv.	"The first question I'd like to ask you is "why do you think it's warmer in the summertime and colder in the wintertime?"
00:07	William	Because I think the uh earth is uh closer in the summer than uh winter.

When asked to draw, William made the diagram shown in Figure 3 which simply shows the earth closer to the sun in the summer and farther from the sun in the winter. In both his verbal response and his drawing, there is no suggestion that the earth orbits the sun.

Side-Based DMCs. One final category of DMC played an important role in our corpus: Students sometimes explained the seasons by saying that the side of the earth facing the sun experienced summer while the other side experienced winter. Although this category of DMC appeared with significant frequency in our corpus, it has been only rarely reported by other research.[6] The initial explanation given by Denise illustrates this type of DMC:

00:00	Interv.	So the first thing I want to know is why is it warmer in the summer and colder in the winter?
00:07	Denise	Cause the earth is rotating and it's closer to the sun when it's like, when it's summer is when your part of the country is closest to the sun and winter is like when it's on the other side.

In this explanation, Denise appears to be saying that the earth's rotation causes first one side, then the other, to be closer to the sun, thus causing the cycle of the seasons. When asked to draw a picture, Denise made the diagram shown in Figure 4, which is in alignment with this interpretation.

One of the nice attributes of a side-based DMC is that it is consistent with the idea that there can be DIFFERENT SEASONS IN DIFFERENT LOCATIONS on the Earth at a given time, a fact with which some students seemed to be familiar. There is just a hint that this is what Denise has in mind when she says "when it's summer is when your part of the country . . .," a framing that suggests other parts of a "country" might be experiencing something different.

Other DMCs. The three categories of DMCs discussed in the preceding sections capture many of the DMCs we saw students construct. However, there were other DMCs that do not fall neatly into one of these categories. Some of these other DMCs were very fleeting and vague. Consider for example, Randy's initial response to the interviewer's request to explain the seasons.

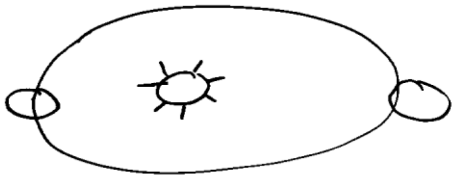

Figure 2. Kelly's drawing showing the earth orbiting so that it is sometimes closer and sometimes farther from the sun.

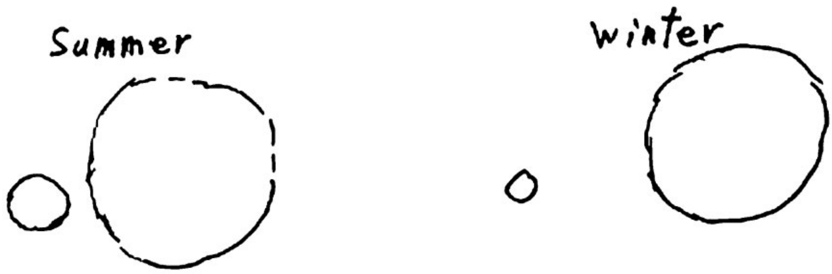

Figure 3. William's drawing showing the earth closer and farther from the sun.

00:03	Randy	Because of the earth's movement? Right?
00:08	Interv.	How do you mean?
00:09	Randy	Umm, like, the world turns on an axis and stuff. And uh when it turns it—uh it's the angle of where the sun hits it. And in the wintertime, the sun, I mean the earth, moves probably farther away or something.

In the above excerpt, Randy begins by asserting that the earth's movement causes the seasons. This assertion might seem, to some, to have no substance at all. But it represents a significant step in the right direction. Compare, for example, a student who begins with the assumption that the seasons have something to do with the jet stream (Atwood & Atwood, 1996). Furthermore, having a sense that the explanation of the seasons is somehow rooted in the movement of the earth, even in a vague way, can be an important starting point. Indeed, even in the short passage above, we see that Randy immediately began to flesh out his model of the earth's movement and his explanation of the seasons.

In other cases, students constructed non-standard but quite elaborate explanations that they worked hard to develop and explain. Usually these appeared later in the interview, in response to challenges from the interviewer. For example, in response to challenges, one student, Robbie, developed a model in which the earth rotates on its axis and revolves around the sun as usual, but also tumbles end over end, so that one pole, then another, faces toward the sun.

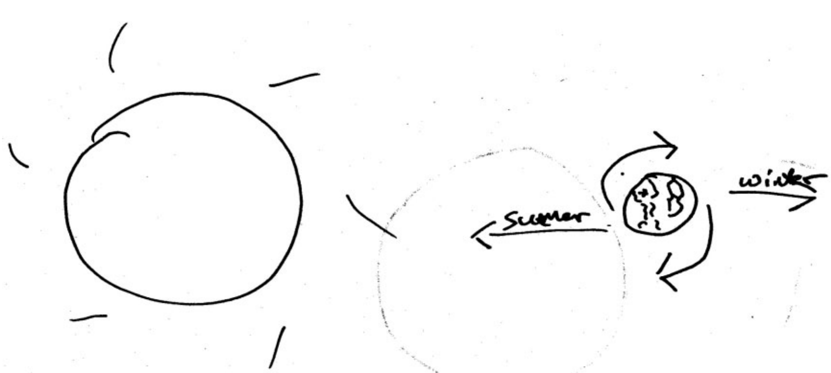

Figure 4. Denise's drawing showing a side-based explanation of the seasons.

Conceptual Dynamics in Interviews

In the introduction to this manuscript we stated that our goal was to understand the conceptual dynamics that occur as an interview unfolds. In this section, we address this task directly. Using the machinery set up in the preceding sections, we will describe some recognizable patterns in conceptual dynamics—patterns in the knowledge resources drawn on by students, how these resources are assembled into an explanation, and how this changes as an interview unfolds.

Initial Dynamics

We begin with a discussion of what happens immediately after a student is first asked to explain the seasons. Much of the most interesting dynamics transpire in these first few moments. Although these dynamics can pass quickly, we believe that it is still possible to unpack and make sense of student reasoning on this short timescale.

Mode Skimming and Initial Steps Toward DMC Construction. In one type of initial response, students responded immediately, and sometimes spoke at length, but without immediately giving a direct response to the question. Instead, their utterances took the form of a list of relevant—or nearly relevant—information. For example, in Leslie's initial response, which we quoted in earlier sections, she provided a long list of loosely related ideas, including "time savings" and facts about India.

We call this type of behavior *mode skimming*. The idea is that the question activates a mode, but it is a mode that does not immediately privilege any specific DMC. Thus, the student begins by "skimming the surface" of the mode, simply taking a tour of some of the nodes in the mode.

Why do students engage in mode skimming? We believe that, for a number of reasons, this behavior is not very surprising. The students are being asked science questions by a researcher, and while being videotaped. Thus it makes sense that they would want to display some of their knowledge. More importantly, mode skimming can be a productive way for a student to begin their reasoning. If a student does not immediately know an answer to the seasons question—if no single DMC is strongly privileged by the mode—it makes sense for the student to consider a variety of related ideas before trying to piece those ideas together into a DMC.

Indeed, mode skimming did generally lead, relatively quickly, to at least some first stabs at a DMC that explains the seasons. Consider the following episode, in which Ali was first asked to explain the seasons. She began by just asserting that the answer has something to do with the sun and the movement of the earth.

09:35	Interv.	The question is why is it warmer in the summer and colder in the winter? That's what I want to know.
00:09	Ali	Because of the su- because of the umm earth's movement <makes circling gesture with hand raised>.

The interviewer responded by just saying "mm hmm." Then, after a brief pause, Ali engaged in some mode skimming, tossing out a list of loosely related information, including the ideas that the earth goes around the sun, and that it is tilted and rotates every 24 hours.

00:13	Interv.	mm hmm
00:14	Ali	Er. Yeah. The axis of the earth.
00:17	Interv.	So how exactly does that work? How does it make it-?
00:22	Ali	Well, like when the earth goes around the sun it's kind of tilted. It turns too <rotates finger> like every 24 hours it turns and so that changes our seasons

Next, after, the interviewer began to ask for more elaboration, Ali responded with a statement that took a step closer to an explanation of the seasons. Here, her explanation is based just on the idea that the Earth is ''away from'' the sun in the winter, and ''directly in front'' of the sun in the summer.

00:38	Interv.	But how does-
00:39	Ali	So when it's away from the sun it's colder and when it's like directly in front of the sun it's hot.

We are seeing here cases in which students' activated modes do not have a ready-made answer to the seasons question, but in which they nonetheless have knowledge out of which they can begin to build an answer. Generally, the students seem to be listing related information—skimming the mode—before trying to fit together the pieces into an answer.

When the Mode Has the Explanation. One of the most important features of our framework is that we are careful to contrast student knowledge (the modes and nodes) with the mental state that is constructed in the moment (the DMC). However, as we discussed earlier, there may be cases in which the DMC is highly constrained by the activated modes and nodes. This would be the case, for example, if a student has heard the seasons question before, and simply recalls all or part of an answer.

For example, in our discussion of common DMCs, we presented an example in which Mark immediately responded to the initial question with a tilt-based explanation. The fact that Mark was able to respond immediately with this explanation is likely a sign that he has heard—or at least thought hard about—the causes of the seasons, and that he associates the seasons question with a particular DMC.

However, even when there is a strong initial association of this sort, there can still be variety in the conceptual dynamics that follow. A student can be asked to engage in new reasoning—to draw novel conclusions—given the current DMC. In addition, as we will see, a student may shift DMCs, especially in response to challenges from the interviewer. Mark, as it happened, stuck closely to his initial tilt-based DMC throughout his interview. In part this was due to the fact that his explanation was largely correct, and thus was able to account for most of the relevant phenomena that must be explained by a model of the seasons.

There were also cases in which the seasons question seemed to be strongly associated with a single DMC that deviated more substantially from the standard explanation. For example, as we saw, Angela responded to the seasons question by immediately giving an explanation centered around the notion that the earth orbits and is sometimes closer to the sun and sometimes farther away.

00:05	Angela	That's because like the sun is in the center and the earth moves around the sun and the earth is at one point, like in the winter, it's on- it's like farther away from the sun and towards the summer it's closer, it's near, towards the sun.

Note, in the above excerpt, how Angela begins her statement by saying ''That's because . . .'' That statement, her immediate response, and her confident tone, suggested to us that she believed she was reporting a known answer, rather than something she was figuring out in the moment.

Stable Reasoning With an Existing DMC

We now consider the conceptual dynamics that occur after a student has settled, at least for a moment, on a stable DMC. Once a DMC has been established, it can permit some reasoning that is of a relatively unproblematic sort; reasoning can be done without substantial change to the current DMC. This is one place where a more conventional understanding of mental models fits within our analysis. For example, if the DMC consists of a constructed mental model, then that model may be mentally ‘‘run’’ to deduce entailments of the model.

For example, in response to the initial prompt, Jill gave a standard closer-farther explanation, and she produced the diagram shown in Figure 5. The interviewer then challenged her, asking if she had ‘‘heard that when its winter in the United States it's summer in Australia.’’ Jill replied that she had not heard this, and argued against it by reasoning from her model.

00:00	Interv.	I've heard that when it's uh winter in the United States it's summer in Australia, have you heard that?
00:12	Jill	[shakes head no and smiles]
00:14	Interv.	No? Yeah, I was just wondering. Yeah, I uh that's what I hear, so I was just wondering why er how that would work given what we've talked about the description.
00:29	Jill	Um, um, I th- maybe um, where Australia is placed on the earth it's where the sun hits it less but I don't think it ac- so I think it's just colder there, but I don't think it's actually like s- I think the whole earth is at summer at one time and winter at like like it goes together but maybe where Australia is placed it gets like weird seasons because of that, like the temperatures of the seasons are different.

In the above passage, Jill uses her current DMC to argue against the possibility that it would be summer in Australia when it is winter in the United States. Essentially, her argument is that the ‘‘whole earth’’ moves as one, closer and farther from the sun, and thus Australia must experience summer at the same time as the United States. In this case, Jill's application of her DMC was rapid and relatively easy. But we also saw episodes in which students attempted to construct a DMC that incorporated the sun, an orbiting moon, and a tilting, orbiting, and rotating earth. Using such a DMC to make inferences could be difficult.

Upsetting the Apple Cart: Shifting DMCs

Thus far, we have talked about the initial dynamics that follow the introduction of a new topic, the initial construction of a DMC, and the reasoning that can occur with a DMC. We now consider the possibility that there may be a more radical shift in the DMC as an interview unfolds. Such a

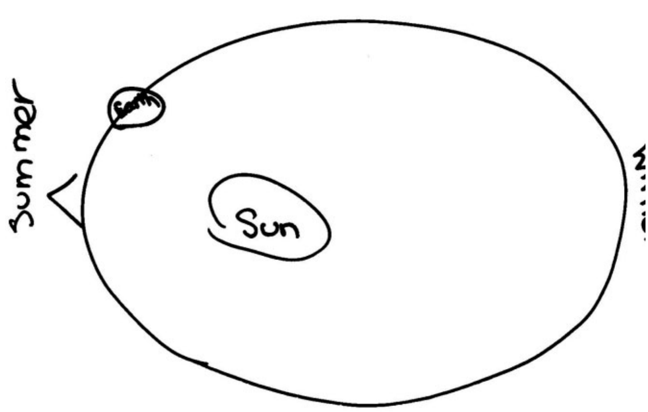

Figure 5. Jill's diagram.

shift could occur for multiple reasons. It could occur, for example, because the student believes that the interviewer has suggested—implicitly or explicitly—that their current DMC is not correct. Or it could occur because the interviewer introduces or highlights information that the student was not previously considering.

In our interviews, we included some prompts that were intended to attempt to provoke shifts. In the preceding section, we saw an episode in which Jill was directly challenged by one such prompt. In Jill's case, it happened that she was resistant to this challenge. For whatever reason, she was comfortable treating Australia as a special case.

However, we did see cases in which students abandoned a DMC. As we discussed earlier, Angela initially constructed the standard closer-farther DMC. When the interviewer introduced the idea that different locations can experience different seasons, Angela was visibly troubled; she laughed nervously, and she asked for a new sheet of paper so she could create a new drawing. It was clear from her demeanor that she understood the challenge and saw it as posing a difficulty for her explanation:

03:49	Interv.	One thing I wanted to ask you though about though was, um, one thing that you might have heard is that at the same time—tell me, you can tell me if you've heard this—when it's summer here, it's actually winter in Australia.
04:07	Angela	Mm hmm <laughs nervously>
04:08	Interv.	Have you heard that before?
04:09	Angela	Yeah.
04:10	Interv.	So I was wondering if your picture the way you drew it can explain that or if that's a problem for your picture.
04:15	Angela	Uh::::. I need another picture.

In response to her request, the interviewer handed Angela a new sheet of paper. She struggled, but could not immediately construct an alternative explanation.

04:24	Interv.	So is that a problem for you picture? <hands new paper to her>
04:25	Angela	Yeah, that is. Cause, okay, um. There's like the sun. <starts drawing a new diagram> And, okay, yeah, I remember that now cause um it's like [pause] I guess as the world is rotating, or is go- orbiting, it's rotating too, so-[pause] I don't really I guess I don't understand it. Um.
04:27	Interv.	Were you saying as the earth is going around here, <gestures a circle following the orbit path drawn on the original diagram> it's doing what?
04:33	Angela	It's like spinning <gestures spinning motion>, because that's how it's day and night too.

In this excerpt, Angela is trying to construct an alternate explanation of the seasons. Note that Angela is attempting to build her explanation on some of the same ideas—the same nodes—as in her previous explanation. For example, she is still focusing on the orbital motion of the earth about the sun, and she assumes that the sun is the source of the earth's heat. However, she now tries to weave in some new ideas. In particular, she now mentions that the earth rotates and she references the day/night cycle. In effect, the interviewer's challenge has sent her back to square one. She is engaging in a broader mode skimming in order to search for a new explanation.

Note that it is not simply the case that the interviewer's challenge has given Angela the signal that her preceding explanation is wrong. Rather, it has brought to prominence an existing node that she had available. This, we believe, was evident from her change in demeanor. In fact, Angela went on to mention that she had personal experience that was directly relevant. Immediately following her attempt to construct a new explanation, she commented:

05:12 Angela So::: I guess I really don't understand that that much. But, um, yeah, I have heard that, uh, cause I was supposed to go to Australia this summer but um and it was going to be winter when I was going, but um their winters are really warm.

In the end, Angela could not find a new DMC to replace the one she had abandoned. In other cases, however, we did see students shift from one relatively clear and well-established DMC to another. For example, Edgar began with a clear side-based DMC, producing the diagram shown in Figure 6.

00:33 Edgar Here's the earth slanted. <He's drawing as he speaks>. Here's the axis. Here's the North Pole, South Pole, and here's our country. And the sun's right here <draws the circle on the left>, and the rays hitting like directly right here. So everything's getting hotter over the summer and once this thing turns, the country will be here and the sun can't reach as much. It's not as hot as the winter.

Note that, in Edgar's initial side-based explanation, he had not mentioned that the earth orbits the sun, he only said that "this thing turns." The interviewer set out to determine if Edgar was aware that the earth revolved around the sun. He asked, in reference to the earth's rotation: "Is that the only way the earth moves, or does it move in some other way too?" In response, Edgar revealed that he did, indeed, seem to know that the earth orbits:

01:24 Interv. So the sun is here and the earth's here and it kind of goes like that <gestures the rotation of a stationary earth over diagram>
01:27 Edgar Like that, and go all around. <gestures an orbital pathway over diagram>
01:29 Interv. Oh, it also goes around like this? Okay. <gestures orbital pathway over diagram>
01:31 Edgar Orbits.

The interviewer then asked Edgar to focus on the location of the earth in its orbit. He asked him to assume that his drawing showed the position of the earth in summer, and to show where the earth would be in the winter. There was a pause of a few seconds before Edgar responded. In his response, he shifted his DMC dramatically, and gave a standard closer-farther explanation of the seasons, rather than a side-based explanation.

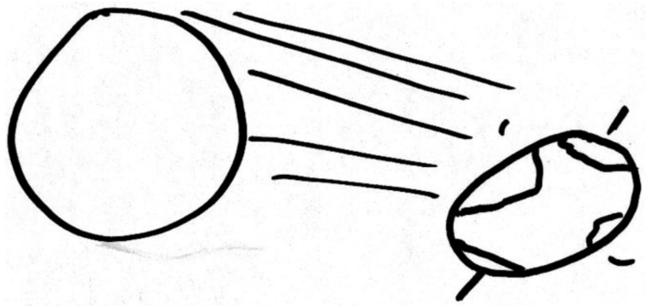

Figure 6. Edgar's diagram of the earth–sun system.

01:32 Interv. Let's say we're here and it's summer, where is it, where will the earth be when it's winter?
01:40 Edgar [pause] Actually, I don't think this moves <indicates earth with pencil on pencil>—it turns and it moves like that <gestures orbiting and spinning earth> and it turns and that thing like is um further away once it orbit around the s- earth- I mean the sun. <gestures over diagram, showing earth rotating and orbiting>
01:50 Interv. It's further away?
01:51 Edgar Yeah, and somehow like that going further off and I think sun rays wouldn't reach as much to the earth.

Thus, Edgar has shifted from a clear side-based DMC to a standard closer-farther DMC. When asked, Edgar seemed to be aware that he had shifted explanations.

01:58 Interv. Oh, in the winter it's further away. So is that, is that, is that a different explanation that-? Before you said it has to do with this thing of—<points to drawing>
02:10 Edgar Yeah, that's a different explanation cause I thought it wrong.

Edgar's new DMC is substantially different than the DMC he constructed initially. Nonetheless, like Angela, he weaves many of the same ideas—the same nodes—into his new explanation. Like most seasons explanations, it still assumes that the sun is the source of the earth's warmth. And, although there is less focus on the fact that the earth rotates, it nonetheless still appears in edgar's utterances: "it turns and it moves like that and it turns and it's further away once it orbits around the sun." The big change, of course, is that the DMC now makes central use of an idea that did not appear earlier, that the Earth's distance to the sun might change.

Drawing-Related Dynamics

Recall that, in all of our interviews, we asked students to draw a picture in order to illustrate their explanation of the seasons. This might, at first blush, seem to be a relatively insignificant move by the interviewer. However, as we discussed earlier, some prior research has found that the use of artifacts, such as globes, or modeling tools, such as clay, can have a dramatic influence on the types of explanations given by participants (Bryce & Blown, 2006; Nobes et al., 2003; Siegal et al., 2004; Siegal & Surian, 2004). Indeed, in our own data the request to draw seemed be a powerful intervention. One way we can go beyond the prior research is to attempt to unpack, in a fine-grained manner, how it is that drawings can work to drive student reasoning in particular directions.

For illustration, we return to our interview with Ali, which we discussed in our section on initial dynamics. Recall that the first section of Ali's interview concluded with a pair of fairly vague explanations. She said: "Well, like when the earth goes around the sun it's kind of tilted. It turns too like every 24 hours it turns and so that changes our seasons." And: "So when it's away from the sun it's colder and when it's like directly in front of the sun it's hot." At this point the interviewer might have asked Ali to elaborate, and to explain what she meant by "away from the sun" and "directly in front of the sun." Instead, he asked Ali to draw a picture, and she produced the diagram in Figure 7, which shows the earth on the left, the sun on the right, and the orbital path of the earth encircling the sun. Initially, the two stick figures on the earth did not appear.

To this point, Ali's diagram can be seen as a restatement of some of the ideas she previously expressed, in particular, those having to do with the structure and movement of the earth. Next, the interviewer asked Ali to show where we are on the diagram during the summer. In response, Ali drew the stick figure at the top-right on the earth. The interviewer then asked Ali to locate us in

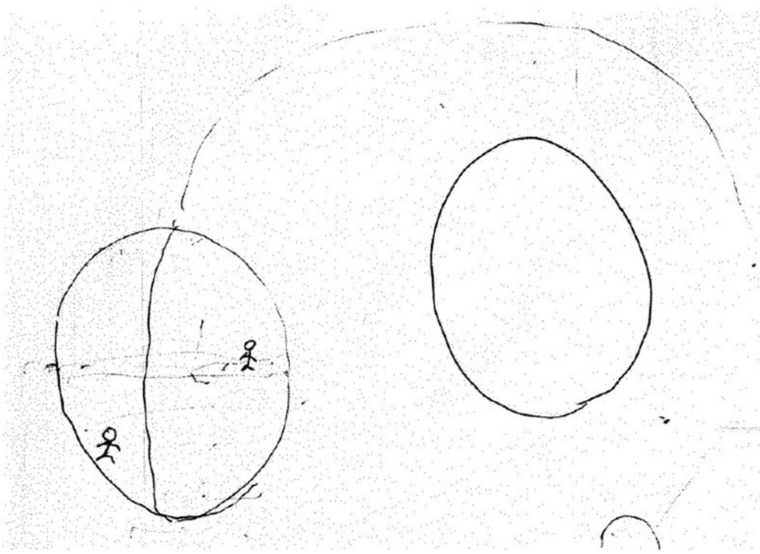

Figure 7. Ali's diagram. The diagram initially did not include the two stick figures.

the winter. Ali made the figure at the lower left and explained that it is colder there "because it's away from the sun."

02:29	Interv.	So that's us in the winter. And why is it colder then?
02:35	Ali	Oh, oh, because it's away from the sun.

With this response, Ali seems to have shifted to a side-based DMC, in which the side facing the sun experiences summer, and the side facing away experiences winter. Our interview with Kelly provides a similar example. As described earlier, Kelly began by giving the standard closer-farther explanation, and she made the diagram shown in Figure 2.

Then the interviewer asked Kelly to locate us, on her diagram, during the summer and winter. In response, Kelly added small stars to her diagram, as shown in Figure 8. As expected, she associated the right-hand earth—the one that is farther from the sun—with winter, and the left-hand earth with summer. But note also that Kelly has drawn the winter star at the edge of the earth farthest from the sun. The interviewer then asked her to explain her positioning of the stars. In response, Kelly gave what seemed to be a side-based explanation:

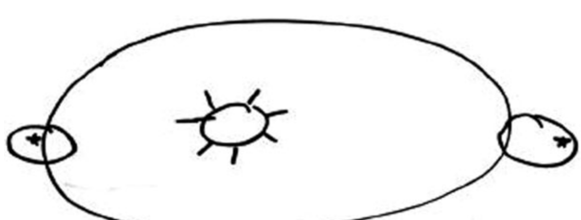

Figure 8. Kelly's diagram with stars added to show our location during the summer and winter.

02:06 Interv. Why did you draw us over here <refers to right-hand side> for winter?
02:09 Kelly Because umm, the hemisphere, when we're having um, when we're having summer, the hemi- our hemisphere will be facing the sun, and when we're having winter, the other hem- the other part of the hemisphere is having summer and we're having winter.

The interviewer continued to prompt for elaboration, and Kelly gave clear evidence of having shifted to a side-based DMC.

03:16 Kelly Because when the earth is rotating and we're- if we're having winter, the um the other part like in Europe or some other place it will be having summer because we're facing away from the sun and they are facing toward the sun.

Thus, we have seen that both Ali and Kelly shifted to a side-based DMC when asked to locate us on diagrams they had produced. We believe that, in retrospect, this is not surprising. Once a student has produced a static diagram that shows the sun and earth, that diagram might lead the student to locate winter on the side of the earth away from the sun. Furthermore, once this explanation is stumbled upon, a student might see that it has some nice properties; most notably, it is consistent with the fact that different locations experience different seasons. In fact, Kelly commented on just this fact, in her utterance above, when she said: "if we're having winter, the other part in like Europe or some other place it will be having summer."

Given these observations, it seems possible that the prominence of side-based explanations in our data corpus might be due, at least in part, to some particular features of our interview protocol. We asked all students to make diagrams to support their explanations, and we asked all students to locate us on their diagrams. This might have driven students in the direction of a side-based explanation. Indeed, Lee (2010) found that showing students orbit diagrams (which they had not themselves constructed) did seem to sometimes have the effect of pushing students toward side-based explanations.

In sum, the fact that we saw strong effects from asking students to draw is very much in line with the prior research that documented the effect of giving students models or modeling tools. What we have attempted to show here is that it is possible to understand this impact in a fine-grained manner, as just one part of a larger dynamic of node rearrangement and construction. In our case, we can see how the drawings we asked students to create afforded specific inferences, which led them to construct explanations of a particular sort.

Shifting Modes

Following the logic dictated by our theoretical framework, we should at this point be discussing circumstances in which we observed shifts in the *mode* that is active for a particular student. Such a shift would be more dramatic than the shifts in DMCs discussed in the preceding section. However, we have concluded that the reasoning that we see students engaging in during our seasons interviews is most appropriately treated as taking place within the context of a single mode. Although, students construct and reconstruct their DMCs over the course of our seasons interview, we saw that they generally do so with a relatively consistent set of nodes; it is as if they are trying to find the right way to put a given set of puzzle pieces together, rather than discarding the pieces and trying another set. For example, with only a few exceptions, explanations given by students in our seasons corpus involved the sun as a source of the earth's heat, and the changing spatial relationship of the earth in relationship to the sun.

This need not have been the case. It is possible that student explanations could have ranged much farther afield. In pilot interviews, we saw some cases in which students initially were puzzled about what sort of explanation to give, and attempted to appeal vaguely to such things as the wind and lava at the center of the earth. (As mentioned above, Atwood & Atwood (1996) cite some students as giving an explanation that invokes the jet stream.) But, in the corpus of interviews we examined for this manuscript, the students seemed to trigger, and stick to, a relatively consistent set of nodes.

In other articles, we have discussed interview data that we describe as involving regular transitions among modes (Kanter, Sherin, & Lee, 2006). Interested readers should look there for more extended discussion of modes and mode shifts.

Why Do Students Converge on a Few DMCs?

Before leaving our discussion of conceptual dynamics in interviews, we want to consider one final question. We encountered some DMCs that were unique to individual students. But we also stated that there were a few categories of DMCs that captured many of the core explanations given by students. The question is, given the complexity of the processes involved, why do students, so frequently, converge on a few categories of DMCs?

We believe the answers to this question are multifarious. First, although there is variety in the knowledge possessed by the students we interviewed, there is also a great deal of overlap. For example, all of the students we interviewed knew that the earth and sun were large spheres in space, and most knew that the earth rotated and orbited the sun. In addition, many had likely even heard, at some point, the correct explanation of the seasons.

Furthermore, adding to this overlap in the knowledge possessed by our interviewees was the fact that there was significant consistency in the manner in which our interviews were conducted—in the questions we asked and the prompts and challenges we employed. There was some variability; our interviewers were free to ask for elaboration and to devise follow-up questions. But our interviews all followed the same basic skeleton of prompts.

Thus, the convergence on a few DMCs can in part be attributed to the fact that some of the same constraints governed the dynamics across students: they possessed much of the same knowledge and they were guided in a similar manner by interviewers. We also think it is helpful to think of some DMCs as having properties that make them attractive as convergence points. These DMCs have properties that lead students to evaluate them positively, when they judge their quality.

Note that, in our above discussion, we were implicitly relying on the ability of a student to evaluate the quality of a DMC—to judge that a DMC is "good enough," or preferable to another candidate DMC. For example, when reminded of the fact that different locations on the earth can experience different seasons, Angela judged that the explanation she had previously given was no longer adequate. This is presumably because she believes (at least implicitly) that an explanation should be consistent with all known facts, especially well-established ones. And because Angela's family was planning a trip to Australia this fact was, for her, quite well established.

These intuitive judgments of the validity of explanations have been the focus of some researchers in science education and psychology. For example, Brewer, Chinn, and Samarapungavan (1998) list a number of attributes that they say we all look for in judging the quality of explanations: accuracy, scope, consistency, simplicity, and plausibility. In a more elaborated line of work, Thagard and colleagues have constructed and tested an explicit computational model, which they call ECHO, which attempts to model our drive for explanatory coherence (Thagard, 1989). ECHO uses a connectionist framework to model how people weigh computing facts and hypotheses in judging the quality of an explanation, and choosing one explanation over another. It has primarily been applied to model historical change in the theories preferred by scientists. But it has also been applied to model real-time reasoning by students in an interview context (Ranney & Schank, 1995; Schank & Ranney, 1991).

The argument we are making is that some DMCs do well when evaluated according to these metrics. Consider the standard closer-farther explanation, exemplified in the explanations given by Angela and by Kelly in the preceding section. This explanation integrates just enough information to be compelling, and it does so with a pleasing simplicity. Many people have heard that the earth's orbit is, in fact, elliptical. The fact that the standard closer-farther explanation incorporates this technical bit of information means that it might acquire, by association, some of the weight of authority. And there is much that this explanation can predict that is correct. In particular, it predicts that the cycle of the seasons will be repeated with a period of one year, and it links this cycle to the earth's orbit.

The side-based explanations we discussed also have some pleasing properties that might help to explain their frequent appearance in our corpus. In some ways, their strengths and weaknesses are the reverse of those of the standard closer-farther explanation. Side-based explanations can be consistent with the fact that different parts of the earth experience seasons at different times. But, they predict that the seasons will be repeated with a period equal to the rotational period of the earth (which is 1 day).

These mechanisms that explain why students might tend to prefer certain explanations also suggest that the attractiveness of a particular DMC may be highly idiosyncratic. For example, a student might attach high importance and reliability to an individual node, even an idiosyncratic node, and might place a high priority on finding an explanation that incorporates, or is at least consistent with, that node. For example, Angela's planned trip to Australia may have led her to attach particular importance to the idea that different locations can experience different locations.

The Limits of Consistency. One important feature of ECHO is that, although coherence and consistency are preferred, it is not an absolute requirement. Our own mode-node framework is also tolerant of such inconsistency, and we can see examples in our corpus in which students give answers that embody inconsistencies. To illustrate we return to our interview with Edgar. We have not yet presented what Edgar said when he was first asked the seasons questions:

00:00	Interv.	The first thing I want to know is why is it warmer in the summer and colder in the winter?
00:07	Edgar	For us?

When Edgar responds "For us?" this suggests that he is aware, in some manner, that seasons occur at different times in direct locations. Recall further that, in his first description of his side-based explanation, he talked about what happens for a particular country, which he pointed to on his drawing. However, when Edgar shifted to the standard closer-farther explanation, there was apparently no recognition that there could be different seasons on earth at the same time. And, as we have noted, the standard closer-farther explanation is inconsistent with the "different seasons" idea. How can Edgar give an explanation that is inconsistent with an idea that he apparently considered just moments before?

One possible explanation is that we are simply incorrect in our suggestion that the different seasons idea was active for Edgar earlier in the interview. But, even if we are correct, this does not pose any difficulties for our analysis; our framework, in fact, expects inconsistencies of this sort in student explanations. Some nodes may become more or less prominent as the interview unfolds. And, there are many considerations that a student needs to keep track of when explaining the seasons. Thus, a student may assemble some nodes into an explanation, and judge it only in a relatively local manner. They may be unaware of inconsistencies with earlier statements unless they are pointed out by the interviewer.

Our interview with William provides another example of this sort of local reasoning. Recall that William constructed a DMC to explain the seasons in which the entire earth moved closer and farther from the sun without any specification of how precisely the earth moved (refer to Figure 3). Immediately following William's statement of this DMC, the interviewer asked if William had "ever heard that, for instance, when it's winter in Chicago, it's summer somewhere else," thus introducing the "different seasons" idea. In response, William said that he *had* heard that this was true. Then the interviewer asked where on the Earth it would be winter when it's summer in Chicago. William said that it would be summer at the location that is the "opposite" of Chicago, China:

01:06	Interv.	Um now have you ever heard that say for instance when it's winter in Chicago, it's summer somewhere else?
01:11	William	Yeah
01:12	Interv.	Do you know like where it might be summertime when it's winter in Chicago?
01:19	William	Like the opposite of the place that Chicago.
01:24	Interv.	Uh huh. Like what? What place would that be?
01:26	William	China.

Of course, these statements are, from a scientist's point of view, inconsistent with William's closer-farther explanation of the seasons; if the seasons depend only on the distance of the entire earth from the sun, then the entire earth should experience summer at the same time. William does not seem aware of the inconsistency here. Instead, we believe he is reasoning from the simple idea—a node—we call OPPOSITES, in a very local manner; if it is summer in Chicago, it must be winter on the opposite side of the earth. Note that this does not need to require that William is tolerant of inconsistencies. He simply might not notice that there is a conflict.

Summary and Conclusion

Summary of the Manuscript

We began this manuscript with the assertion that there is a surprising lack of consensus among researchers concerned with intuitive knowledge and conceptual change in science. We further suggested that many of the problems seem to be methodological at their core; for example, some of the debates hinge on the issue of how questions should be posed to students in an interview. In response, we argued that we need to understand and model student reasoning as it occurs in the interviews that we employ for studying student knowledge.

As analysts, our data consist of the visible features of an interviewing interaction, including the verbalizations and gestures of the interviewee. Ultimately we would like to be able to see through these visible features to the student knowledge that, in part, generates the data we perceive. This is difficult since, in general, there will be a complex relationship between the knowledge possessed by students and the statements they make as the interview unfolds.

The central point of this manuscript is that this process is complex but not intractably complex. It is possible to understand how the answers that students give are generated, in part, by the knowledge they possess. This manuscript was largely an exercise in attempting to convince the reader of this possibility.

Our theoretical framework was based on a relatively simple set of theoretical constructs. We described the knowledge of students as consisting of a large number of elements of diverse types we called *nodes*. When the interviewer asks a question, this triggers a *mode*, which selects a subset of nodes from the larger conceptual ecology. Reasoning with these nodes then leads to the generation of a *dynamic mental construct*. As the interview unfolds, the DMC may be refined, or the student might shift to another DMC. Shifts between modes are also possible, though we did not observe such shifts in the context of our seasons interview.

We used our theoretical machinery to characterize some of the phenomenology of the unfolding patterns of conceptual dynamics in interviews. We list here some of the most salient and important phenomena:

- We saw students engaging in what we called *mode skimming*. After a question was asked, a student would skim the surface of the mode, tossing out a list of loosely related information.
- We saw students pick and choose among nodes and assemble them into a DMC. Some of this was clearly visible. For example, in our first example, we could see Leslie consider an explanation and then correct herself.
- Students frequently converged on one of a few types of DMCs. The reasons for this convergence could be understood as following from features of student knowledge, as well as features of our interviews, and properties of the explanations themselves.
- We saw clear cases in which students shifted from one DMC to another. For example, when students began with the standard closer-farther explanation, a challenge based on the ‘‘different seasons’’ idea could cause them to shift DMCs, often to a side-based explanation. However, we saw that this challenge did not always lead to a shift and that, even when it did, the new DMC still employed some of the same nodes.
- We saw that judgments of the reasonableness of a DMC by students could be made in a local manner, sometimes ignoring nodes mentioned moments earlier.
- We saw that student reasoning, and the DMC constructed, could depend strongly on idiosyncratic knowledge. For example, Angela’s reasoning depended on recalled information about a planned trip to Australia.

These phenomena help to show the reasonableness and usefulness of our focus on conceptual dynamics during interviews. They show that there *are* real conceptual dynamics that occur over the seconds to minutes that elapse in a clinical interview, and that these dynamics are visible enough that we can make them an object of study. We also believe that some readers will see some of these phenomena as familiar from their own work, even if those dynamics have not yet been explicitly analyzed as objects in their own right. That should lend some additional plausibility to our claims.

Moving Beyond the Coherence Question

In the introduction to this article, one way that we motivated this work was through a discussion of the ‘‘coherence’’ debate: the question of whether student commonsense science knowledge is in the form of a consistently applied and coherent theory or model. The goal of this article has not been to answer this question; it has been to argue for new questions and a new empirical program. Nonetheless, before concluding this article, we consider whether, within this new program, questions remain that are related to the original coherence debate.

We begin with some clarification of the coherence question. diSessa et al. (2004) have argued that the very notion of *coherence*, as it appears in the literature, is itself problematic. They state, first, that any judgment of coherence depends on a frame of reference against which we judge whether an appropriate range and selection of phenomena are covered. Furthermore, they point out that, at the highest level, there are two distinct and possibly conflicting meanings of ‘‘coherence.’’ One, which they call *contextual* coherence, relates to the consistency of answers across questions and contexts. Thus, if we were concerned about contextual coherence we would define some appropriate *regime*—a range of questions across which we would expect students to answer consistent with a given model or set of beliefs. If students' answers were consistent across this regime, we would say they were coherent.

The second meaning, which diSessa and colleagues call *relational* coherence, pertains to the internal relational structure of the knowledge that is employed when answering questions. The point is that it is possible for someone to consistently apply some set of beliefs which are not related to each other in any way, so they might exhibit contextual coherence, without relational coherence.

Given the frameworks and analyses presented in this article, can we pose any questions related to these two meanings of coherence? We can begin by thinking about the DMCs that students construct. We can ask, for example, whether the DMCs constructed by students are consistent across contexts, and whether they are internally (relationally) coherent. However, we must be aware that any answers we obtain might well be specific to population, subject matter, and the types of interview questions we pose. This might be acceptable if the populations and subject matter are of sufficient interest, and if the interviews themselves are appropriately representative of the reasoning tasks students face. Nonetheless, from a scientific point of view, this type of narrowness is somewhat unsatisfying.

Fortunately, the observations and analyses presented in this manuscript point to ways in which we can draw more interesting and general conclusions. First, we can observe that we do not need to stop with an analysis at the level of DMCs. We can seek to draw conclusions about the knowledge (modes and nodes) that generated those DMCs. This requires that we understand the dynamics of the interviews; we need to attempt to unpack how the DMCs we observe are a product of the knowledge possessed by students, as well as the properties of the interview, and the particular way in which interviews unfolded. Once again, our hope is that we have shown that such an analysis is difficult, but not impossible.

If we can identify this underlying knowledge, then we can ask questions of contextual and relational coherence with respect to that knowledge. For contextual coherence, we can attempt to examine the range of contexts across which modes and nodes are applied. For relational coherence, we can look at the internal consistence of the knowledge, and how conflicts are resolved, if they are encountered. Our results will still be bounded by population and subject matter. But, if successful, this type of analysis allows us to see through the specifics of the design of interviews to the underlying knowledge; in other words, we need not see our results as entirely specific to the design of our interviews.

We can conduct these types of analysis, in a limited manner for the data presented in this article. The picture that emerges is somewhat mixed. We argued that the mode that was activated stayed constant within the bounds of our interview; students consistently answered questions about the seasons by appealing to the sun and earth and their relative motion. This is in agreement with what other researchers have found (Lelliott & Rollnick, 2010). However, we did see clear circumstances under which students shifted DMCs. With regard to relational coherence, we did see cases in which students (such as Angela) explicitly strived for internal consistently. However, we also presented cases in which students seemed to make judgments of the validity of arguments only locally, and ignored relevant contradictory nodes.

Still, all of these questions and answers are scientifically narrow; they are still tied to specific populations and specific subject matter. Are there any big coherence questions that remain, questions that truly span population and subject matter? We believe that there are, but they are of a somewhat different form: they focus on the dynamics that produce coherence. For example, we can ask:

- What, in general, makes a DMC attractive as a point of convergence? The work on explanatory coherence, discussed above, provides a partial answer to this question. But, because DMCs consist of a heterogeneous collection of knowledge resources, we believe there is much more to be done to answer this question, and really understand what makes some DMCs "attractive."
- On what features does the stability of a DMC depend? Under what conditions will students shift from one DMC to another? What types of inconsistencies will students tolerate?

If questions about coherence are rephrased in terms such as these, the field may have a better chance of achieving the consensus that has eluded it for the last two decades.

On Modes, Nodes, DMCs and Sociocultural Theories of Science Learning

Before proposing instructional implications of our work, we want to discuss one final set of theoretical issues: the relationship between our own work and sociocultural theories of learning. Our stance throughout this work has been unapologetically cognitive; we see our work as ultimately seeking to characterize the knowledge that is possessed by individuals. However, we also strongly believe that the framework and analysis we proposed are congruent with more situated and sociocultural views of science learning. We will elaborate briefly.

First, we have attempted to be clear that we see our clinical interviews as themselves a variety of social context (diSessa, 2007). One of our central points is that we cannot treat an interview as an instrument that allows us to "read out" the knowledge of a student in any simple way. The interviews are dynamic interactions that must themselves be understood in order to properly analyze our data.

Second, we believe that our type of analysis is consistent with a perspective that emphasizes the important role of tools and artifacts in thinking in general, and scientific thinking in particular (e.g., Latour, 1990; Roth & McGinn, 1998). For example, in our discussion of drawing-related dynamics, we attempted to show how the explanations constructed by students could change dramatically when they were asked to draw a picture. In our analysis, we essentially argued that the DMCs constructed by students depended both on their knowledge (the active nodes) and on the affordances of the drawings. Our stance is that such a recognition does not mean that it is not possible to identify elements of individual knowledge. However, it does point to a need for theoretical and methodological care in identifying knowledge.

Finally, we want to emphasize, more generally, the type of dynamism that is built into all of our framework and analyses. In her book *Plans and situated actions*, Lucy Suchman likened human reasoning to the canoeing of a rapids (Suchman, 1987). Her central point, in our view, was that cognitive science has tended to overestimate the generality and power of cognitive structures. In Suchman's account, human reasoning and action are not, in general driven by plans or other large, overarching structures. Instead, like the actions of a canoeist, our thinking behavior emerges in interaction with the world. We believe that our own account is quite congruent with that perspective. We attempt to identify the knowledge possessed by individuals. But we also assume that the particular reasoning behavior we see in an interview emerges in interaction with the interviewing context.

Implications for Instructional Practice

In some respects, the aims of this article have been several steps removed from educational practice. We have instead proposed a new way to focus our commonsense science research, namely on the unfolding dynamics of the interviews we employ. For that reason, we must not expect immediate implications for practice. Even in the long run, we do not expect implications from this work that follow simply and directly from research results. The problem is that there is much that instructional design must consider beyond the details and dynamics of the cognitive landscape.

Nonetheless, we believe deeply that the understanding produced by research of the sort described here can provide important inputs to instructional thinking. All research on student conceptions of science is motivated by the belief that a better understanding of student conceptions—both in general and for specific domains—is essential for designing instruction. Our research seeks to contribute to that larger endeavor, by improving our understanding of interviews, which are the windows through which we look to see student conceptions.

We want to conclude by mentioning one final kind of instructional implication that might build more directly on research of the sort we described. It is possible that the stance we adopt in understanding interviews can be applied to aid in the understanding of what goes on during classroom instruction. For many years, it has been the received wisdom in the science education community that it is helpful for teachers to, as much as possible, "draw out student conceptions." This might occur, for example, when the teacher leads the entire class in a discussion (e.g., Hammer, 1996; van Zee & Minstrell, 1997). In this way, teaching is sometimes, and in some respects, akin to interviewing. This opens the possibility that what we learn from better understanding clinical interviews—such as how an interviewer's prompts affect conceptual dynamics—can help us to better understand the mechanisms that govern science learning in the classroom. For example, when a teacher leads a whole-class discussion, they can expect to see something akin to mode-skimming, as students throw out ideas. And they should be aware that the way that they pose questions can have subtle effects on any class-wide consensus that is reached.

In some respects, this is the flip-side of the point with which we began the article. We asserted that clinical interviews are themselves a time during which a sort of conceptual change can occur, albeit on a small scale. In the same way, we may be able, in some cases, to think of classroom processes as similar to those that occur in the interviews that we have studied. While much work remains to be done, this is one way in which our contributions could ultimately lead to new ways of thinking about science teaching practice.

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Notes

[1]See, for example, the extensive bibliography assembled by Duit (2009).

[2]There are some cases in which the analytic methods also are in dispute. For example, Nobes et al. (2003) have called into question the analytic methods used by Vosniadou and Brewer (1992) to identify mental models in their data. Also, in some cases, the data are disputed. For example, working in the domain of student understanding of the concept of force, diSessa et al. (2004) found that they were unable to replicate the results of Ioannides and Vosniadou (2002), using nearly identical methods.

[3]All names are pseudonyms.

[4]Times listed are from the moment when the question about the seasons was first posed, not from the start of the interview.

[5]Throughout this manuscript we use small caps to highlight the name of nodes we identified. Although we use short phrases to name nodes, this should not be taken as implying that nodes are all propositional in nature.

[6]Lee (2010) is a recent instance in which this pattern is also seen.

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