ABSTRACT

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Education research continues to struggle with how to characterize students' engagement in the doing of science. Too often, educators and researchers reduce doing science to learning particular facts and explanations, or participating in narrowly-defined, de-contextualized ways of reasoning and arguing. In this dissertation, I review prominent work that attempts to characterize students' engagement in one aspect of doing science—seeking coherence. By seeking coherence, I mean trying to make information "hang together" in meaningful, mutually consistent ways. Using examples from a variety of science classrooms, I show that these prominent approaches fail to provide substantive accounts of students' work to form connections between information. To address those weaknesses, I develop, refine and illustrate an alternative perspective on coherence

seeking in science education, one that emphasizes what information students are trying to fit together, how they are trying to fit it together, and toward what ends.

DEVELOPING AN ALTERNATIVE PERSPECTIVE ON COHERENCE SEEKING IN SCIENCE CLASSROOMS

By

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Chapter 1: Introduction

“The ability to relate and to connect, sometimes in odd and yet striking fashion, lies at the very heart of any creative use of the mind, no matter in what field or discipline.”

—George J. Seidel

1.1 Introduction

Making connections is a fundamental part of human nature. “Connexions”, in Hume’s (1910) language, are absolutely central to our ability to function in the world. It is through our ability to make connections that we can use our prior experiences to make predictions about the future. In a linguistic sense, the act of verbalizing or interpreting even a single sentence requires finding ways to connect ideas together, and ideas to words (Stevenson, Knott, Oberlander, & MacDonald, 2000). Connections are so important that the presence of gaps or mismatch between our ideas may lead us to severe psychological discomfort (Festinger, 1957; Wilson, 2002).

Despite evidence that humans continuously seek to connect information in the world around them, educators continue to express concern that students are not making these connections in science class. Education researchers and practitioners alike lament that students see science as “a heap of disconnected facts" (Lerner, 2000, p. 288)—that students often fail to make connections, or to seek coherence, in science (Covitt, Gunckel, & Anderson, 2009; National Research Council, 2007; Nordine, Krajcik, & Fortus, 2010; Songer, 2006).

And yet, we know that students can seek coherence. Students' nascent abilities to find and reconcile inconsistencies (Berland & Lee, 2010; Engle & Conant, 2002; Hammer & van Zee, 2006; Smith, Maclin, Houghton, & Hennessey, 2000), and to build relationships between information via analogies and explanations (May, Hammer, & Roy, 2006; Kelly & Crawford, 1997; Sandoval, 2003; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001) are well-documented. These abilities constitute a rich foundation from which students might develop ways of seeking coherence often identified as characteristic of more experienced scientists (Chinn & Brewer, 1993; Hammer, 1995; Thagard & Nowak, 1988).

Some work attributes the discrepancy between the studies that say children can seek coherence, and the studies showing they do not, to poorly designed and fragmented curricula (Nordine et al., 2010). But what if the discrepancy is largely a matter of perspective? When researchers and teachers comment on student thinking, we tend to notice the inconsistencies students ignore, the information they fail to relate, and the connections they do not make. We then make the problematic generalization that because students are not making particular connections, they are not seeking coherence at all. Really, we mean they are not connecting information together in the ways that we would expect or desire:

> The arguments in favor of the position that children are self-contradictory and inconsistent often do not take into consideration that what may appear as contradictory and inconsistent from the adult or expert point of view may not be contradictory from the point of view of the child. (Vosniadou & Brewer, 1992, p. 580)

This tendency to look only for particular kinds of coherence seeking has limited the field from developing more nuanced interpretations of coherence seeking as it occurs in the classroom. In order to fill this gap, and begin to provide a more nuanced account of coherence seeking, I adopt a perspective that looks closely at the information students are connecting together. Rather than ask if students seek coherence or when, I ask: What information do students try to connect together? And what are the connections that they try to make?

1.2 Research Questions

At the outset of this study, I had hoped to use existing frameworks for coherence to build accounts of coherence seeking in science classrooms. However, when I began to look at classroom data, I found current approaches for looking at and talking about coherence in the science classroom largely unsatisfactory. As illustrated in Chapter 2, these approaches left out much of the nuance and the dynamics of students' coherence seeking. Thus, I decided to refocus my dissertation on creating an alternative perspective that considers coherence seeking as:

- a dynamic, ongoing, and active process, emphasizing coherence *seeking* rather than the resulting coherence between ideas
- having multiple, context-dependent meanings determined by participants, teachers, and researchers

My dissertation tells the story of how I constructed and refined this perspective. Some of these refinements were made in response to theoretical or philosophical dilemmas—for example, making claims about where coherence seeking "lives." But more importantly, I tell the story of refining my perspective in response to data, as I try to build accounts of coherence seeking in my participant classrooms. In each account, I consider:

> In what ways do students seek coherence, with respect to what information, and to what ends?

With respect to the first two parts of that question, the focus is on the “what” of coherence seeking. What kinds of information do students try to fit together? What connections do students make between this information? What tensions arise as students determine what information should be connected, how, and for what purpose? These questions are largely descriptive, but they begin to highlight aspects of coherence seeking that to this point have been overlooked by the literature.

Moving beyond just description, I also ask: To what end(s) do students seek coherence? I consider the question of ends from the students’ perspective, trying to make sense of what purposes and reasons students might have for pursuing particular kinds of connections, in particular moments, in science class. Though I intentionally distinguish these claims from the purposes that expert scientists and educators might see in students’ coherence seeking, the analyses in this study nonetheless contribute to existing literature that identifies potentially productive aspects of students' engagement in science (Engle & Conant, 2002; Ford, 2006; Hammer & van Zee, 2006; Russ, 2006; Varelas, Pappas, & Rife, 2006; Smith, Maclin, Houghton, & Hennessey, 2000).

Though they are largely descriptive and normative, these questions are a necessary step in working towards a more nuanced account of coherence in the science classroom. In this study, I present accounts of coherence seeking drawn from a range of formal science learning experiences, including elementary classrooms and teacher professional development workshops. Together, these accounts serve as an assessment of the strengths and weaknesses of my perspective, and lay the groundwork for continued work on the dynamics of students’ coherence seeking.

1.3 Structure of the Dissertation

The construction and refinement of any framework, perspective, or theory necessarily involves tension, as such work challenges the status quo, but at the same time attempts to build on it with an eye toward what could be. In conducting, documenting, and writing up my work on coherence seeking in narrative form, I felt tension over when to complexify and when to simplify, when to generate and when to prune ideas, when to analyze data systematically and when to let disjointed insights emerge, and when to fragment and when to unify (Conlin, 2012; Levrini et al., submitted).

In selecting a narrative form to capture these struggles, I opted to focus each chapter on one or two important aspects of the development of this perspective. For example, Chapter 4 considers in detail issues of what counts as evidence of coherence seeking, and in that section I discuss relevant literature, theoretical and analytical challenges, tentative findings, and unanswered questions. Likewise, in Chapter 5, I explore from multiple angles the challenge of determining what information students try to connect, and in what ways. The narrative arc of the dissertation spans from largely theoretical and research-centered in the early chapters, to increasingly empirical and focused on issues of practice in the later chapters.

1.4 Overview of Dissertation Chapters

Chapter 2: Motivation and Literature Review

This chapter offers a comparative analysis of three prominent coding schemes for coherence, as well as a description of how my work builds on and deviates from these approaches.

Chapter 3: The Beginning of Constructing a Perspective on Coherence

This chapter presents the evolution of my methodological approach for building and refining a perspective on coherence, which I illustrate through successive analyses of classroom data. I conclude with a detailed explication of the principles underlying my approach.

Chapter 4: Identifying Evidence of Coherence Seeking in Science Classrooms

Building on the theoretical framework outlined in Chapter 3, this chapter considers in detail the various categories and forms of evidence for coherence seeking, contextualized with examples from participant science classrooms.

Chapter 5: Considering What Information Students Try to Connect—Examples from 5th Grade Experiments on Evaporation

In this chapter, I focus on students' coherence seeking within the context of another highly studied phenomenon in science class—students' response to anomalous data. Through an analysis of students' experimental work over the course of multiple days, I consider the analytical challenges of identifying the "information" that students try to connect, and the "meaningful relationships" they try to form.

Chapter 6: Intent and Coherence Seeking—Examples from a 4th Grade Class Arguing About the Contents of a Battery

Both the terms "seeking" and "trying" attribute to students some sort of awareness, or even intentionality, in their sense-making around natural phenomena. In this chapter, I present a series of clips from a 4th grade class reasoning about the contents of a battery to suggest that perceptions of students' intent are intimately tied to our understanding of what information they are trying to connect.

Chapter 7: Reflections on Defining and Seeing Evidence of Coherence Seeking

Having outlined and illustrated the main components of coherence seeking in previous chapters, in this reflection I comment on the strengths and weaknesses of the perspective, and make suggestions for future refinement.

Chapter 8: Discussion and Implications for Pedagogy

Finally, this chapter positions the analytical and theoretical findings of the dissertation within the broader context of education research and practice, with particular focus on implications for science curriculum.

Chapter 2: Motivation and Literature Review

"Whether that coherence obtains universally is a question that need not be answered here since only those parts where the coherence has actually been found become part of Science." *—Wilhelm Ostwald*

2.1 Introduction

We have good reason to think that adults and children are constantly connecting information about the world together in ways that allow them to make sense of the world. And yet, education research lacks clarity on if and how students make these connections in science class.

I hope to work towards some clarity in this regards, by beginning with a relatively simple question: What does it look like when students try to find coherence in science? Consider the following excerpt from a 5th grade discussion about clouds. One student, Raphael, spontaneously finds a way to connect clouds, fog, water, the sun, and evaporation:

> Raphael: Uh, well I think that uh when the sun comes up, the // it pushes the clouds down and that's the morning and uh they turn into fog. And they go and they form puddles. And then when the sun gets really hot // uh hotter like later in the afternoon, the puddles evaporate. And that's, and the clouds are connected to the fog and the water [*gestures with right hand, palm facing up*] and the sun [*lifts hand up*] // evaporation.
>
> Ms. M: Okay, so there's some // now you're bringing back in what we talked about yesterday. There's some connection with all of this.
>
> Raphael: Yeah, the ice, because they're made of ice, ice can melt. And since they're so close to uh, the sun, the sun will push em down [*moves left hand in a patting motion*] because // and then they'll turn into fog and they'll, they'll melt and then the water that's left will go into the puddles and the sun will evaporate the puddles [*moves left hand slowly up*] later on in the afternoon.

What evidence of coherence or coherence seeking (if any) can we see in this clip? In Chapter 3, I will argue that this clip contains ample evidence of coherence seeking, both on Raphael's and Ms. M's behalf. I will further argue that one's ability to notice this evidence requires a broader notion of coherence than what currently exists in the literature.

But first, I review existing literature in the form of a comparative analysis. In the next section, I present the theoretical underpinnings of three prominent coding schemes for coherence, as represented in Vosniadou and Brewer (1992), Thagard (1989), and Sandoval (2003). Then, I apply each of these coding schemes to the Raphael clip above. Finally, I discuss the strengths and weakness of each approach in terms of their ability to help us see coherence seeking in classroom data.

2.2 Defining Coherence—Three Approaches from the Literature

2.2.1 Stella Vosniadou and Colleagues: Coherent Mental Models

Education research has turned to the construct of coherence mainly to (i) characterize the knowledge in students' minds, (ii) model how students' ideas change, and (iii) assess the quality of students' verbal and written work. Exemplifying the first use of coherence, Stella Vosniadou and her colleagues have written extensively on the structure of students' knowledge about the shape of the Earth.

Vosniadou and Brewer (1992) begin with the presupposition that students have evidence to think the Earth is flat. They walk on a ground which feels and looks relatively flat, and they have seen maps depicting a flat Earth. On the other hand, in elementary school, students hear stories about a round Earth and they see globes representing the Earth as a sphere. With all of this contradictory evidence about Earth's shape, what shape do students think the Earth has?

Some research suggests that there is no single answer to this question. The fragmented or manifold resources view of knowledge claims that students have many bits of knowledge about Earth's shape, and they coordinate these bits dynamically when trying to make sense of the world around them. Sometimes they think or will say the Earth is flat, other times that it is round, and sometimes they will say both or neither of these. Students' answers appear inconsistent because the resources they draw upon in constructing their ideas depend on the situation. When playing outside, it makes sense to think of the Earth and ground as flat. When a teacher asks you what the shape of the Earth, it makes sense to say that it is round. In other words, students think the earth is both flat and round.

Vosniadou and Brewer (1992) dispute the fragmented view of cognition, instead suggesting that children's intuitive knowledge about the shape of the Earth "can be conceptualized as consisting of a coherent and systematic set of ideas which deserve to be called a theory" (p. 537). In this unitary approach, students may have evidence that the earth is round or flat. But, they combine these experiences into relatively static "hybrid" models of Earth's shape.

To marshal additional evidence for the unitary view of cognition, Vosniadou and Brewer attempt to show that students' seemingly inconsistent answers to questions about the shape of the Earth are actually indicative of a single underlying coherent, but incorrect theory (a hybrid model). Their approach was as follows: Ask students a series of questions about the shape of the Earth. Through the line of questioning, intentionally make space for students to contradict themselves. For example, if a student claims the Earth is round, the interviewer asks a series of questions to see if the student will also say the earth is flat (“draw the Earth”, “Does the Earth have an edge?” etc.). Finally, analyze these responses to see if somehow even the apparently contradictory responses fit together into a wrong, but coherent model to the student. For example, if a student describes the Earth as both *round* and *having an edge*, maybe the student is reasoning from a coherent “pancake” model of the Earth. In their quest for evidence of cognitive coherence, the authors identify five hybrid models of the Earth, and further argue that most of their research participants appear to reason from one of these five models.

2.2.2 Paul Thagard and Colleagues: Explanatory Coherence and Theory Selection

Vosniadou and Brewer’s work on coherence primarily serves to marshal evidence for a particular theory of knowledge. Paul Thagard and his colleagues also use coherence as a way of describing the mind, but they do so from an entirely different theoretical and analytical perspective.

In the late 1980s, Paul Thagard, trained in philosophy of science, set out to understand how scientific communities come to accept one theory over another. He worked under the basic assumption that scientists prefer the explanation that is more “coherent” or that “fit[s] together” best with available evidence (Thagard, 2000, p. 17). Thagard developed this assumption into a more detailed theory of *explanatory coherence*, which he and his colleagues formulated into a computer program (ECHO) that can evaluate the “explanatory coherence” of any theory (Ranney & Schank, 1998; Ranney & Thagard, 1988; Schank & Ranney, 1992).

According to Thagard, statements and ideas either “cohere (fit together) or incohere (resist fitting together)” (Thagard, 2000, p. 17). Just as there are different ways that ideas can fit together, so there are multiple kinds of coherence. Throughout their publications Thagard and his colleagues identify a number of different kinds of coherence: analogical, conceptual, deliberative, deductive, emotional, ethical, explanatory, linguistic, and perceptual. Each form of coherence involves different kinds of ideas, and different relationships between those ideas. All are the result of "maximal satisfaction of multiple constraints" (p. 17). In other words, coherence describes the extent to which a set of ideas fit together.

Among the variety of ways that people can fit ideas together, Thagard identifies explanatory coherence as the fundamental form of coherence in science because the work of science is to develop the most robust explanations for phenomena.[1] The details of his Theory of Explanation Coherence (TEC) and its "seven principles of explanatory coherence:" symmetry, explanation, analogy, data priority, contradiction, competition, and acceptability appear in Thagard (1989). Simply speaking, the theory says that for ideas to be coherent, they must not contradict, and they must also "speak" to each other. In other words, a collection of non-contradictory, but random facts is not coherent in the TEC. The TEC applies both locally (coherence between two ideas) and globally (coherence among a set of ideas).

Alongside the development of the philosophical aspects of TEC, Thagard and his colleagues designed a computational model, called ECHO, to measure the coherence of explanations. They applied ECHO to theory selection situations from history of science and science education. Thagard and Nowak (1988), for example, showed that Wegener's initially unpopular theory of plate tectonics was ultimately accepted over competing

[1]Within philosophy, the role of coherence in science has been explored extensively. Two lines of such work are *inference to the best explanation* and *coherence theory of truth.*

theories because it was more coherent with geological evidence. Later, Ranney and Thagard (1988) showed that ECHO could predict how students might revise their beliefs in physics "in ways driven by considerations of explanatory coherence" (p. 4). But, unlike Vosniadou, Thagard does not willingly leap from explanatory coherence to cognitive coherence. That is, while he suggests that students might revise their beliefs to maximize explanatory coherence, he does not make specific claims about individual students' cognitive structures in his work.[2]

2.2.3 William Sandoval: Causally Coherent Explanations

Finally, and most recently, William Sandoval's (2003) work aims to assess how well students' written explanations "hang together." His work is part of a larger trend in science education research to help students develop their abilities to engage in disciplinary practices (Driver, Newton, & Osborne, 2000; Kuhn & Pease, 2008).

According to Sandoval, we can view students' explanations as stories—uninterrupted, written descriptions of a phenomenon that explain why an event happened. To assess these stories, we might compare them to the scientifically accepted ones, i.e. to determine whether the students' ideas are "correct" or "incorrect." Davis' (2003) coding scheme for the coherence of ideas in students' written work takes such an approach:

> The coherence of students' ideas in their letters is a strong measure of knowledge integration because it measures both the degree of linkedness and the conceptual validity. By *linkedness* I mean both links that were made between evidence and claims and the extent to which ideas cited do or do not contradict each other (i.e., whether links are made between contradictory principles like "black absorbs light" and "black attracts heat"). By *conceptual validity* I mean whether the ideas the students cite are scientifically normative. (p. 112)

[2] Ranney & Thagard (1988) do not comment on cognitive structures, but do "conceive of the networks as models of the current contents of working memory" (p. 10).

However, Sandoval suggests that the disciplinary practice of constructing explanations involves more than concepts. Students must also come to develop sophisticated epistemic criteria, such as coherence, for evaluating explanations. Thus, unlike Davis (2003), Sandoval distinguishes between conceptual validity and coherence. He suggests that students might develop explanations that are internally consistent and causal, yet not scientifically normative.

To analytically separate correctness from coherence, Sandoval draws on the studies of causal cohesion in literature as discussed in Trabasso, Secco, and Van Den Broek (1982). In the "story model," a coherent explanation is one that contains a central causal chain, or cause-and-effect story. The more aspects of the explanation that are explicitly connected to this chain, the more coherent the explanation. For example, one student in Sandoval's study concluded that weight was an important factor for predicting Finch's survival of a drought, writing:

> The trait selected by the pressure of the drought is weight. This is because with less food, the finches began to lose weight. The heavier finches before the drought had an advantage over the lighter ones when the drought occurred. If the heavier finches were either fatter or more muscular they could survive better. The fatter ones could live off their fat, thus needing less food while the muscular finches could obtain the food better due to their physical superiority. (Sandoval, 2003, p. 29-30).

Though the student incorrectly identifies weight as the important trait (beak size is the "correct" answer), Sandoval assigns his explanation a perfect coherence score because it is articulate, hangs together, and the student did not have access to data that would contradict his weight claim.

2.3 The Analyses

Each of the three approaches to coherence differs in their motivations, theoretical underpinnings, and analytical approaches. In this section, I demonstrate that each of these approaches allows us to see different aspects of coherence in the Raphael clip.[3] I conclude with a summary of the strengths and limitations of these approaches, in terms of finding evidence of coherence in Raphael's ideas.

2.3.1 Analysis 1: Vosniadou and Brewer's Mental Models

The Vosniadou and Brewer analysis begins with two questions: Are the ideas in Raphael's explanation consistent with each other? And if so, does that mean that Raphael has a coherent mental model for thinking about water-related phenomena?

The first chunk of the transcript offers clear evidence that Raphael thinks his ideas about rain, the puddles, clouds, etc. fit together. And the fact he has fit all of these ideas together is precisely the thing he wants to share with the class. He says in lines 4-6:

> And that's, and the clouds are connected to the fog and the water [*gestures with right hand, palm facing up*] and the sun [*lifts hand up*] // evaporation.

Raphael explicitly states that in his story, he has found a way that clouds, fog, water, the sun, and evaporation are connected, but how?

Typically, the interviewers in Vosniadou and Brewer's studies would ask probing questions to help interpret Raphael's explanation as he constructs it; however, because this data comes from the classroom, rather than a clinical interview, I do not have the advantage of looking at Raphael's responses to probing questions. Nevertheless, I can try to make sense of his ideas, starting with the first chunk of explanation:

> Raphael: Uh, well I think that uh when the sun comes up, the // it pushes the clouds down and that's the morning and uh they turn into fog. And they go and they form puddles. And then when the sun gets really hot // uh hotter like

[3] These analyses represent my interpretation of each of these researchers' frameworks.

4 later in the afternoon, the puddles evaporate. And that's, and the clouds are
5 connected to the fog and the water [*gestures with right hand, palm facing up*]
6 and the sun [*lifts hand up*] // evaporation.

In lines 1-2, he begins with a description of how fog forms: in the morning, the sun rises and "it" (presumably the sun) pushes the clouds down, turning them into fog. It is not clear exactly how the sun pushes the clouds down, and how that leads to fog and puddle formation. In the last step of Raphael's explanation, the puddles evaporate as the sun gets hotter in the afternoon.

Raphael concludes the first portion of his explanation with a statement that is reminiscent of the water cycle—that clouds, fog, water, evaporation, and the sun are all connected. Next, Ms. M comments on the nature of Raphael's idea. She notices that Raphael draws on the previous day's discussion about the puddle, and made "some connection" between the various topics they have discussed. Raphael confirms this interpretation ("yeah"), and continues:

9 Raphael: Yeah, the ice, because they're made of ice, ice can melt. And since
10 they're so close to uh, the sun, the sun will push em down [*moves left hand in*
11 *a patting motion*] because // and then they'll turn into fog and they'll, they'll
12 melt and then the water that's left will go into the puddles and the sun will
13 evaporate the puddles [*moves left hand slowly up*] later on in the afternoon

This second chunk of explanation fills in some of the missing mechanisms from lines 1-6. According to Raphael, clouds are made of ice, which can melt, and also, clouds are close to the sun. So when the sun rises, it melts/pushes down the clouds, forming fog and puddles. Then, in the afternoon, the sun warms up and the puddles evaporate.

While there is outside information that I might draw on to further understand Raphael's story, Vosniadou and Brewer are careful to limit their analyses to the information that the students share during the interviews. In other words, the goal is to check whether Raphael's explanation is internally coherent, rather than to see if this explanation is coherent with other outside experiences.

To determine if Raphael's explanation is internally coherent, I looked for contradictions in his explanation. Overall, Raphael's explanation is remarkably internally coherent. I could find only one inherent contradiction in his explanation, related to whether it is hot or cold close to the sun. Raphael says that clouds are made of ice, which implies that it is cold up high where clouds are. Later, however, he claims that the sun is warm and melts the clouds, suggesting that up higher, closer to the sun, its warmer. So is it warmer up high, or colder? One possibility is that Raphael does not notice or see this contradiction. Another possibility is that Raphael thinks that in the night, when the sun is down, it is cold in the sky. Then, when the sun comes up, the sun is hot so it is warm up high. Either way, it is plausible that Raphael's ideas fit together, to him.

Other than the one contradiction, Raphael's story is relatively internally coherent, from my perspective. But does the coherence of his explanation suggest cognitive coherence, that is, a coherent mental model? In making this leap in their own data, Vosniadou and Brewer (1992) write:

> It is not clear from the results of this study whether the models we have identified represent precompiled theories which are stored in long-term memory or whether they are constructed by the children on the spot under the influence of our questions… (p. 575-576)

In Raphael's case, he most likely created his explanation on the spot; in fact, we see him adding to it in the moment, suggesting that prior to his sharing it, it did not exist in his mind in a pre-compiled form.

One of the strengths of the Vosniadou and Brewer approach is that it asks us to distinguish between how ideas fit together to a student, and how they may (or may not) fit together to more knowledgeable others. More broadly, their work suggests that coherence, or the extent to which ideas hang together, should be measured not in absolute terms, but rather, from the perspective of the sense-maker.

But Vosniadou and Brewer's approach does not lend itself to considering the dynamic construction of ideas. In the generative, dynamic classroom environment, students like Raphael are continually constructing ideas, and seeking coherence in the process. Even in their interviews designed to illicit underlying student thinking, Vosniadou and Brewer (1992) struggle to make sense of the origin of student's ideas:

> Some children appeared to be very certain about their views and expressed them with such speed and lucidity that it is unlikely that they constructed them on the spot. In other cases, the sequence of responses to our questions suggests some model construction while answering the questions. (p. 576)

Vosniadou and Brewer do not elaborate on the evidence for "model construction while answering questions"; their focus is on evidence of consistent and static models, rather than dynamic ones. However, in re-visiting Vosnadiou and Brewer's data, I found additional evidence of coherence, but not in the ways that the authors suspected. A third grade child named Darcy ("C" in transcript), for example, appears to try to fit her responses to the interviewer's ("E") prompts:

> E: Now that's a really good picture. Now show me where the people live.
> C: (Child draws house at the border of the paper.)
> E: Can you show me in your picture where the people live, Darcy?
> C: Down over here? (Child draws another house along the same border.)
> E: Is that where people live on the earth?
> C: Child (giving in to the implicit demands of the experimenter) erases one of the houses and draws a person inside the circle.
> E: Here is a picture of a house. This house is on the earth isn't it? How come the earth here is flat but before you made it round?
> C: I don't know.
> E: Is the earth really round?
> C: No.
> E: It's not really round. Well, what shape is it?

C: Yaa, it's round. (Vosniadou & Brewer, 1992, p. 570)

The clip above illustrates clearly why it is important to distinguish between *coherence* and *coherence seeking*. A static view of coherence suggests that Darcy has in her mind a set of ideas about the earth. The interviewer's job is to pull that set of ideas out and examine it, to see how it fits together.

A dynamic view of coherence seeking suggests that Darcy (and also the interviewer) continuously tries to fit information together. For example, after Darcy draws a picture of the Earth, the interviewer asks Darcy to show "where the people live." Darcy had not included this information in her drawing, so now, in response to the interviewer she must fit people into her drawing. She draws a house, and then another, on her picture. The interviewer, apparently unsatisfied, again asks where the people live. Darcy, sensing that she has not fulfilled the interviewer's demands, again changes her picture and draws a person inside her circular earth. In these moments, Darcy likely coordinates a variety of information: her own drawing, her interpretation of the interviewer's question, her many ideas about the shape of the earth and people and houses, her ideas about the social expectations of the interview (for example, that she should fulfill the interviewer's requests), non-verbal cues from the interviewer, her own feelings about how the interview is going, etc. The process of coordinating all of this information is the essence of coherence seeking, and Vosniadou and Brewer's relatively static conception of coherence misses these dynamics in Darcy's ideas, and also in Raphael's explanation.[4]

[4] Vosniadou & Brewer (1992) do allow for some dynamism in the construction of mental models. They suggest that students may construct mental models on the spot, but that "stable underlying conceptual structures…constrain the range of possible mental models that children can form" (p. 576).

2.3.2 Analysis 2: Thagard, Ranney, and Schank's Connectionist Model

To take a second look at Raphael's explanation, I used a graphical adaptation of Thagard's ECHO program, called ConvinceMe. The program is publicly available, and comes with a handbook describing in detail how to code explanations for entry into ConvinceMe.[5]

In some sense, the ConvinceMe program itself is unnecessary; the analysis of coherence occurs during the formatting and coding Raphael's explanation for input into ConvinceMe. The first step of formatting is to clean up the explanation. I deleted Ms. M's comments and combined Raphael's statements into one block of text. Then, I labeled these ideas according to hypothesis (H) or evidence (E) as described by Schank and Ranney (1992):

> Uh, well I think that uh [H1][when the sun comes up, the // it pushes the clouds down] and [E1][that's the morning] and uh [H2][they turn into fog]. And [H3][they go and they form puddles.] And then [H4][when the sun gets really hot] // uh [E2][hotter like later in the afternoon], [H4][the puddles evaporate]. And that's, and [H5][the clouds are connected to the fog and the water and the sun // evaporation]. Yeah, the ice, because[E3][they're made of ice], [E4][ice can melt.] And since [E5][they're so close to uh, the sun], [H1][the sun will push em down] because // and then [H2][they'll turn into fog] and [H6][they'll, they'll melt] and then [H3][the water that's left will go into the puddles] and [H4][the sun will evaporate the puddles] [E2][later on in the afternoon].

[5] http://www.soe.berkeley.edu/~schank/convinceme/software.html

Because explanatory coherence is "fundamentally a matter of there being a causal relation between what is explained and the representations that do the explaining", the coding for (H) and (E) is perhaps the most important step in the coding (Thagard, 2000, p. 65). However, the phenomenon that Raphael was trying to explain was not well-defined, so it was not easy to distinguish between hypotheses and evidence. For example, in lines 3 and 4, Raphael says that when the sun gets hotter in the afternoon, the puddles evaporate. Is this a hypothesis he about what makes puddles evaporate? Or is he providing evidence for his later claim that clouds, fog, the sun, and evaporation are all connected in lines 5 and 6? In general, I counted as evidence any pieces of information that Raphael likely takes as "observable truths"—that ice melts, that clouds are made of ice, that the sun is hotter in the afternoon. I labeled the more tentative statements (indicated by tone or linguistic markers such as "I think") and explanatory statements as hypotheses.

After coding the statements, I used the linguistic cues identified by Schank and Ranney (1992) ("because", "since", "so") to determine the explanatory links and contradictions in the explanation. I also inferred some connections based on the structure of Raphael's argument (for example, that all E's and H's explain H5).

E3, E4, E5 explains H1, H2, H6

All E's and H's explain H5

H1 explains H2

H1 explains H3

I tried to enter these relations as I thought Raphael might see them. However, Raphael uses words in a story-like manner ("And then…"), as though he is narrating the movement of water from cloud, to fog, to puddle, and back to evaporation. As Ms. M notices, Raphael is clearly drawing connections between water-related phenomena; unfortunately, these connections do not easily translate into a set of "explain" and "contradict" relationships. In fact, Ranney and Thagard (1988) note that "translating utterances into propositions" can be problematic because coders may add links between propositions that are not linked in the mind of the subjects, or misinterpret what the subjects view as evidence, fact, or explanation (p. 13).

In a sense, most of what the ConvinceMe approach allows us to see in terms of coherence is revealed in these preliminary steps—the formatting and coding of the explanation. For example, we see that Raphael's explanation contains an intimately connected set of hypotheses and evidence, and that he identifies the sun as a central causal element in the formation of puddles, fog, and evaporation. He does not identify any explicit contradictions in his explanation, nor does he cite counter-evidence. All of the elements in his explanation are connected to at least one other element—there are no isolated, disconnected facts presented in his explanation.

In the final and perhaps superfluous step, I entered all of these codes into the ConvinceMe program. The program requires setting a variety of parameters related to hypotheses and evidence (i.e. reliability, priority, believability). For the first run, I kept all of these parameters at the default setting. After each run, a window pops up that says "The correlation between you and ECHO: #." The number, between -1.0 and 1.0, represents the degree to which ECHO agrees with the user's coding of the explanation, and is indicative of the explanation's coherence.

After my first run, the correlation was 0.0. In terms of coherence, ECHO neither agreed nor disagreed with how I coded Raphael's explanation. For the second run, I changed the parameters on the hypotheses and evidence to reflect the degree to which Raphael might "believe" or trust in each statement. For example, I know that Raphael probably very much believed that clouds are made of ice when he gave his explanation because the teacher had just confirmed this idea. After adding in plausible values for the believability and source of Raphael's ideas, ConvinceMe returned a score of -0.07. The negative score means that ConvinceMe disagrees with my coding; or in other words, Raphael strongly believing that clouds are made of ice actually makes his ideas less coherent, to ECHO. For the third run, I attempted to aim for a perfect coherence score (1.0) by playing with the parameters. I was able to achieve a score of 0.94, solely by adjusting the values of "believability" for each of Raphael's comments in his explanation.

Finally, to see what affect an implicit contradiction would have on the scoring, I entered a contradiction between H1 (the sun pushes clouds down) and H4 (the sun makes puddles evaporate). These ideas, in fact, could be seen as contradictory (how can the sun both push water down, and make it rise up?), but there is no evidence that Raphael sees them as contradictory. But just to test whether this contradiction would change the score, I inserted it into the coding for Run 3, which previously had a nearly perfect coherence score. The result was a new score of 0.85, slightly lower than before. That is, the explanatory coherence score of Raphael's ideas depends not only whether the explanation contains contradictions, but more importantly on the weighting of these ideas in terms of trustworthiness, believability, etc. The quantitative scores are thus ambiguous, and really tell us little about what kinds of connections Raphael might be trying to make among his experiences of water-related phenomena.

2.3.3 Analysis 3: Sandoval's Story Model

On the surface, Raphael's explanation seems tailored for Sandoval's story model analysis. The explanation sounds like a story (And then…and then…) and clearly contains non-canonical elements. For example, Raphael's story for what causes fog goes something like this:

> *Clouds are made of ice, and are high up in the sky. When the sun rises, it melts and pushes down the clouds, which makes fog.*

Raphael's fog story, while fascinating, is clearly incorrect. Fog generally forms when water vapor cools and condenses at relatively low altitudes, not when ice is heated at high altitudes. Davis (2003) would suggest that Raphael's story is incorrect and therefore relatively incoherent. However, Sandoval's work suggests that while incorrect, Raphael's story might still be causally coherent.

The first step in Sandoval's approach is to break down the explanation, verbatim, into propositions of causes and effect, or antecedents and consequences. Though his approach was designed for written explanations, for the purposes of this analysis, I treated Raphael's entire statements above as a single "explanation" and neglected Ms. M's contributions. I also deleted repeated ideas, per Sandoval's recommendation:

a) well I think that uh when the sun comes up, the //
b) it pushes the clouds down and
c) that's the morning
d) they turn into fog.
~~And they go and they form puddles.~~
e) when the sun gets really hot // uh hotter
f) like later in the afternoon
~~the puddles evaporate.~~

g) the clouds are connected to the fog and the water and the sun // evaporation.
h) because they're made of ice
i) ice can melt.
j) And since they're so close to uh, the sun,
~~the sun will push em down~~
~~because // and then they'll turn into fog~~
k) and they'll, they'll melt
l) and then the water that's left will go into the puddles and
m) the sun will evaporate the puddles
~~later on in the afternoon.~~

Next, I attempted to organize these ideas into causal chains, a step made difficult by the fact that there is no single phenomenon that Raphael appears to be trying to explain. Among the possible questions he addresses are:

How does fog form?

How does the puddle form?

Where do puddles go in the afternoon?

How are clouds, fog, water, the sun, and evaporation connected?

Like Thagard, Ranney, and Schank's work, Sandoval's work is limited in that he assumes that the phenomenon to be explained is clear and well-bounded, so that it is easy to establish what is being explained and to identify the causal story in that explanation. For Raphael, neither is the case.

However, for the purposes of continuing with the analysis, I identified causal chains in Raphael's statements, which are represented graphically in Fig. 1. For example, I inferred from Raphael's statements that one of the things he was trying to explain was the opening question—why puddles would disappear in the afternoon (n). The causal story for this phenomenon is that (a) the sun rises, (k) the clouds melt, (l) the remaining water goes into puddles, and then (m) the sun evaporates these puddles.

To calculate a final score for coherence, Sandoval takes the ratio of propositions in the central causal chain to the total number of propositions in the network, resulting in a score from 0 to 1 (p. 26). In Raphael's case, the total number of nodes in the causal chain is 9 (h, i, j, a, b, d, k, l, and m) and the total number of nodes is 13 (n is an inferred node, which does not count as part of the scoring). The coherence score for his explanation is 0.69. For comparison, Sandoval found that the mean coherence of the explanations provided by biology students in his study was 0.70; however, scores ranged from 0 (completely incoherent) to 1 (completely coherent). Coherence generally dropped when students failed to use "clear causal language" or when they made "unconnected causal claims" (p. 33).

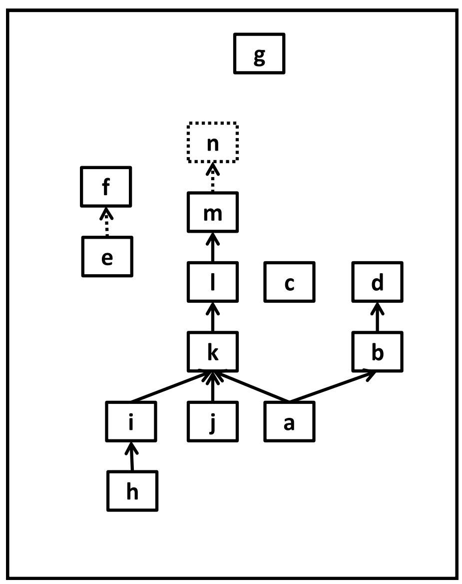

Figure 1: Causal Chain for Raphael's Cloud Story

Solid arrows represent causal chains. Dashed lines indicate implicit units of information or causal relationships.

Sandoval's analysis combines important aspects of Vosniadou and Brewer's and Thagard's work. Like Vosniadou and Brewer, Sandoval considers how ideas might be connected to the student, and he distinguishes between the correctness and the coherence of an explanation. And like Thagard, Sandoval's quantitative coding scheme focuses on one particular kind of coherence—causal/explanatory.

By grounding his coding scheme in reading comprehension literature, Sandoval's work has the potential to draw attention to aspects of coherence that are often overlooked—including linguistic and narrative coherence. Raphael's explanation is not only a collection of causes or effects, hypotheses and evidence, but it is a story about how "the clouds are connected to the fog and the water and the sun // evaporation" (line g). In summing up his ideas in g, Raphael explicitly tries to connect a series of ideas together in a part-to-whole, or cyclical relationship. In that way, his explanation is very similar to the kind of relationships described in classroom versions of the water cycle. However, in Sandoval's approach, g actually counts against Raphael because it is not explicitly part of a causal chain—it does not describe explicitly a cause and an effect. Because Sandoval focuses only on one kind of relationship, a causal one, his coding scheme not only misses the part to whole/cyclical relationship in g, but in fact line g counts as evidence *agains*t students' ability to attend to epistemic criterion of coherence. Such a tendency to define coherence narrowly, according to the researcher's preferences about what is most important in science, is common in the literature. And, ironically, the focus on causal chains in the "story model" analysis leaves out important aspects of Raphael's coherence seeking—that he is trying to create a *story* of the water cycle!

2.4 Discussion

2.4.1 Motivation for Continued Work on Coherence

The literature reviewed here suggests a variety of reasons to study coherence in science classrooms. As Thagard's work demonstrates, coherence appears to play an important epistemological role in scientific progress. Generally speaking, scientists work to increase the explanatory coherence of theories—that is, they work to increase the extent to which models and theories align with observations of the natural world.[6] For example, coherence between theory and observation drives work on cosmological models in astronomy:

> Observations are providing progressively tighter constraints on cosmological models advanced to explain the formation of large-scale structure in the Universe. These include recent determination of the Hubble constant…and measurements of the anisotropy of the cosmic microwave background. Although the limits imposed by these diverse observations have occasionally led to suggestions that cosmology is facing a crisis, we show here that there remains a wide range of cosmological models in good concordance with these constraints. (Ostriker & Steinhardt, 1995, p. 600)

Sometimes, the discrepancies between observation and theory within a field become so untenable that a "paradigm shift" must occur (Kuhn, 1962). But beyond coordinating theory and observation, there are other types of coherence seeking in science as well. Physicists have sought to fit together the four fundamental forces into a coherent, all-encompassing model of matter and energy under a "grand unified theory" or the even more elusive "theory of everything" (Ellis, 1986). The coherence they seek is between theories, rather than between theory and observations. Interdisciplinary fields, such as atmospheric science, can require additional kinds of coherence. Our recent advances in

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[6] Increased coherence, though, depends on one's perspective. Furthermore, as Chinn and Brewer (1993), Frisch (forthcoming), and Meheus (2002) show, scientists may respond locally to inconsistencies in any number of ways, including ignore or discount them. But among the aims of scientific explanation more broadly is "an objective kind of insight that is achieved by a systematic unification, by exhibiting the phenomena as manifestations of common underlying structures and processes that conform to specific, testable basic principles" (Hempel, 1966, p. 83, quoted in Weber & De Clercq, 2002, p. 165).

understanding the diurnal variation of some atmospheric constituents (Su et al., 2011), as well as the effect of aerosols on precipitation (Li et al., 2011), have come as a result of coordinating formerly competing physical and chemical perspectives.

Coherence (or seeking coherence) also pays a central part of students' science learning. Both the fragmented knowledge and intuitive theory perspectives on knowledge state that learning requires fitting and re-fitting information (broadly defined here to mean observations, ideas, theories, etc.) together. In fact, an entire pedagogical method called *discrepant events* aims to capitalize on the importance of coherence seeking in conceptual change (Gonzales-Espada, Birriel, & Birriel, 2010; O'Brien, 2010).

Finally, as an aspect of sense-making, coherence seeking cuts across many of the disciplinary practices under study in the field of education research. Though rarely identified as "coherence", many researchers have identified how trying to put information together in meaningful, mutually consistent ways is central to learning to do science. In describing productive disciplinary engagement, Engle and Conant (2002) state:

> …students' engagement is productive to the extent that they make intellectual progress, or, in more colloquial language, "get somewhere" ... What constitutes productivity depends on the discipline, the specific task and topic, and where students are when they begin addressing a problem. In the FCL case, we show that the students' arguments for their claims became increasingly sophisticated over time (Hatano & Inagaki, 1991), and that their discussion prompted them to raise new questions. In other situations, such productivity might involve things like recognizing a confusion, making a new connection among ideas, or designing something to satisfy a goal. (p. 403)

In trying to "get somewhere" in their reasoning about the natural world, one of the things students do is seek coherence—they try to find gaps in their understandings, they try to make new connections among ideas, they check if their ideas are consistent, and so on. The coherence seeking may take the form of argumentation (Driver, Newton, & Osborne, 2000), explanation building (McNeill, Lizotte, Krajcik, & Marx, 2006), experimentation (Ford, 2006), or modeling (Schwarz et al., 2009). Regardless of the form, we can aptly describe students' inquiry as "the pursuit of coherent, mechanistic accounts of phenomena" (Hammer, Russ, Scherr, & Mikeska, 2008, p. 150).

2.4.2 Learning From Existing Coding Schemes

The three perspectives reviewed in this chapter reveal some important insights for continued work on coherence. First, coherence must not be confused with, or even linked to, correctness. Sandoval's analysis shows that a wrong explanation can still hang together. Raphael's explanation was relatively coherent (0.69), even though it contained glaringly wrong ideas about the water cycle. Thagard's coding scheme does not even take correctness into account—none of his parameters rely on the evidence, hypothesis, or the relations between them being true or aligned with the canon. And finally, Vosniadou and Brewer's work shows that students' wildly non-canonical ideas about the shape of the Earth might still fit together for the child in important ways. In other words, all of these schemes allow us to see that there are productive aspects of students' otherwise incorrect ideas.

Secondly, the literature suggests that there are many ways that students can connect information together. Analogies, contradictions, consistencies, narratives, cycles, and syllogisms are all ways of fitting information together, and coherence seeking in science might involve any of these and more. Vosniadou and Brewer's work goes to great lengths to explore internal consistency, and explanatory coherence has been the focus of many other studies (Chinn & Brewer, 1993; diSessa, Gillespie, & Esterly, 2004; Samarapungavan & Wiers, 1997). The studies described in this section focus narrowly on one or two forms of coherence. More work needs to be done to look at the multiple kinds of coherence students seek in science and to consider how students develop criteria for coherence. Some work that considers multiple aspects of coherence seeking, though under different names, will be helpful in this regard (see for example Hammer, 1997; Engle & Conant, 2002; Ford, 2005; Smith et al., 2000).

And third, coherence is perspective-dependent. Thagard showed that whether a scientist judges an explanation to be coherent or not depends on the information available to that scientist. In fact, Wegener had to marshal evidence in support of his theory for precisely that reason. He showed that the coastlines seem to fit together, and noted that there are similar fossils on both sides of the Atlantic. Without knowledge of these and other observations, it is unlikely that the scientific community would have considered Wegener's theory to be any more coherent than competing Contraction Theory. Because researchers, teachers, and students have very different knowledge and experiences, they are also likely to make different judgments about whether an explanation is coherent. Evaluating a students' explanation from a researcher's (or teacher's) perspective does not give us much information about *how* a student pursues coherence, only that a student failed to access or explicitly account for some particular piece of knowledge. But evaluating coherence from the *students' perspective* requires a large number of inferences about knowledge available to the student. Sandoval's coding system and the highly adjustable parameters of Thagard's connectionist computer program demonstrate the problematic nature of making such inferences.

Finally, coding schemes that treat coherence as a static characteristic of students' understandings or explanations do not allow for study of students' in-the-moment sense-making. Vosniadou and Brewer's clinical interviews miss the coherence seeking that students do as they interpret and respond to the interviewer's verbal and non-verbal cues. Sandoval's coding scheme tells us nothing about the process that students went through in constructing their explanations. But Thagard's Theory of Explanatory Coherence, which again treats coherence as a static quality of explanations, also holds that scientists prefer and in fact search for coherence. That is, scientists *try to fit ideas and information together in ways that are meaningful and mutually consistent*. It is this aspect of Thagard's work that I argue can be productively adapted to research on students' engagement in science. Rather than consider whether students' explanations are coherent, we might consider what information students are trying to make cohere.

Chapter 3: The Beginning of Constructing a Perspective on Coherence

"Only connect! That was the whole of her sermon.

Only connect the prose and the passion, and both will be exalted,

And human love will be seen at its height.

Live in fragments no longer.

Only connect..." —*E.M. Forster, in Howards End*

3.1 A More Expansive View of Coherence

Among the important findings in science education research is that all students, even very young ones, can "do science" (NRC, 2007; Bransford, Brown, & Cocking, 2000). That is, students are able to make sense of the physical world, and engage others in that sense-making.

In science, sense-making leads to, among other things, more refined explanations. Philosophers have explored the many dimensions along which an explanation might be refined—mechanism, consistency, consilience, simplicity, elegance, intelligibility, and the focus of this study—coherence. In science, and in the literature reviewed in the previous chapter, coherence often refers to the internal consistency of an explanation and how well an explanation hangs together with other knowledge available at the time.

In helping students work towards more sophisticated engagement in science, we might prefer that students come to seek coherence in ways that are valued by current scientific practice and that lead to currently accepted explanations of phenomena. In physics class, for example, we may ask students to model current electricity as flowing water, or compare light waves to water waves, as these analogies have proven fruitful for science. For varying reasons, the existing work in science education takes just this approach—it defines coherence narrowly, focusing on only particular kinds of connections commonly accepted as important in science. In turn, these frameworks recognize only a small portion of the coherence seeking in, for example, Raphael's cloud story (see Chapter 2). In the rest of this chapter, I motivate and illustrate the beginnings of an approach to broaden what counts as evidence of coherence seeking in science class. I conclude with a pre-/post- analysis of a single clip to illustrate the potential insights that a broader notion of coherence seeking affords.

3.2 The Case for Defining Coherence Broadly

In Chapter 2, I used comparative analyses of the Raphael Cloud Story clip to suggest that a broader definition of coherence seeking, combined with the working assumption that students are always seeking coherence, reveals new insights into students' reasoning in science class not captured by existing coding schemes. But a compelling case for re-conceptualizing coherence can also be made using findings from studies of science and education research more generally.

I begin with a description of a popular Newton's Third Law lab utilized in many high school and college physics classes. The lab opens with a prediction task. Students must anticipate the magnitude and direction of forces on two cars of different masses as they collide with each other. Usually (and incorrectly), students predict that the smaller car will feel a bigger force when hit by the heavier car. Having elicited students' prior conceptions about the relative forces on the cars, the activity then requires students to test out their predictions using force probes. The probes reveal that despite the mass difference, the cars experience "equal and opposite" forces. The hope is that, in recognizing their predictions were incorrect, students will re-construct their ideas about forces in ways that align with Newton's Third Law. That reconstruction requires, among other things, that students seek particular kinds of coherence—to recognize that their predictions and observations do not match, and modify their predictions (and underlying ideas) accordingly. Some versions of the activity also ask students to coordinate Newton's Second and Third Laws to explain why the lighter car appears to recoil more than the heavier car, upon collision.[7] In the instances that students fail to form these particular coherences, educators accuse them of failing to account for anomalous data (Kuhn, 1989), or failing to seek coherence at all.[8] Coherence seeking becomes dichotomous—students either are or are not seeking coherence.

In my initial analyses of classroom data, I often used language indicative of viewing *evidence of coherence seeking* as a single, dichotomous category (see Appendix A for an example of an analysis using such language). Though I recognized that the category might be further refined into subcategories, and also, that these categories might be context-dependent, I still assumed that there ought to be some set of behaviors or language that count as evidence of coherence seeking and another set that does not. But forcing the category *evidence of coherence seeking* to take a dichotomous form may be problematically artificial. Rosch's (1973; 1975) prototype theory suggests that humans employ and reason about category membership not in dichotomous terms, but as a matter of degree. Just as a robin might be more of a "bird" than a "penguin", or a "sofa" might be more of a piece of furniture than a "pen", some kinds of behaviors and discourse

[7] For an example of student reasoning around such a tutorial, see Chapter 6.
[8] I elaborate on the pedagogical implications in Chapter 8, and also in a NARST paper presented in March, 2012, Indianapolis, IN.

moves might seem more central to coherence seeking than others.[9] Importantly, the perceived centrality of an item in a category likely arises in one's interaction with the world and depends on one's experiences, culture, perspective, etc. In describing what coherence seeking looks like in science class, educators might refer to students' building textbook explanations, fitting their ideas with their everyday experiences, trying to find causal relationships, or checking the internal consistency of a model. These are examples of prototypical evidence of coherence seeking, the *kinds of evidence that we might prefer or most highly value*. Centrality, certainly, might vary according to the context. Before a standardized test, a teacher may value textbook explanations far more than students' drawing on everyday experiences. But during a discussion to open up a new unit, teachers might see drawing on everyday experiences as central to students' coherence seeking in science.

Perhaps at the periphery of category of evidence, students also seek coherence in ways that seem to deviate drastically from the practices of normative science. Students may ignore anomalous data to maintain the coherence of their own ideas (Kuhn, 1989) (though as Chinn and Brewer (1993) point out, scientists do this too!), they may select explanations based on principles of fairness or for entertainment's sake, rather for how these ideas explain natural phenomena. Beyond the purely conceptual, students also fit information together as they communicate, evaluate the intentions and emotions of

[9] Lakoff (1999) cites two common misinterpretation of Rosch's prototype theory, namely that prototype effects i) reflect some truth about categories "out there" in the world, or ii) reflect a cognitive structure. Lakoff argues instead that prototype effects arise from interaction between observers and the world, and that certainly one aspect of that interaction may involve correlative cognitive structures. Here, I argue that regardless of their source, the existence of prototype effects within natural categories such as color and furniture might warrant a degree-of-membership approach to constructing the artificial category (or categories) "evidence of coherence seeking."

others, construct a sense of what an interaction or activity is about, and locate themselves socially and physically within a class. The coding schemes reviewed in Chapter 2 (Sandoval, 2003; Vosniadou & Brewer, 1992; Thagard, 1989) do not recognize these forms of sense-making as coherence seeking. Perhaps in a clinical interview, like those employed by Rosch (1975), researchers and educators might demonstrate prototype effects with respect to coherence seeking—that remains an open empirical question. My argument is that, given the existence of prototype effects in many domains, it seems reasonable to try out a degree-of-membership approach to constructing the category (or categories) *evidence of coherence seeking*. And that approach would involve allowing even non-normative kinds of sense-making to count as evidence of coherence seeking.

Though I did not initially set out to think of coherence seeking in terms of prototype theory, it serves as a useful analogy for describing the intellectual work of creating an alternative perspective on coherence seeking. Re-constructing evidence of coherence seeking from a dichotomous category to a degree-of-membership category would require two steps. First, the category must be expanded to include ignoring anomalous data, making sense of social and affective information, etc. as evidence of coherence seeking, even if only peripherally. Secondly, prototype effects must be explored, to understand how we determine the centrality (and value) of these kinds of evidence in both classroom data and expert scientific practice. Analogous to that first step, I developed an approach to coherence seeking that assumes students are always seeking coherence with respect to something. And, akin to the second step, I intentionally tried to distinguish between *evidence of coherence seeking* and *evidence of good/productive/sophisticated coherence seeking* in my analyses of classroom data.

Maintaining that distinction proved quite challenging, and in retrospect, I was not completely successful. I tended to ignore episodes in classroom data that did not jump out at me as particularly productive or sophisticated, resulting in a sort of selection bias. Appendix B includes an annotated example of an episode that I initially overlooked because of such bias.

But despite the challenge of doing so, studies of science warrant reconsidering, or perhaps even blurring, the line between sophisticated and “other” forms of coherence seeking in science. Existing coding schemes overlook many kinds of evidence of coherence seeking in part because they de-contextualize coherence seeking as it occurs in expert scientific practice. Scientists conduct their work within social, political, personal, cultural, and gendered worlds; as such, their work involves aligning theory and evidence, but also coordinating elements of information that do not seem to be so much about concepts as about being human (though some might argue these elements are inextricably intertwined) (Latour & Woolgar, 1979; Solomon, 1992; Solomon, 1994). But even within studies of science that focus specifically on conceptual information, a context-sensitive image of scientists’ coherence seeking emerges. Dunbar’s (1999) description of work in a biology lab, for example, illustrates how scientists’ treatment of unexpected experimental results varies. While a single surprising result was likely to result in “replication, change in protocol, or use of an entirely new protocol” a series of such results would lead scientists to “offer new more general models, hypotheses, or theoretical explanations” (p. 6). No single kind of coherence seeking is uniformly valued and sought by practicing scientists; rather, scientists have an appreciation of the affordances and limitation of pursuing different kinds of coherence at different times, within their larger communal effort to understand natural phenomena.

The value educators place on certain kinds of coherence seeking can also stem from, or reinforce, a more general deficit model of student cognition. These deficit views are perhaps most evident curricula designed to expose students to dissonant information, and then walk them through ways to reduce that dissonance. Discrepant events curricula and counterintuitive problems were designed in response to the general finding that that students can leave science class with their intuitive ideas about the natural world (also problematically referred to as “misconceptions”) intact:

> students will often reinforce misconceptions by incorrectly incorporating new information on an incorrect framework. It is also possible for students to reject new information when it contradicts what they think they know. (Everett & Pennathur, 2007, p. 3)

Rather than recognize students’ maintenance of intuitive ideas as coherence seeking—which could be used in quite productive ways in science class—discrepant events curricula seeks to supplant students’ “incorrect” thinking with a certain way of connecting information. Furthermore, educators assume that by presenting a discrepancy, students will naturally recognize it as such and seek to reconcile it in the same ways as the educator would, as though the learning physics is purely a matter of applying objective logic. But perhaps not surprisingly, students often respond to discrepancies in ways that deviate from the intentions of the curriculum, leading to frustration on behalf of the educator and possibly humiliation for the students (Everett & Pennathur, 2007).

Rather than treat students’ reasoning as something to be corrected or modified, as was common in the decade following the onset of misconceptions research, science educators have re-discovered students’ reasoning as the starting point for science learning. A narrow definition of coherence underestimates the “raw materials” that students bring to science class, but a nuanced understanding of these raw materials is the very thing that teachers must deeply understand if they are to develop their curriculum and instruction around it (Hammer, 1996; Hammer, Goldberg, & Fargason, in press).

The educator who attends only to students’ seeking of explanatory or causal coherence, to the exclusion of all other forms of coherence seeking in which students are engaged, also assumes that the path from students’ current ways of thinking to other “more sophisticated” forms is linear, i.e. the inputs have a one-to-one correlation with the desired outputs. However, along with valuing the resources that students bring into the classroom, education research has also begun to productively characterize learning as a complex process, with multiple possible ways that those resources might be activated, intertwined, and refined over time. Through these complex dynamics, ways of thinking that are traditionally considered far outside the realm of science, including anthropomorphism (Bang & Medin, 2010), humor (Nespor, 1994) and even furniture design (Calabrese-Barton, Ermer, Burkett, & Osborne, 2003) have been shown to play potentially productive roles in students’ science learning. Coding schemes for coherence that omit these forms of reasoning fail to acknowledge the role they might play in students’ coming to seek other, more traditionally valued, forms of coherence in science. And finally, for students to fully appreciate why particular kinds of coherence are important in current scientific practice, they must have the opportunity to consider, refine, and evaluate multiple ways of making sense of phenomena (Bang & Medin, 2010; Coffey, Hammer, Levin, & Grant, 2011). Thus, determining what kinds of evidence of coherence seeking we most value becomes far more complex; a de-contextualized hierarchy will not suffice. I explore approaches to making normative claims about coherence in more detail in Chapter 8.

To summarize, science education and studies of science speak to utility of a broader and at the same time more nuanced conception of what constitutes coherence in science class. If students are to see science as more than a set of disconnected facts, they must have the opportunity to refine their seeking of coherence, and evaluate the usefulness of the coherences they seek. If we limit the refining to only those kinds of coherence that we think most important in science, we not only oversimplify the practice of science, but also discount the demonstrated complexity of science learning. An approach that considers evidence of coherence seeking as a matter-of-degree aligns with the working assumption that students are always seeking coherence, while also allowing space for scientists, educators and students to value some kinds of coherence seeking more than others, in different moments.

3.3 Methodological Approach

3.3.1 Overview

The construction, refinement, and illustration of a perspective on coherence seeking—a process outlined in pieces throughout this dissertation—involved a reflexive relationship between theoretical elements and the analysis of data, and also between myself and my work. In telling the story of that work for this dissertation, however, I opt for what some might call a post-positivist form of expression; the dissertation explicitly focuses on the logical and intellectual rather than the emotional and personal aspects of constructing a perspective. Though I omit an extensive discussion of my own subjectivity in the dissertation, maintaining an awareness of it and how it "may be shaping (my) inquiry and its outcomes" as documented in analytical memos, a research journal, and a sketchbook was an important component of my methodological approach (Peshkin, 1988, p. 17).

In terms of approaches to analyzing data, each chapter includes a description of methods used to make claims about coherence seeking in the focal episodes. However, all of the analyses share commonalities with respect to data sources, modes of interpretation, episode bounding and selection, coding, and transcription, as discussed in the next sections.

3.3.2 Data Sources

The primary data source for this study is a three-year, multi-site National Science Foundation-funded research project to develop learning progressions for scientific inquiry in the context of energy.[10] The project worked with a handful of participating elementary and middle schools in San Diego, California, a large, urban, diverse school district. Specific school sites were chosen so as to maximize the chance of having students participate over multiple years as they moved from grade to grade. (Raphael, for example, participated in both 5th and 6th grade). Across the 11 schools, fourteen elementary and middle school teachers (two 3rd grade, five 4th grade, five 5th grade, and two 6th grade) and their students were recruited for the project.

The Learning Progressions (LP) project involved three major components: professional development, curriculum design, and research on student and teacher learning. The professional development work consisted of a series of bi-weekly meetings

[10] *Learning Progressions for Scientific Inquiry: A Model Implementation in the Context of Energy* (NSF DRL 0732233)

throughout the year, a two-week long summer workshop each summer, classroom observations, and informal communication via phone and email. In each of these contexts, LP staff and teachers worked together to find ways to facilitate students' inquiry in the classroom. In professional development meetings and workshops, we split our time between watching and discussing classroom video and doing science together, as described in Chapter 8 and in Lineback (2012).

Like the professional development, the purpose of the curriculum development aspect of the project was to open up space for scientific inquiry in the participant classrooms. To that end, LP staff created a series of prototype science curriculum modules for energy (3rd grade), batteries and bulbs (4th grade), the water cycle (5th grade), and burnability/composting (6th grade). These topics were chosen to align with district standards for each grade. Each 20-hour module opens with a question designed to elicit student ideas around the focus topic. From there, the curriculum provides teachers with ideas for "next moves" to build upon the students' ideas and reasoning. The curriculum modules differ from the standard curriculum implemented in San Diego[11] in that the modules do not have a pre-defined set of activities or content objectives; rather, the primary goal of the LP modules is to facilitate students' "pursuit of coherent, mechanistic accounts of phenomena" (Hammer, Russ, Mikeska, & Scherr, 2005, p. 150). In later years of the project, the teachers worked alongside LP staff to revise the modules based on their experience using them in the classroom.[12]

[11] San Diego utilizes the Full-Option Science System (FOSS) Curriculum for grades K-5. The two sixth grade teachers implement a district-wide curriculum.
[12] Readers may access the modules at http://cipstrends.sdsu.edu/water_module/

Finally, the third aspect of the LP project involved research on student and teacher learning, with an emphasis on characterizing student and teacher progress in scientific inquiry. The teachers videotaped their implementation of at least one curriculum module each year, though some teachers chose to implement more than one module with their students. I focused primarily on these module implementations, as well as some of the teachers' scientific inquiry during the professional development meetings, to construct a perspective on coherence seeking. Though I have collected episodes from most of the classrooms in the study, the episodes in this dissertation come primarily from one of four sources: Ms. M's water cycle module from Year 1, Ms. H's water cycle module from Year 1, Ms. F's electricity module from Year 2, and a teacher professional development workshop from Years 1 and 3. I chose to focus on these sources because they contain particularly rich and varied evidence of coherence seeking. To speak more broadly about coherence seeking across the spectrum of science learning, I supplement the Learning Progressions data with data from other published work. Appendix C includes a complete list of the data presented in each chapter.

3.3.3 Continuously Revisiting Data

In first viewing classroom video, I generally just watched for something "interesting"—something that exemplifies, extends, or challenges my current lens for looking at coherence seeking. The Raphael episode, for example, exemplifies how a student spontaneously tries to build cycle-like relationships between ideas. The Learning Progressions data contains many interesting examples of coherence seeking, so choosing which episodes to present in this dissertation was challenging.

Once I identified a moment as compelling, I revisited the data using a variety of analytical tools, to build up my interpretations of the data. The process was highly nonlinear, but included i) bounding the episode, ii) transcription, iii) breaking transcripts into stanzas according to topic (Nathan, Eilam, & Kim, 2008), iv) writing analytic memos of multiple plausible interpretations (Emerson, Fretz, & Shaw, 1995), v) sharing interpretations with colleagues, vi) constructing a narrative of the episode, and vii) writing summary tables with codes.

3.3.4 Episode Selection and Bounding

My episode selection process was strongly guided by the overarching purpose of this work—perspective-building. I did not try to select clips according to arbitrary, objective, or randomized criteria; rather, I actively searched for and selected episodes that exemplify, challenge, or help to refine the perspective. Other perspective or theory-building work has taken similar approaches, for example Hammer, Elby, Scherr, and Redish's (2004) work on resources and framing, and Lave and Wenger's (1991) work on legitimate peripheral participation.

Generally, the episodes in my analyses have multiple boundaries. For example in the Raphael episode, I initially bounded the episode to include the whole of Raphael's "cloud story" (lines 1-13). But, in order to make sense of some of the ideas that Raphael was sharing, I had to work outward from narrowly bounded episode. To find the potential origins of Raphael's idea that it is "cold up high", I worked backwards in the video data, and found that Raphael may have gotten this idea from a flight attendant. In determining purposes that story might have served for Raphael and the class, I looked forward in the data, and found that Raphael later challenges his own cloud story on the grounds that it contains an internal inconsistency. In a sense, then, the episodes of coherence seeking are bounded on multiple levels, and driven by my attempt to see how ideas and relations play out over the course of students' sense-making.

By selecting and bounding episodes in these ways, I cannot make more general claims about the kinds of coherence seeking that happen in most science classrooms; my data comes from classrooms that are particularly conducive to sense-making, and from those, I select particularly rich episodes of coherence seeking. In addition, my work does not provide a complete characterization of the coherence seeking in any single classroom, though that future work building on this dissertation might pursue such characterizations.

3.3.5 Coding

Researchers who study students' engagement in the practice of argumentation tend to draw on well-established, Toulmin-inspired coding schemes (Sampson & Clark, 2008). While one logical step in this work would be to develop such a coding scheme for coherence seeking, I instead focused my efforts on constructing a language and perspective for looking at and talking about coherence seeking. Two key aspects of that lens are: i) to focus on the information students try to connect, and the ways in which they connect it, and ii) to assume students are always seeking coherence with respect to something.

Through this lens, I tried to balance "looking for" coherence seeking with seeing what emerged from the data. I coded both inductively and deductively, at all times wondering, "What sorts of things might I hear and see students doing when they are seeking coherence in particular ways?" The deductive codes come from my operational definition of coherence seeking: "trying to form meaningful, mutually consistent relationships between information (broadly defined).” Examples of deductive codes include pointing out an inconsistency or showing surprise at an observation. I also coded inductively, continually asking “How might that student’s statement/gesture/facial expression be evidence of coherence seeking? And with respect to what information?” (Strauss & Corbin, 1994). I kept track of these codes in a working table of evidence (see Appendix D). The codes serve two purposes. First, they are a concise tool for keeping track of the kinds of coherence seeking within and across episodes, i.e. they give us a flavor of what kind of coherence seeking is occurring in an episode. Secondly, the codes may help reveal patterns in the data that warrant further investigation. For example, do students in Raphael’s class tend to seek narrative coherence often, or does that seem to be specific to Raphael?

Appendix D does not constitute a rubric for evaluating students’ coherence seeking, nor does it encompass all possible kinds of evidence of coherence seeking. In that sense, my “coding” for coherence seeking in this work is markedly different than those used to study scientific argumentation in classrooms. Many Toulmin-inspired coding schemes for argumentation reduce the practice to a series of behaviors: make a claim, state data, and offer a warrant to the data to the claim. While convenient, these coding schemes are reductionist, sometimes dichotomous, and often lose the “holistic” sense of the practice (Sampson & Clark, 2008, p. 469). Cognitively, we can think of coherence seeking as arising from a complex interplay of conceptual, epistemological, affective, cultural, linguistic, etc. resources. As such, it cannot be meaningfully reduced to a list of behaviors. And within a sociocultural perspective, coherence seeking arises in interaction, and is *an act of language* (Lindfors, 1999). Since there are no context-independent linguistic markers (Tang, 2010), there can be no context-independent codes for coherence seeking. Still, Lindfors does emphasize the importance of multimodal discourse analysis, including gesture, tone, and expression, in studies of children's inquiry. Chapter 4 discusses evidence of coherence seeking in greater detail.

3.3.6 Transcription

An important aspect of coherence seeking is the conceptual content of what students are saying: the relations students make between information about the natural world. Thus, transcripts must facilitate interpretation of the content of what students say. In instances where content is central, Oliver, Serovich, and Mason (2005) recommend a more denaturalized approach, with more focus on what people say and less emphasis on how they say it. On the other hand, students seek connections not only between conceptual information, but also between linguistic, epistemological, cultural, personal, social, emotional, material, etc. information. A naturalized approach that includes details such as intonation, pause, and overlapping speech may reveal these other aspects of coherence seeking. Gestures and gaze can also illuminate the conceptual information that student try to connect. The transcripts in this work represent a "hybrid" between the naturalized and denaturalized approaches, and follow conventions similar to those used by Varelas, Pappas, Kane and Arsenault (2007) (see Appendix E). Transcripts are indexed according to episode and utterances number.

3.4 Coherence Seeking in Raphael's "Cloud Story"

To illustrate the more dynamic, contextualized approach to studying coherence seeking offered in this work, I must begin by putting Raphael's episode in a larger context. As aforementioned, at the time of data collection, Raphael was a 5^{th} grade student in Ms. M's class. Ms. M and her students were completing a novel curriculum module about the water cycle. The module began by asking students to brainstorm what might have happened to a puddle that disappeared over the course of the day. The rest of the module was relatively open, allowing Ms. M to focus on students' reasoning, rather than on a strict order of lessons and activities.

On day two of the module, Ms. M draws students' attention to the clouds outside in the hopes of opening up a discussion about types of clouds. She opens the classroom door, looks up, and asks:

> "[This morning] there were clouds and now there aren't clouds. Where did the clouds go?"

In *identifying a phenomenon to be explained*, Ms. M opens up space for sense-making. The students talk among themselves for a minute, and then Raphael tells Ms. M that he thinks "clouds need a cold environment" because a flight attendant told him that if a plane window opened, everyone would turn into a "block of ice." Upon further questioning, Raphael also agrees that high clouds are "probably [made of] ice." Ms. M writes Raphael's answer on the board, putting particular emphasis on the fact that clouds can contain ice (one of the state science standards):

1.1 Ms. M: Okay, so, clouds that are higher up [*writing*]
1.2 Raphael: And then when uh the sun comes up it might push it away.
1.3 Ms. M: [*writing*] Higher up contain..ice crystals? Can I say that?

Ms. M does not respond to Raphael's comment that the sun might "push clouds away." But just as Ms. M finishes writing, Raphael interrupts her and exclaims "Oh! I have an idea."

1.4 Raphael: Yeah.
1.5 Ms. M: Wow. That's pretty good. This—

1.6 Raphael: Oh! I have an idea.
1.7 Ms. M: I-I just, yes. [*turning around and putting lid on marker, nodding as she says "yes"*]

What follows is Raphael's "Cloud Story":

1.8 Raphael: Uh, well I think that uh when the sun comes up, the // it pushes the clouds down and that's the morning and uh they turn into fog. And they go and they form puddles. And then when the sun gets really hot // uh hotter like later in the afternoon, the puddles evaporate. And that's, and the clouds are connected to the fog and the water [*gestures with right hand, palm facing up*] and the sun [*lifts hand up*] // evaporation.

In this flurry of ideas, Raphael not only explains what may have happened to the clouds (they were pushed down by the sun), but he also connects his ideas back to the previous days' question about a disappearing puddle (it evaporated). Ms. M recognizes that Raphael has made "connections" between clouds, the topic of the day's discussion, and puddles, the previous days' discussion topic:

1.9 Ms. M: Okay, so there's some // now you're bringing back in what we talked about yesterday. There's some connection with all of this.
1.10 Raphael: Yeah, the ice, because they're made of ice, ice can melt. And since they're so close to uh, the sun, the sun will push em down [*moves left hand in a patting motion*] because // and then they'll turn into fog and they'll, they'll melt and then the water that's left will go into the puddles and the sun will evaporate the puddles [*moves left hand slowly up*] later on in the afternoon.

In a holistic sense, segments [1.7] and [1.9] illustrate Raphael's seeking of narrative coherence. He tries to fit the puddle, the clouds, fog, the sun, and evaporation together in a narrative, or story. The story contains both temporal and causal/mechanistic relationships, which are central to coherence seeking in text comprehension seeking (Russ, 2006; Trabasso, Secco, & Van Den Broek, 1982). The temporal relations connect phenomena the class had been discussing over the course of two days—cloud movement, fog and puddle formation, and evaporation. Raphael also describes a cause and effect relationship between the sun, cloud disappearance, and fog formation, though the details of the relationship are unclear. He says that the sun *pushes down* clouds, and uses a patting gesture to indicate the clouds literally being pushed down. But, he also says that the clouds can melt, and it is unclear if and how the melting and pushing are related for Raphael. In the next part of Raphael's story, the melting/pushing down of clouds leads both to fog and puddle formation. (Interestingly, he makes no mention of rain as the source of puddles). Finally, the driving force of the entire story, the sun, evaporates the puddles in the afternoon.

The story, both in substance and in language ("and then"… "and then"), is linear. However, if Raphael also thinks that evaporation leads to cloud formation, then he may actually be seeking a cyclical story, literally his own version of the water cycle. Regardless, his excitement and repetition of his ideas suggests that for Raphael, this story hangs together quite nicely, and he is probably proud of it. In addition, the construction of the story represents not only conceptual coherence seeking, but also coherence seeking with respect to classroom norms. Raphael uses his story to answer two of Ms. M's questions: the opening question about what happened to the puddles, and her question about what happens to clouds over the course of the day. We do not know whether Raphael thinks that Ms. M wants him to connect the answers to these questions together, or whether he makes these connections for some reason other than to please Ms. M. Regardless, at least part of Raphael's sense-making involves answering Ms. M's questions.

Clearly, my analysis overlaps with some of the findings presented in Chapter 2. Like Vosniadou and Brewer (1992), I see how Raphael's story may hang together for him. I recognize many of the causal relationships that Thagard's (1989) and Sandoval (2003)'s approaches revealed, for example, that the sun's warmth causes clouds to melt. However, my analysis adds an attention the conceptual, epistemological, and linguistic coherences of Raphael's story, maintains a holistic sense of the coherence that Raphael seeks, and interprets that coherence seeking within the context that it occurred.

3.5 Principles of Analysis for Local Moments of Coherence Seeking

Raphael's cloud story illustrates clearly that existing approaches to analyzing students' coherence seeking, while reasonable as a starting point, need refinement. In trying to build a broader but also more nuanced perspective on coherence seeking, I adopted two intellectual strategies, or principles of analysis, relatively early into my work.

First, I approached data under the assumption that even students who seem like they are not seeking coherence are still seeking coherence with respect to *something*. From a psychological and cognitive perspective, the assumption is not so far-fetched. Both bodies of literature suggest that human perception and cognition involves continual integration of information, in ways that are both intentional and unconscious. In science class, we tend to focus on students' integration of conceptual information in ways that align with the scientific canon. However, learners' coherence seeking may involve not only unexpected conceptual and epistemological elements, but also cultural, linguistic, social, material, and affective elements which are often overlooked in science education.

Secondly, much of the existing literature considers coherence primarily, or even solely, as a characteristic of scientific products—explanations, arguments, etc. As Sandoval's (2003) and Vosniadou and Brewer's (1992) work shows, assessments of how[13] students' explanations "hang together" provide some insight into what elements a student finds relevant to answer a prompt, and which relationships between those elements seem important. Raphael's cloud story, for example, tied together a series of elements (puddle, sun, evaporation, clouds, fog) into a causal story. However, Raphael's story was just one moment in a larger inquiry that his class engaged during the Water Cycle Module. The moments leading up to that story, and the way it is taken up later, are as important to understanding Raphael and his classmates' coherence seeking as a static analysis of the explanation itself. That is, coherence is an aspect of products of science, but it is also something that students seek together as they try to make sense of natural phenomena. Emphasizing coherence seeking as an activity complements current work aiming to characterize students' engagement in doing science, or "the nature and quality of students' participation in exploration, invention, and discourse" (Hammer, 1997, p. 488). And from a research perspective, it follows that work on coherence seeking must analyze students' reasoning in context. Work that looks only at the internal coherence of a single sentence that a student writes is unlikely to reveal much useful information about students' thinking and doing of science.

Through multiple analyses of Raphael's cloud story, I have begun to demonstrate how a perspective built around these two principles offers more insight into students' coherence seeking than otherwise available through existing coding schemes. But the adoption of these principles also greatly impacted the way I approached data analysis over the course of the study. The working assumption that students always seek

[13] How, not how well, it hangs together. If we assume that the students are seeking coherence as they construct the explanation, then the explanation likely hangs together *in some way* for that student. In addition, the extent to which an explanation seems coherent is observer-dependent.

coherence was especially transformative in that it completely shifted not only how I selected episodes, but what evidence of coherence seeking I saw within them. To demonstrate that shift more clearly, I present in the next section two analyses of a single clip: one conducted before I assumed that students always seek coherence, and one conducted afterward.[14]

3.6 Jason and the Magnets: Comparison of Original and Refined Coding Schemes

In my initial exploration of hundreds of hours of classroom video, only a few moments clearly stood out as examples of coherence seeking, one of which was the Raphael Cloud Story discussed earlier. Another example came from a 4th grade discussion about magnets. On the day prior to the discussion, the students discovered that they could make a toy car move using small magnets. The students attached one magnet to a car with tape, and brought a second magnet toward the first. Depending on the alignment of the poles, the car either moved away from the incoming magnet, or moved toward it. The next day the teacher, Ms. B asks the students to explain how the magnets make the car move. Caitlin suggests that the magnets contain "electricity" in them, an idea which puzzles both Ms. B and another student named Jason. A discussion around the idea of electricity being inside magnets ensues:

2.1 Caitlin: Umm, well, the magnets have some electricity in them, and it--
2.2 Ms. B: They have electricity in them?
2.3 Caitlin: Yeah, so sometimes--
2.4 Ms. B: How can the magnets have electricity? I didn't, 'cause it doesn't have a plug on it [*moves arm back and forth as if plugging in a cord*], so I'm getting confused.

…(lines omitted)…

2.15 Jason: Um, how could it have electricity in it because, because metal conducts electricity. When it hits it it goes through to wherever it is.

[14] Analysis 1 was last edited on June 23rd, 2009. I first presented the intellectual strategy that students are always seeking coherence on April 12th, 2010. Analysis 2 was last edited in May, 2012.

2.16 Ms. B: And what is the toy car made of?
2.17 Jason: Plastic.
2.18 Ms. B: And so you're asking why is the magnetism // you [*Jason, Joe, and another student off camera*] need to sit down so everyone can see--
2.19 Jason: No, how could, how could the magnet be part of...How could it have um, electric in it because if it conducts to metal, electric when it hits it, it would just travel through until, until there's no other metal on it.
2.20 Ms. B: Does anybody know the answer to that? He wants to know why is it working when it should be made of metal, and the toy car is made of plastic. So why is it still working, Michael?
2.21 Michael: Well, I just wanted to say (*** ***) found out something *else* about the toy car. Um, we tried that same magnet on the back of the car and if you pushed the other magnet closer to it, it moved forward…from the back.
2.22 Ms. B: So why is that working because that's what Jason's confused about. Why would that be working when the toy car is made of plastic so he's saying it's not conducting the whatever that is.
2.23 Jason: No, I'm saying how could, how could a magnet have electricity in it because, isn't a magnet metal too? sort of? If it had electricity in it, it would go out. Because once electricity hits metal it goes, it keeps going in the metal until it goes // until there's no other metal on to for it to travel through and then it goes out.

In the clip, Jason challenges the idea that a magnet can have electricity inside of it on the basis that electricity flows through and out of metals. Ms. B works to understand Jason’s concern, and in the process points out some inconsistencies that she herself sees, for example, that the plastic car can be moved by magnets.

3.6.1 Analysis 1: Before Presuming That Students Always Seek Coherence

In creating an initial coding scheme for coherence seeking, I focused on two aspects of coherence often discussed in the literature—consistency and relationships. Consistency, as an aspect of coherence, means non-contradiction. But a set of facts or words can be consistent, and yet apparently have nothing to do with each other, i.e. they do not seem to “hang together.” Thus, the second piece of coherence seeking involves building relationships between ideas. In conceptualizing what evidence of these two aspects of coherence seeking might look like in the science classroom, I further unpacked these two aspects of coherence into constituent parts, based on both my own experience in science and literature on coherence. In particular, I limited "relationships" to those often recognized as important in science, i.e. causal, functional, part-to-whole, etc.:

Table 1: Initial Coding Scheme for Coherence Seeking

Consistency	**Relationships**
o Identifying contradictory pieces of information. o Questioning a result or idea that disagrees with what the student already knows. o Noticing something unusual or unexpected. o Attempting to reconcile inconsistencies/explain the unexpected.	o Describing ideas or evidence in terms of causal, functional, part-to-whole, etc. relationships. o Identifying missing information needed to complete an explanation. o Attempting to reconcile inconsistencies/explain the unexpected.

Using the coding scheme in Table 1, I found two kinds of evidence of coherence seeking in the clip: Ms. B and Jason *identified inconsistencies* and *requested reconciliation of these inconsistencies.* I distinguished between identifying an inconsistency and requesting reconciliation for it on the basis of how the inconsistency was brought to the attention of others. For example, in line 2.4, Ms. B asks a question about the inconsistency, suggesting that she wants Caitlin to elaborate (request reconciliation), whereas in line 2.23, Jason appeared to be conveying a point about why Caitlin's idea does not make sense to him (identifying inconsistency):

2.22 Ms. B: How can the magnets have electricity? I didn't, 'cause it doesn't have a plug on it, so I'm getting confused.

2.23 Jason: No, I'm saying how could, how could a magnet have electricity in it because, isn't a magnet metal too? sort of? If it had electricity in it, it would go out. Because once electricity hits metal it goes, it keeps going in the metal until it goes // until there's no other metal on to for it to travel through and then it goes out.

At the time, the distinction between identifying and requesting seemed important; coherence seeking at its fullest, I thought, must involve finding contradictions *and* doing something about them. (While I maintain that noticing and addressing contradictions in some way constitutes an important aspect of the scientific community's coherence seeking, I have since abandoned the idea that an individual's noticing an inconsistency in a moment is *a priori* less sophisticated or less central to coherence seeking than noticing and reconciling it in that moment.)

The codes also focused strictly on conceptual and some epistemic components of Jason's and Ms. B's reasoning, with little attention to the social, affective, cultural, and linguistic aspects of students' sense-making. As Table 2 shows, I parsed participants' utterances primarily in order to unpack the conceptual information that they were trying to make cohere. For example, in line 2.23 Jason says:

> Jason: No, I'm saying how could, how could a magnet have electricity in it because, isn't a magnet metal too? sort of? If it had electricity in it, it would go out. [*gestures with scissors*] Because once electricity hits metal it goes, it keeps going in the metal until it goes—until there's no other metal on to for it to travel through and then it goes out.

I coded the statement as: *request reconciliation of an inconsistency; identify an inconsistency between perceived facts (magnet is metal, electricity goes through metal) and Caitlin's claim*. That coding left out the fact that Jason recognized that Ms. H was misinterpreting his idea ("No, I'm saying how could…"), and also expressed frustration over it, as indicated by his tone. The approach also located coherence seeking within the minds of individuals and merely expressed in language. The initial coding scheme did not recognize acts of communication as coherence seeking in their own right.

Finally, and notably, in this initial analysis, most of the transcript was discarded as "noise." I did not see any evidence of coherence seeking in Michael's utterances, for example, and so omitted them from the analysis entirely. Likewise, I considered Caitlin's contribution part of the conditions supporting Jason's coherence seeking, rather than evidence of her own coherence seeking.

Table 2: A Preliminary Analysis of Jason and the Magnets

Line	Speaker	Transcript	Analysis	Code
2.4	Ms. B	How can the magnets have electricity? I didn't, 'cause it doesn't have a plug on it, so I'm getting confused.	Inconsistency between claim (Caitlin's claim that magnets have electricity in them) and idea (Ms. B's idea that things with electricity [in them?] require plugs).	Identify inconsistency (teacher) b/t claim (student)-info (experience); request reconcilation
2.15	Jason	[*standing*] Um, how could it have electricity in it because, because metal conducts electricity. When it hits it it goes through to wherever it is.	Indentifies an inconsistency b/t Caitlin's claim (electricity in magnets) and perceived facts (metal conducts electricity/electricity goes through metal)	Identify inconsistency (student) b/t claim (student)-info (perceived facts); request reconciliation (partnered with repeated requests)
2.19	Jason	No, how could, how could the magnet be part of… [*sits down*] How could it have um, electric in it because if it conducts to metal, electric when it hits it, [*moves hand*] it would just travel through until, until there's no other metal on it.	Restates/identifies inconsistency from 18 b/t Caitlin's claim and perceived facts (electric travels through metal—implies that magnets must be metal, which Jason says in 2.19).	Identify inconsistency (student) b/t claim (student)-info (perceived facts); request for reconciliation
2.20	Ms. B	Does anybody know the answer to that? He wants to know why is it working when it should be made of metal, and the toy car is made of plastic. So why is it still working, Michael?	the car moves, the toy car is made of plastic, car needs to be made of metal to go	Identify inconsistency (teacher) b/t three pieces of information: 1) the car is moving (observation), 2) the car is made of plastic (she gets this answer from Jason), 3) the car should be made of metal in order to move (misinterpretation of Jason's statements in 18, 22); request reconciliation of an inconsistency

2.22	Ms. B	So why is that working because that's what Jason's confused about. Why would that be working when the toy car is made of plastic so he's saying it's not conducting the whatever that is.	Ms. B is re-explaining her interpretation of Jason's question and asking for a reconciliation.	request reconciliation of an inconsistency
2.23	Jason	No, I'm saying how could, how could a magnet have electricity in it because, isn't a magnet metal too? sort of? If it had electricity in it, it would go out. [*gestures with scissors*] Because once electricity hits metal it goes, it keeps going in the metal until it goes—until there's no other metal on to for it to travel through and then it goes out.	Jason realizes, again, that Ms. B is misinterpreting his question. He restates, this time adding that magnets might be made of metal, so they can't keep the electricity in.	request reconciliation of an inconsistency; identify an inconsistency b/t perceived facts (magnet is metal, electricity goes through metal) and Caitlin's claim

3.6.2 Analysis 2: After Presuming That Students Always Seek Coherence

As I revisited the Jason and the Magnets clip over time, with a broader perspective on what coherence seeking means and looks like, I likewise saw more evidence of coherence seeking in the data. The working assumption that students are always seeking coherence with respect to something revealed not only additional aspects of Jason's and Ms. B's coherence seeking, such as linguistic coherences, but also highlighted Caitlin's and Michael's coherence seeking, which I had previously overlooked as noise.

In my most recent analysis of that clip, I constructed a narrative, rather than a tabular analysis of evidence. Starting with line 3.1, Caitlin suggests that "magnets have some electricity" in them:

2.1 Caitlin: Umm, well, the magnets have some electricity in them, and it—

She never has a chance to fully articulate her thoughts, but she might mean that some active ingredient in magnets, call it "electricity", accounts for their behavior (Watts, 1983). Or, perhaps Caitlin sees (or is *trying to form*) a relationship between electricity and magnets. For example, two magnets sticking together might remind Caitlin of how static electricity makes a balloon stick to the wall. Regardless, Ms. B appears to treat Caitlin's idea literally:

2.2 Ms. B: They have *electricity* in them?
2.3 Caitlin: Yeah, so sometimes—
2.4 Ms. B: How can the magnets have electricity? I didn't // cause it doesn't have a plug on it [*moves arm back and forth as if plugging in a cord*], so I'm getting confused.

In [2.2] and [2.4] Ms. B implicitly identifies a contradiction between Caitlin's idea and her own knowledge about magnets and electricity. Ms. B has apparently observed that objects that require electricity have plugs. So if magnets do not have plugs, how can they have electricity in them? She also gestures as though she is plugging a cord into a wall, perhaps further implying that electricity comes from the wall socket and is carried by the plug or cord.

In identifying this contradiction, and also bringing it to Caitlin's attention, Ms. B seeks coherence. Her coherence seeking takes the form of a question, and also a syllogism. In Deductive-Nomological (D-N) form, the syllogism is:

s1. Things with electricity have plugs.

s2. Magnets do not have plugs.

p. Therefore, magnets *do not* have electricity

In addition to this coherence seeking, Ms. B's comment "so I'm confused" could be interpreted as a performative move, evidence of her taking on the role of the unknowing teacher who needs to be enlightened by the student. And, though she does not specifically ask a question, Caitlin interprets Ms. B's utterance in [2.4] as a request for additional information. Caitlin demonstrates that if she holds a magnet in her hand, and brings another magnet near it, the magnet in her hand jumps up. After Caitlin's demonstration, Ms. B opens up the floor to other students, and a student named Jason asks a question about Caitlin's idea:

2.15 Jason: [*gaze in Ms. B's direction*] Um, how could it have electricity in it because, because metal conducts electricity? When it hits it it goes through to wherever it is.
2.16 Ms. B: And what is the toy car made of?
2.17 Jason: Plastic.
2.18 Ms. B: And so you're asking why is the magnetism // ##you [to Jason, Michael, and another student off camera] need to sit down so everyone can see## —
2.19 Jason: ##No, how could## // well how could // how could the magnet be

part of // How could it have um, electric in it because if it conducts to metal, electric when it hits it, it would just travel through until, until there's no other metal on it.

Like Ms. B, Jason uses an interrogative form to point out an inconsistency between some of the things he knows about metal and magnets, and Caitlin’s idea. The gist of his concern is this: Magnets are made of metal. Metal does not “hold” electricity, rather, electricity travels through it. In that case, magnets cannot have electricity in them. Or again, in D-N format:

s1. magnets are made of metal

s2. electricity goes through metal

p. magnets *cannot* have electricity in them

Ms. B re-voices Jason’s question to the class, and calls on Michael, who has had his hand raised since Caitlin’s magnet demonstration:

2.20 Ms. B: Does anybody know the answer to that? He wants to know why is it working when it should be made of metal and the toy car is made of plastic. So why is it still working, Michael?

2.21 Michael: Well, I just wanted to say (*** ***) found out something *else* about the toy car. Um, we tried that same magnet on the back of the car and if you pushed the other magnet closer to it, it moved forward…from the back.

Michael’s phrasing “I just wanted to say” and “found out something *else*” suggest that he is aware that his statements will not directly answer Ms. B’s question. Instead, Michael reports that his group was able to make the toy car move by taping a magnet to the back of one car, and bring the other magnet near it. Interestingly, Michael’s observation is precisely opposite of what Caitlin showed. When Caitlin brought the magnets together and they stuck together; when Michael brought them close together, they pushed apart. Michael’s tone and expression do not clearly indicate if he is actually trying to show that his observation is the opposite of, and thus inconsistent with, Caitlin's. However, by marking his utterance as something other than an answer to Ms. B's question, Michael certainly tries to fit his observation into the flow of the conversation, a sort of linguistic coherence seeking. Ms. B redirects Michael and the rest of the class back to her interpretation of Jason's question:

2.22 Ms. B: So why is that working because that's what Jason's confused about. Why would that be working when the toy car is made of plastic so he's saying it's not conducting the whatever-that-is.

Ms. B notices that Jason is concerned about an inconsistency. She thinks that he is concerned about the toy car being made of plastic [2.20, 2.22], because electricity only travels through metal. Her interpretation of Jason's idea likely resonates with her own ideas about what kinds of materials conduct electricity. But Jason re-explains himself, pointing out that he is not concerned that the toy car is made of plastic, but that the magnet is made of metal:

2.23 Jason: [*now holding a pair of scissors*] No, I'm saying how could, how could a magnet have electricity in it because, isn't a magnet metal too? sort of? If it had electricity in it, it would go out. [*waving scissors, from the left, to the right, seeming to show how electricity would move*] Because once electricity hits metal it goes, it keeps going in the metal until it goes…until there's no other metal on to for it to travel through and then it goes out.

2.24 Ms. B: Alright, so how many of you agree that we have a lot more experimentation with the magnetism until we understand it?

Thus, Jason's utterance in [2.23] not only indicates his coherence seeking with respect to Caitlin's initial suggestion that magnets contain electricity, but also indicates that he checks to see if Ms. B's rephrasing aligns with the substance of question. Given the argumentation literature's emphasis on students' being able to recognize and distinguish "plural interpretations of phenomena," it seems important for a coding scheme to pick up that additional aspect of Jason's coherence seeking (Driver, Newton, & Osborne, 1998, p. 299). That is, argumentation:

> …is not only about learning to coordinate evidence with claims and being causal in one's theorizing, it is also about resolving differences of opinion by developing a shared understanding of complex concepts, persuading others about science-related disputes, using sophisticated linguistic structures, making personal decisions that are consequential, and navigating the accountability structures of formal schooling. (Bricker & Bell, 2008, p. 496)

Ms. B, perhaps sensing that she has not been able to establish a shared understanding with Jason, puts his concerns aside for the moment and moves the class on to other ideas [3.24].

Judith Wells Lindfors (1999) describes wondering discourse as the construction of an "inquiry text" (p. 31). In the Jason and the Magnets Episode, the students and Ms. B collaboratively construct an inquiry text around their observations and questions about magnetism. Each person in the class who participates in the construction of this inquiry text, either as a listener or as a speaker, must seek coherence in a linguistic or narrative sense (Tapiero, 2007; Levy & Fowler, 2004). For example, for Michael to even recognize that the discussion was about magnets, he must have at some point constructed connections between Ms. B's, Caitlin's, and Jason's contributions. More generally, making sense of a conversation requires that students evaluate how statements in a conversation might be related to each other (Graesser, Mill, & Zwan, 1997; van Dijk & Kintsch, 1983; see also Bartlett, 1932).

In addition to the linguistic and conceptual coherence seeking taking place, the students are also connecting together information about each other, their surroundings, the kind of activity in which they are engaged. In other clips, discussed in Chapter 7, these "other" aspects of coherence seeking are glaring, and they pivotal role in (and sometimes overshadow) students' pursuit of coherence among more "conceptual" information. In the Jason and the Magnets clip, students' connecting of social and affective information certainly occurs, but perhaps in less obvious ways. Jason's change in tone as he continues to re-state his concerns in line 2.19 and 2.23 indicates an increasing frustration. But he also expresses tentativeness, for example, when he asks, "aren't magnets metal too, sort of?" The tentativeness could indicate his own uncertainty about the idea that magnets are metal, or he might be uncertain about the social situation, i.e. *if the teacher and other students do not see understand what I am saying, then maybe what I am saying does not make sense*. As Jason continues to speak, he becomes more animated, physically and verbally, and begins to rise out of his chair. Ms. B asks him to sit down in line 2.18, enforcing a classroom norm (it is customary for students to stay in their seats in Ms. B's class). In fact, much of the work that Ms. B and the students are doing in the days leading up to and after the Jason and the Magnets clip involves making sense of and negotiating "what's going on here" as they work through a science curriculum module unlike any they have participated in together that year (Hammer, Elby, Scherr, & Redish, 2005).

Tracking not only the conceptual coherences, but also all of the other kinds of coherence seeking going on in these moments made the use of the table analyses increasingly unwieldy. Narratives (with video stills), annotated transcripts, and diagrams became the most pragmatic way to keep track of the linguistic, social, affective, epistemological, etc. evidence of coherence seeking (as intertwined with conceptual information), whereas the table remained a useful tool for distilling students' coherence seeking in terms of ideas about natural phenomena.

3.7 Conclusion

The question of how to define coherence is not merely a philosophical musing; rather, definitions of coherence drastically affect how researchers and educators interpret students' sense-making in science class. As the Raphael Cloud Story and Jason and the Magnets analyses illustrate, a perspective built on the assumption that students are always seeking coherence with respect to many kinds of information has the potential to enrich our understanding of how students collaboratively construct knowledge (their "inquiry texts") in science class.

In the next chapter, I further substantiate the working assumption that students are always seeking coherence, as well as outline more systematically categories of evidence for coherence seeking.

Chapter 4: Identifying Evidence of Coherence Seeking in Science Classrooms

"Meaning is not cut and dried; it is a matter of imagination and a matter of constructing coherence. The objectivist emphasis on achieving a universally valid point of view misses what is important, insightful, and coherent for the individual."

-Lakoff and Johnson, Metaphors We Live By

4.1 Introduction

In the last chapter, I argued that much of the richness in Raphael's Cloud Story lies in recognizing that he constructs that story dynamically in the moment, as he pieces together ideas that the class had been discussing over the past two days. That is, in interpreting Raphael's participation as a search for coherence, we can begin to make sense of how he pieces together ideas about clouds, water, evaporation, fog, and even his experiences flying. I also showed how although Raphael's idea is incorrect from a scientist's point of view, there is reason to value Raphael's explanation in that it shows he is *trying* to make sense of, and to seek coherence, between ideas. He suggests that many of the water-related phenomena that his class has discussed, including the disappearance of clouds and puddles, and the formation of rain and fog, are actually causally connected. The sun heats clouds in the morning, causing the clouds to melt and form rain and puddles. Then, as the sun gets even warmer in the afternoon, the puddles evaporate. Raphael's satisfaction and excitement with this story, as indicated by his tone and facial expressions, suggests that Raphael believes he has not only sought, but also achieved a sense of coherence for himself.[15]

Raphael's cloud story contains many different kinds of evidence of coherence seeking. Pauses, repetition, and preliminaries ("Oh! I have an idea") are evidence that Raphael is thinking through his ideas as he is sharing them—that is, he is literally constructing the explanation in the moment. His speech contains linguistic markers that indicate causal relationships ("and then"). He explicitly identifies some of the conceptual information that he tries to connect in these causal relationships ("the sun", "the puddles", etc.). Raphael's meta-cognitive comments about his idea ("And that's, and the clouds are connected to the fog and the water") indicate not only how he was connecting information, but also his intention and awareness in making those connections. Finally, Raphael's gestures, facial expressions, and tone of voice help illuminate how Raphael sees and feels about the connections he is making.

Raphael's Cloud Story is just one example of what coherence seeking can look like in science class. However, in this chapter, I move beyond Raphael's story to consider more broadly what constitutes evidence of coherence seeking in science classrooms. I begin with a working definition of coherence seeking, and proceed to illustrate various forms of coherence seeking using data from participant classrooms.

4.2 A Working Definition of Coherence Seeking

In the broadest terms, coherence refers to how well ideas "hang together" (Buchmann & Floden, 1992, p. 4). A search for coherence, then, is an attempt to make

[15] Bartlett (1932/1995) describes the end state of seeking connections as "primarily affective." That is, "an attitude best describes as 'the attitude in which no further questions are asked'" (p. 85).

ideas fit together in some way. But there are a variety of ways to make ideas or information fit together, some of which seem to have very little utility in science. Crossword puzzles, for example, invite readers to connect together terms and phrases in a visual way. Advertisers try to make viewers associate their products with ideas and feelings of enjoyment, happiness, or success through carefully constructed commercials. Even choosing an outfit for the day involves coherence seeking; garments must quite literally "hang together" in a visually pleasing way. In each of these scenarios, the standards for what counts as coherent are determined in interaction with the designers (puzzle, clothing, commercials) and the users.

As scientists make sense of phenomena, they also construct criteria for coherence. For example, in evaluating cosmological models, scientists generally prefer models that can postdict the currently accepted values for cosmological parameters (Ostriker & Steinhardt, 1995). In atmospheric science, weather models are constrained both by accurate prediction of local conditions now, as well as accurate prediction of weather conditions in the future (Kalnay, 2003). In materials science, theoretical models of a substance's electronic properties (i.e. Mott-Anderson Theory) must align with both observation and fundamental laws of physics (Mott, 1974). Though scientists determine specific criteria for coherence dynamically as they make sense of phenomena, generally speaking, two key criteria for coherence seem relatively stable in science—non-contradiction and explicit relationships. That is, in searching for coherence, scientists both check that information is consistent, and explicate the relationships between this information.

In some sense, the *non-contradiction* criterion is self-explanatory. Ideas that are contradictory cannot fit together. Or, in the language of logic: If *p* implies *not P*, Then *p* and *P* contradict and do not cohere (Thagard, 1989). It seems that such logic should be universal, and independent of the observer. But, as Vosniado and Brewer (1992) describe, non-contradiction is not absolute, especially in the science classroom. While a teacher might think that the earth is round (p) logically implies the earth is not flat (not P), students can see these two ideas as consistent (the Earth is both p and P).

The second criterion—*coherent explanations explicitly describe the relationship between statements*—also seems to make sense intuitively. In searching for coherence, scientists do not simply look to accumulate a list of consistent facts. Rather, they try to find relationships between these facts, often in the form of causal explanations. But like consistency, relationships are also perspective-dependent. Raphael's explanation, which brought together various pieces of knowledge about the water cycle, clearly contained meaningful relationships for him despite many non-canonical elements. The explicit statement of relationships also seems to be a commonly held value in science and science education. For example, Ng and.Mooney (1990) defined coherence as "how well the various observations are 'tied together' in the explanation" (p. 2). Similarly, Sandoval (2003) described coherence as how well the explanation "hangs together" and "the extent to which students are explicit about how claims relate to each other" (p. 25-26). The danger of coding schemes that require explicit relationships are twofold. First, they miss evidence of students' coherence seeking when the relationships that students build are unarticulated or described in everyday or non-standard language. Second, the coding schemes may give false positives, attributing coherent conceptual knowledge to students who have actually just mastered the game of connecting vocabulary.

But, as a starting point, I suggest the following working definition for coherence seeking: *trying to fit ideas and information together in ways that are meaningful and mutually consistent*. Aspects of this definition are intentionally ambiguous, including the terms “trying”, “information”, and “meaningful” to allow space to interpret these ideas in the context of analyzing classroom episodes.

4.3 The Learning Progressions (LP) Project “Responsive” Curriculum

The episodes in this chapter come from a series of elementary classrooms and one teacher professional development meeting, during units specifically designed to allow learners to construct, share, refine, and revise their ideas about energy, electricity, and the water cycle.

The elementary curriculum modules, designed specifically for use in the Learning Progressions (LP) project, differ drastically from the typical curricula implemented by the teachers. The standard science curriculum at these schools, called Full-Option Science System (FOSS), consists of a sequence of activities designed to help students master important concepts. For example, the 4^{th} grade Electricity & Magnetism Module contains five activities, which students must complete in order. The first activity asks students to observe various magnetic effects, the second involves building a basic circuit, the third activity consists of experiments with parallel and series circuits, the fourth activity has students build an electromagnet, and in the final activity, students build a telegraph system. In each activity, the students must follow specific instructions, and complete a set of questions at the end to check for understanding.[16]

In contrast, the LP modules are designed to be responsive. Rather than follow a strict sequence of activities, teachers determine what to do next with students based on the ideas that students raise in class. Each module begins with one opening question (see Table 3). For example, the water cycle module begins with the question:

> Suppose that one night it rains. When you arrive at school you notice that there are puddles of rainwater in the parking lot. But when you go home you notice that the puddles are gone. What happened to the rainwater?

After the opening question, the module implementations vary. In Raphael's class, Ms. M guided students into a discussion about clouds and cloud types. Ms. H, on the other hand, followed the opening question in her class with a series of experiments outside related to puddles and evaporation. In both cases, students' ideas were central to the lesson.

Table 3: Learning Progressions Modules and Focus Classrooms

	Batteries and Bulbs	Water Cycle	Rain Workshop
Grade	4th grade	5th grade	Teachers & Staff
Focus Classrooms	Ms. B Ms. F	Ms. M Ms. H	N/A
Opening Question/Activity	Lighting a bulb: How can you make a bulb light using a battery and wire?	Suppose that one night it rains. When you arrive at school you notice that there are puddles of rainwater in the parking lot. But when you go home you notice that the puddles are gone. What happened to the rainwater?	Given its proximity to the ocean, why doesn't it rain very often in San Diego?

[16] For more information, see http://www.fossweb.com/ca/summaries/MagElec/MagElecSummary.pdf.

The purpose of the LP responsive curriculum is to make space for students' inquiry in a way that a more strict sequence of activities may not. Freed from the constraints of "the curriculum," teachers are able to pursue student thinking, and to help students refine that thinking in ways consistent with the disciplinary practices of science (Hammer, Goldberg, & Fargason, in press). As a corollary, the responsive curriculum also has the potential to open up space for particular kinds of coherence seeking that might otherwise be limited. In particular, when the pressure to move from one topic to the next is relieved, students have the opportunity to build upon their ideas in ways that involves looking for:

- Alignment and misalignment between peers' ideas
- Connections between their everyday experiences and the phenomena under investigation
- Consistency in their models/theories over time
- Gaps in their explanations/unexplained phenomena
- Alignment between their own ideas and the evidence available to them

And conversely, other kinds of coherence seeking that are usually emphasized in science class, such as alignment between students' ideas and those from authoritative sources (the teacher, the textbook) are less emphasized in the LP responsive curriculum.

The teacher professional development in the LP project includes a significant 'doing science' component. Each summer, teachers spend a few hours a day, for two weeks, doing inquiry on a topic from their district standards or some other topic of interest to them. In choosing to spend a significant portion of the workshop time on scientific inquiry, the LP staff hoped to "create an environment in which teachers would actively engage in the practices of knowledge construction in science and would think about how they might create for their students a similar experience" (Rosebery & Warren, 1998, p. 3).

Both the elementary classroom data and the professional development inquiry data provide a rich context for exploring coherence seeking. Within and between these classrooms, the ideas that learners try to connect together, and the kinds of connections they try to make, are complex and varied. The episodes presented in this chapter are meant to illustrate various kinds of evidence of coherence seeking, as well as raise questions about how researchers and teachers attend to coherence seeking in the classroom. In Chapters 5 and 6, I delve into particular implementations of the water cycle and electricity modules in more detail, and reflect on the complexities of identifying evidence of, and interpreting, coherence seeking in science classrooms.

4.4 Contrasting Examples of Coherence Seeking: The Obvious and the Ambiguous

4.4.1 The Obvious: Evaporation in Winter

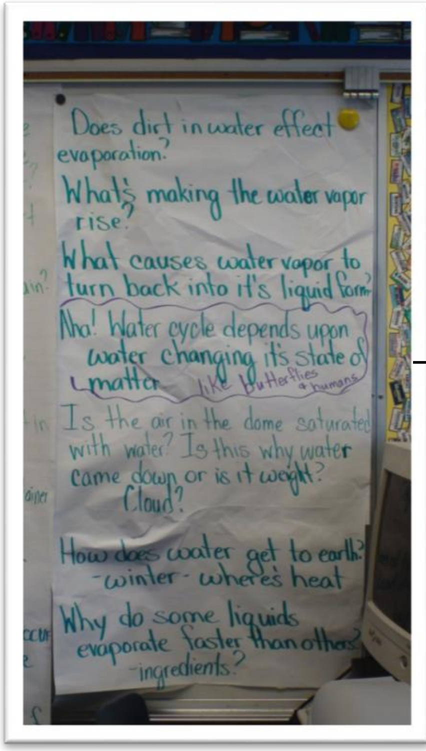
Sometimes a student's sense-making resonates with commonly accepted ideas about what constitutes sophisticated scientific inquiry, i.e. the student tries to make ideas fit together in the way that clearly resembles scientific practice. For example, it is easy to recognize coherence seeking when it clearly opens up a pathway to the currently scientifically accepted answer or when it clearly resembles a disciplinary practice like modeling or forming analogies. There are many clear examples like these in the Learning Progressions data. In the last chapter, I shared an example from a class discussion about magnets in which 4th grade student Jason points out a contradiction he sees in a classmate's idea that magnets contain electricity:

> Jason: [*holding a pair of scissors*] No, I'm saying how could, how could a magnet have electricity in it because, isn't a magnet metal too? sort of? If it had electricity in it, it would go out. [*waving scissors, from the left, to the right, seeming to show how electricity would move*] Because once electricity hits metal it goes, it keeps going in the metal until it goes…until there's no other metal on to for it to travel through and then it goes out.

In identifying an inconsistency, and pushing the class to try to resolve it, Jason clearly attempts to make ideas fit together. Similarly, in a 5th grade classroom studying the water cycle, students developed and implemented a plan to catch evaporation which they claim to have observed rising up off of a puddle. The students put dome over the puddle, as indicated in Figure 2.

Figure 2: Artifacts From the Dome Experiments in Ms. H's Classroom

(A) (B)



Does dirt in water effect evaporation?

What's making the water vapor rise?
What causes water vapor to turn back into it's liquid form?

Aha! Water cycle depends upon water changing it's state of mater. Like butterflies and humans

Is the air in the dome saturated with water? Is this why water came down or is it weight? Cloud?

How does water get to the earth? – winter- where's heat

Why do some liquids evaporate faster than others? -ingredients?

(C)

(A) Drawing of the plan to put a dome plan. (B) Example of one group's experimental set up of the dome test. (C) Partial list of questions students generated the day after the dome experiment. Ms. H's note about Nate's question appears second from the bottom ("How does water get to earth?" –winter- where's heat")

The dome indeed collected water on the inside surface, though there were differences in amount depending on the shape of the dome, where it was located, etc. The day after the students conducted the dome test, Ms. H asked the students to generate questions about the results (see Fig. 2). While generating questions, a student named Nate points out something that seems troubling:

1.1	Nate: [*gaze directed down toward his desk*] Does wa // how like, how does water get from Earth? I know it's evaporation, but [*turns toward Ms.*

H] doesn't heat ha // like, I'm thinking of winter, for some odd reason, with the dome and the water and everything. So when it rains [*briefly looks down; moves hand in an upward motion*], w-when it evaporates, doesn't it need heat to go up, back up in the clouds?

1.2 Ms. H: So you have this question, really, not about how does water get to Earth, but, winter…where's the heat?

1.3 Nate: Ya. [*starts writing on his paper*][17]

1.4 Ms. H: Because you're sitting here saying, "I know heat has something to do with this. But, winter months don't necessarily have *heat*, so how can this // how can this dome thing work if it's cold in there?" Is that what you're going for?

1.5 Nate: Yes [*writing on his paper*].

In [1.1] Nate explains that he is thinking about different pieces of evaporation:

- that water somehow leaves the earth ("how does water get from Earth")
- the name for that process is "evaporation" ("I know it's evaporation")
- water/rain needs heat to go back to the clouds ("doesn't it need heat to go up, back up in the clouds?" + gesture moving hand upward)
- the experiment where students tried to catch evaporation with a dome ("with the dome and the water and everything")
- winter/cold in winter ("I'm thinking of winter… doesn't it need heat to go up, back up in the clouds?")

Unlike Jason, who appeared to have a clearly constructed question before he shared it with the class (despite his apparent trouble being understood), Nate seems to construct his question as he speaks. He starts by asking "how does water get from the Earth?" In the context of the larger class conversation, his question could be a push for mechanism. The class had developed and tested a system for catching the stuff coming off of the puddle

[17] An additional camera angle reveals that Nate might be copying notes off of the front board; however, without copies of his papers, I cannot confirm this interpretation.

(which they interchangeably refer to as heat, evaporation, condensation, and water). However, prior to Nate's question, the class had not developed an explanation for how exactly the stuff rises, other than that it involves heat and/or evaporation. Thus, in [1.1] Nate might be pushing the class to develop a causal account. His discounting of the term "evaporation" as a satisfactory answer is additional evidence that he might be looking for some sort of mechanism, or cause, beyond what the class has described so far.

But then Nate continues into a meta-cognitive comment, and the direction of his question shifts. He says that "for some odd reason" he is thinking of winter. Keeping in mind that this discussion took place nearly in June, and no one in the class had mentioned any ideas about cold or winter up to this point, it is a bit strange that Nate thinks of winter, and he is aware of that. He almost describes his thinking of winter as something that is out of his control, in contrast to ideas that intentionally "shops for" such as the dome and water and heat rising (Sherin, Krakowski, & Lee, 2012; van Zee, Hammer, Bell, Roy, & Peter, 2005). He then starts to ask "when it rains" but gestures his hand in an upward motion. Perhaps the gesture triggers Nate that he has misspoken, because he pauses and re-states "when it evaporates." Finally, the question emerges: "w-when it evaporates, doesn't it need heat to go up, back up in the clouds?" Rather than ask *does it need heat,* Nate asks *doesn't it need heat*. Though seemingly a slight shift in wording, the intention of the question shifts dramatically. Nate is not asking for a mechanism for evaporation (how does it evaporate*?*), but instead rhetorically and implicitly points out a contradiction: how can it evaporate without heat (in winter)?

In [1.2] and [1.4], Ms. H intentionally de-centers to try to see the sense that Nate is making, and the coherence he is seeking (Donaldson, 1979). Her switch in pronoun use in [1.4] from “you’re” to “I” indicates that she actively tries to put on the perspective of Nate. She also pauses and restructures her speech multiple times as she tries to make sense of his idea and share with the rest of the class. She suggests that perhaps the thing troubling Nate is that if evaporation requires heat, then how could water evaporate in the winter? Nate confirms her interpretation.

In terms of instructional moves, Nate’s question jumps out as an opportunity to move the class towards a canonically acceptable understanding of evaporation. Up to this point, the class primarily discusses evaporation as something that requires extreme warmth or heat, i.e. evaporation can only happen in warm areas or on warm days. Students often fail to recognize that water can evaporate at any temperature (Canpolat, 2006). Thus, Ms. H could use Nate’s question as an opportunity to launch into a discussion of vapor pressure and other factors affecting evaporation rates.

Ms. M does not opt to use Nate’s coherence seeking as a path to discussing canonically accepted ideas about evaporation. Rather, she allows the class to continue trying to resolve the apparent contradiction Nate has discovered:

1.6 Molly: For the winter, the-the sun's still out, it's just the-the temperature is colder.
1.7 Ms. H: So the sun's still out, but she says the temperature's colder. But he [*Nate*] still wants to know, but will that cause some other things to happen? Colin.
1.8 Colin: It just, prob-well maybe, maybe it gets all the water in the summer and has like extra.
1.9 Ms. H: So maybe it only functions in the summer?
1.10 Colin: Ya.

Molly seems to take as fact that water evaporates in the winter. Therefore, she looks for what might cause or allow this evaporation to occur, and she identifies the sun as a possible agent. Colin, on the other hand, suggests that evaporation does not actually happen in the winter. Rather, the evaporation happens in the summer, and whatever is left over or "extra" carries over to the winter. Another student chimes in, with an idea that is a bit more difficult to understand:

> 1.11 Ms. H: That's an interesting thought. // Chuck.
>
> 1.12 Chuck: Um, cause like when it's cold in the winter, it doesn't, the snow's still there. It doesn't melt then evaporate. So...But as it gets warmer, then it does. So really, there's not much heat during the winter. But...

Chuck points out that snow exists in winter, but he is not specific about whether he is referring to snow in clouds, or snow on the ground. Either way, the snow stays frozen ("doesn't melt") in the winter. But as the Earth gets warmer, the snow melts and then evaporates. Chuck's point might be that in the winter evaporation does not need to happen because the snow is already in the clouds (similar to Colin's argument). Or, he might simply be claiming that evaporation does not happen in the winter because the snow is frozen, leaving Nate's initial question unresolved.

Ms. H explicitly draws attention to the work that students are doing to make sense of evaporation and cloud formation:

> 1.13 Ms. H: So what would you say then, you think might be going on with this whole process that we've kinda been looking at. We've only seen parts of it, but we're kind of inferring that maybe it goes further. What would you say then, Dale, happens during the winter? How- Does this change? Because that's kind of what Nate wants to know. Does this, what we were seeing yesterday, does that change just because it's winter?

Ms. H's move in [1.13] highlights what I see as an important distinction between coherence and canonical correctness. In Ms. H's words, the class is trying to understand a "process." Though she does not elaborate on the components, or "parts" of that process, we can infer from the conversation that the process has something to do with evaporation, rain, and/or snow. To Ms. H, Nate has recognized a piece of the process that has not yet been explained—if and how that process changes in winter. And despite the students' non-canonical proposed solutions to Nate's question, Ms. H encourages Dale and the other students to continue along this line of reasoning. Even though the students' answers may not seem to align with or even lead to scientifically accepted answers, the work they are doing to try to build a story of this process is coherence seeking, and an important part of their doing science.

4.4.2 The Ambiguous: Jacuzzi Analogy

Finding evidence of coherence seeking in the discussion around Nate's question is easy. The students are relatively articulate in pointing out and trying to resolve an inconsistency—a practice that is highly valued and some would argue even the driving force of progress in science (Dilworth, 1994; Kuhn, 1962; Meheus, 2002).

But within a science class, students do much more than try to resolve inconsistencies. While moments like Nate's question stand out, there are many moments in which students do not seem to be trying to connect any information together at all. For example, a few days after the discussion around Nate's question, a group of four students in Ms. H's class decides to test whether warm or cold water evaporates faster. The students conduct a pair of experiments and find in both that the cold water evaporates *faster* than warm water. Upon completing the second experiment, Molly announces the results:

2.1 Molly: Coldest evaporates first. The warmer it is, the slower than the cold.
2.2 Leah: That's *weird*.
2.3 Molly: Yeah that is weird.
2.4 Leah: Ooh! [*turning to face Molly*] It's kinda like when you go in a pool and a jacuzzi. You go in the pool and then you go-you go in the pool then it's cold then you in the jacuzzi and it's hot. And it's even hotter than usual. So it's kinda like when-you know what I mean?

After the first experiment, Leah was relatively quiet about the fact that the cold water evaporated faster. But upon hearing Molly's summary after the second trial, Leah seems to suddenly realize that the results do not make sense [2.2]. Intuitively, warmer water should evaporate faster, not cold water. Rather than ignore the strange result, Leah tries to explain it with her Jacuzzi analogy [2.4]. Something about Leah's recognizing and trying to explain a strange result suggests coherence seeking. But where exactly *is* the coherence seeking, in Leah's statements?

In her work on inquiry and language, Linfors (1999) argues that even words like "Yuk!" and "That's good", when taken in context, can be evidence of inquiry (p. 35). Likewise, Leah's simple comment "That's weird" is an indicator, in this context, that something does not quite fit or make sense to her, and Molly agrees. "That" appears to refer to the experimental result—that warm water evaporates slower than cold water. The word "weird" indicates Leah and Molly's recognition of some sort of inconsistency, or mismatch—but between what? It is likely that the inconsistency is related to her own experiences with evaporating water: puddles evaporate faster on warm days, steam rises from a warm cup of hot chocolate. These experiences suggest that warm water should evaporate faster than cold water, but the experimental results say otherwise. The mismatch then, is between intuition (likely built on experiences) and an experimental result.

Even noticing that a result is "weird" is evidence of a particular kind coherence seeking. Seeking coherence is about trying to fit ideas and information together in ways that are meaningful and mutually consistent. A weird result—one that does not fit with other information—is troubling or "psychologically uncomfortable" (Festinger, 1957, p.

3). And Leah's comment in [2.2] not only gives us, as observers, evidence that she notices the inconsistency; it also brings the weird result to Molly's attention.

Rather than just ignore the weird result, Leah attempts to reconcile it with other knowledge. Her Jacuzzi explanation is important for a number of reasons. First, it is additional evidence that Leah found the result troubling on some level. Cognitive dissonance theory holds that inconsistencies are psychologically uncomfortable, and that people will attempt to minimize that discomfort (Festinger, 1957). Leah's explanation can be interpreted as just such an attempt—if she can explain the result, then it is no longer problematic.

Secondly, Leah's explanation is evidence that she is trying to fit the result that warm water evaporates slower than cold into experiences and knowledge that she already has. She recounts the experience of going from a pool into a Jacuzzi, and how the Jacuzzi would feel "even hotter than usual" [2.4]. In a sense, Leah has made an analogy: pouring cold water outside on a hot day is like when you move from a pool to a Jacuzzi. In other words, there is some sort of *extra effect* associated with combining objects at different temperatures.

Finally, Leah's appeal to Molly [2.4] is evidence of what Lindfors (1999) refers to as a "reaching stance" (p. 110). Using the pronoun "you" and the phrase "you know what I mean?" [2.4], Leah reaches out to Molly, trying to bring her in as a participant in inquiry, and in the seeking of coherence. Leah's reaching out not only marks her language as an "act of inquiry," but also suggests that she thinks Molly can and should help her in reconciling the weird experimental result (Lindfors, 1999, p. 31).

In this excerpt, it is easy to attribute coherence seeking to Leah. *She* notices a strange experimental result, and *she* constructs an analogy that fits the result in with her own experiences. Thus, it might be tempting to claim that Molly is not seeking coherence in this episode. She hardly engages with Leah’s comments, and does not show any clear evidence of trying to fit together her experiences and experimental observations. One possibility is that Molly does try to make sense of the same inconsistency as Leah, but does not articulate it. Molly’s science journal entry for the experiment may support that interpretation, as she does comment on the skin tingling she experiences when going from a pool to a Jacuzzi. Molly also shares the Jacuzzi analogy with Ms. H during journal writing time.

However, even if it had nothing to do with the experiment, Molly very likely was trying to connect some set of information together. As briefly stated in Chapter 3, I included as part of my approach to analysis of classroom data the assumption that students are always seeking coherence with respect to something. In the next section, I more explicitly outline categories of evidence for coherence seeking in science classrooms, and distinguish between the coherences that students are likely always seeking, and those that they only sometimes seek.

4.5 Categories of Evidence of Coherence Seeking

4.5.1 Brief Reminder of the Literature

Education research studies, if taken separately, have narrowly defined what counts as coherent in students’ reasoning. Each researcher tends to focus on one or perhaps two aspects of coherence that he or she deems most important for scientific reasoning (see Table 4).

Ranney and Thagard (1988) for example, look for evidence of *explanatory coherence* in students' reasoning about motion, that is, how do students modify or retain their beliefs about motion in the face of contradictory evidence. Vosniadou and Brewer (1992) focus on the *internal consistency* of students' responses (both verbal and drawn) during a clinical interview about the shape of the Earth. If, over the course of the entire interview, the student's responses are mostly consistent, then the authors ascribe to that student a coherent model of the Earth. In looking for evidence of students' adherence to the epistemic criterion of coherence, Sandoval (2003) evaluates their written explanations about natural selection for evidence of *explicitly stated causal claims.* The inclusion of extraneous information in his coding scheme is evidence against coherence. Finally, Davis (2003) analyzes students' written letters for coherence, which she defines as a combination of *linkedness and conceptual validity*. Linkedness encompasses both internal consistency (like Vosniadou and Brewer), as well as the explicit articulation of relationships between ideas. Conceptual validity refers to whether or not the students' ideas are scientifically normative.

Table 4: Aspects of Coherence Explicitly Used to Analyze Student Thinking in Science

Paper	**Aspect of Coherence**
Davis (2003)	Canonical correctness; explicit relations
Jimenez Gomez, Benarroch, & Marin (2006)	Internal consistency
Sandoval (2003)	Explicit causal relations
Samarapungavan & Weirs (1997)	Explanatory coherence
Schank & Ranney (1992) Ranney & Thagard (1988)	Explanatory coherence (between hypothesis and evidence); internal consistency
Vosniadou & Brewer (1992)	Internal consistency

Rather than isolate single aspect of coherence, I aim, most generally, to see the sense in what students are doing in science class. To do this work, I must step outside the boundaries that traditionally define coherence in western science (i.e. prototypical coherence seeking), and instead consider the myriad ways that students fit information together, including ways sometimes seen as outside of or even antithetical to science. My approach requires starting with the assumption that students are capable, thoughtful beings who interact with the world in ways that, on some level, make sense to them. That is, students are always seeking coherence with respect to *something*.

4.5.2 Grounds for Asserting that Students are Always Seeking Coherence With Respect Something

As an intellectual strategy, it is useful for educators and researchers to assume that students are always seeking coherence with respect to something. Such a lens requires us to cast aside our notions of what constitutes correct or scientific sense-making, and instead focus on the sense that students are trying to make in the moment. However, there are theoretical and empirical reasons to take literally this intellectual strategy. That is, in the broadest and most general terms, students really are seeking coherence constantly because they are *human*. I briefly present arguments and evidence from three lines of research: perceptual processing, psychology, and linguistics.

4.5.2.1 Perceptual processing.

Humans possess a variety of sensory systems which are constantly streaming information. In order to make sense of this information, we must continually coordinate it, both consciously and unconsciously. For example, in recognizing an object as water pitcher, we must coordinate not only the placement, shape, apparent color and hue of that object, but even our associations with respect to how that object is used (Smith, 2005). The visual arts often capitalize on the human tendency to make sensory information coherent, especially with techniques such as juxtaposition. In looking at the arrangement of fruit in Giuseppe Arcimboldo's work, we cannot help but see a human-looking face. The search for coherence is in some sense automatic, or unconscious. But in entering a museum gallery for the first time, our search for coherence might be more purposeful. We look around to figure out "What kind of exhibit is this? What do these pieces of art have in common?" Part of our expectation of museums is that the pieces shown together have something in common, and so we search for those commonalities. And, these expectations actually shape our sensory experiences. We coordinate bits and pieces of information into our assessment of a situation, and conversely our ideas about what should be happening in a situation quite literally affect the information that we perceive, as demonstrated in for example Daniel Simons' inattentional blindness studies (Simons & Chabris, 1999). The search for coherence occurs across multiple levels, both intentionally and subconsciously.

4.5.2.2 Psychology.

Psychologists offer many different perspectives on coherence and human-ness. But before exploring some of these perspectives, it is useful to think of what the world would be like for an individual who lacks the capacity to seek certain forms of coherence. Oliver Sacks provides the clinical example of Mr. Thompson, who has a form of short term memory loss which prevents him from being able to seek coherence over long (more than a few seconds) spans of time:

> If you walked into a room he might decide that you were a customer entering the delicatessen he used to own and would ask whether you wanted a pastrami or ham

> sandwich. But then "click," change of scene. He might notice that you were wearing a white coat and would invent a new story—you are the butcher from down the street. "Click," new scene. The butcher always had bloodstains on his coat; so you must be a doctor. Mr. Thompson would see no inconsistencies in his changing stories. He came up with perfectly good explanations for his current circumstances, with no idea that these explanations changed from moment to moment." (Sacks, 1985, p. 93-94)

Mr. Thompson's story is an extreme one, and likely does not characterize most students. However, his story illustrates what as educators we may often take for granted: that even in existing and making sense of the world around them, students are seeking coherence. Festinger (1957) and Nisbett and Wilson (1977) have expounded upon two aspects of this innate human capacity—and some would argue proclivity—to seek coherence.

Festinger's Theory of Cognitive Dissonance holds that or misalignment or dissonance between information causes humans psychological discomfort. Because psychological discomfort is unpleasant, we try to minimize it by seeking consonance, or alignment between knowledge and actions. Festinger showed that smokers, knowing their habit is unhealthy, will often reduce cognitive dissonance by rationalizing their habit, rather than quitting it. More recently, fMRI imaging has assisted in the development of a neurological basis for the theory cognitive dissonance. Van Veen, Krug, Schooler, and Carter (2009) showed that specific regions of the brain activate when participants are asked to argue that an unpleasant MRI is enjoyable; furthermore, these regions do not activate in the control group, suggesting that the regions activated by experimental condition are in fact evidence of cognitive dissonance. Festinger's idea of reducing dissonance is in a sense a particular kind of coherence seeking—alignment between behaviors and knowledge. In his work on the adaptive unconscious, Wilson (2004) similarly argues that coherence seeking serves an important role in psychological well-being:

> The psychological immune system uses the "feel good" criterion…namely selecting, interpreting, and evaluating incoming information in ways that maintain our self-esteem. One of the most important lessons from social psychology is that people are masterful spin doctors, rationalizers, and justifiers of threatening information and go to great lengths to maintain a sense of well-being. And the psychological immune system operates largely outside of awareness." (154-155)

Studies of human perception and psyche will not play a major role in my articulation of evidence for coherence seeking in the science classroom, other than to offer some justification for the starting assumption that students are always seeking coherence with respect to something. Occasionally, when it seems particularly relevant for understanding how students construct understandings of physical phenomena, I will comment on aspects of students' perceptual and psychological coherence seeking.

4.5.3 Language and Coherence Seeking

Beyond purely the sensory and psychological arguments, a case that humans are always seeking coherence can be made from work on language—that is, written, spoken, and gestural communication between people. Because language as an act of coherence seeking plays an important role in my analysis of video data, I discuss it at some length.

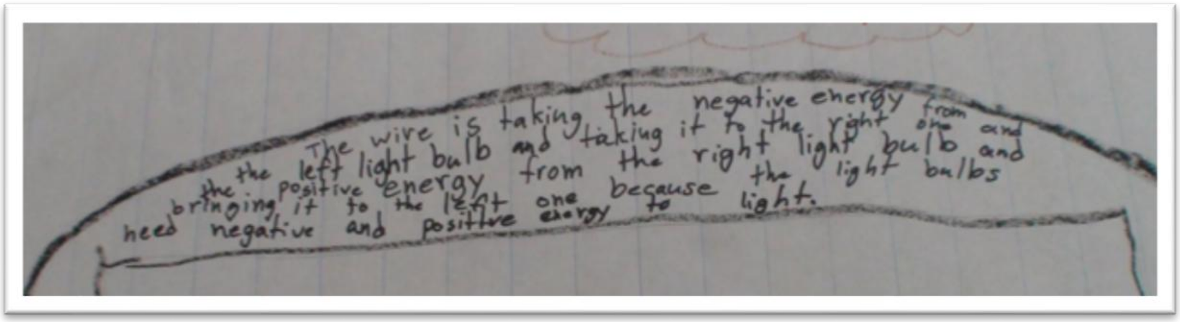
4.5.3.1 Trying to form syntactic relationships.

Communication involves forming sequences of symbols. Within the English language, certain sequences are standardized. For example, the plurality of a pronoun should align with the antecedent ("the dog is", not "the dog are"). The verb generally follows the noun ("the man walked", not "the walked man").[18] When students read or

[18] Certainly, speakers also communicate in non-standard, culturally-specific ways. I use the examples of standardized antecedent agreement because they are prominent in studies of coherence seeking in reading comprehension.

speak in science class, they must work to construct their ideas into an acceptable sequence, and they also monitor ideas for whether or not they follow the sequences, i.e. they seek syntactic coherence. For example, in one participant classroom, a 4th grade student Erin reads from her group's paper a description about how to make a bulb light:

Figure 3: Erin's Group's Explanation for How a Bulb Lights.



3.1 Erin: [*reading*] Okay. The wire is taking the negative energy **from annd**--
3.2 Shaye: No, **from the** ==
3.3 Erin: from the left light bulb and taking it to the **right one and bringing it to the left one** because the light bulbs need **negative and energy po** ... [*At this point Erin starts following the words with her finger as she reads*.]
3.4 Shaye: **##Wait, you skipped a line.##**
3.5 Erin: ##negative and positive## energy to light.

Understandably, Erin makes mistakes while reading; the words curve along the page, making it hard to follow the lines of the paragraph (see Fig. 3). After reading the first line, Erin interprets the word "and" as being part of the first line because of its physical location on the page [3.1]. Realizing that the sequence "from and" does not make sense, Erin hangs on the word "and" as she tries to make sense of the sentence. Shaye also notices the strange sequence, either on his own or perhaps triggered by Erin's pause, and corrects with the phrase "from the." Then, in [3.3], Erin pauses on the phrase "negative and energy po." Erin notices something is wrong with the structure (and possibly the meaning) of the sentence, as indicated by her pause and rephrasing in [3.4] and [3.5]. Shaye points out in [3.4] that Erin had inadvertently skipped a line. Erin does not go back to read the skipped line, but does correct a missed word. The paper says “negative and positive energy” but she reads “negative and energy.” The missing positive might have been not only a syntactic problem for her, but also an issue of meaning. Negative is one kind of energy, to Erin, so the phrasing “negative and energy” does not make sense.

In considering what information students try to connect when speaking, reading, and listening, at least two distinctions need to be considered. First, students seek syntactic coherence, i.e. that the sequence and structure of speech hangs together. Students check for pronoun-antecedent agreement, for word order, and for sentence structure. But as Chomsky demonstrated with his sentence “colorless green ideas sleep furiously”, syntactic coherence does not necessarily make a sentence conceptually meaningful. Another kind of coherence seeking in language, then, is the search for semantic meaning. Again, like syntactic coherence seeking, students’ continuous search for semantic meaning generally proceeds quietly. But when students encounter language that seems incoherent to them, the coherence seeking becomes evident. For example, when 5th grader Chuck recounts an example of density that he read in a book (that corks float in water), he mis-speaks in a way that confuses his group mate Dunn and his teacher:

4.1 Chuck: And then um so the coo // since you know how if you were to put a corkscrew down in the ocean it would go up to the top. It's cuz the corkscrew is less
4.2 Dunn: The cork.
4.3 Chuck: What?
4.4 Dunn: The cork? [*sotto voce; gesturing with thumb and finger about an inch apart, perhaps indicating the size and shape of a cork*]
4.5 Chuck: Yeah, the cork. [*smiling and giggling; Dunn smiles*] Not the corkscrew. Um is more dense than the water so that's why it goes up. And in the--
4.6 Ms. H: Are you sure?
4.7 Chuck: Or is it the other way around. [*looks to group mates and/or chart*]

Chuck refers to putting a corkscrew in water, when actually he means to say a cork. Dunn notices the mistake, and in a questioning voice, suggests “cork” as a replacement. Chuck giggles and smiles, perhaps recognizing that his use of the word corkscrew was not just a syntactic mistake, but that it also rendered his sentence somewhat nonsensical (a corkscrew will not float, though it does contain the word “cork”, perhaps indicating a subconscious connection on Chuck’s part.) In [4.5], Chuck further says that the cork is “more dense than water so that’s why it goes up.” Ms. H stops Chuck here, implying that something he has said does not make sense to her. Chuck, perhaps responding to Ms. H’s tone and content of her speech (and possibly also facial expressions, though they were not visible on the camera), questions himself. He pauses, looks to the chart and his group mates for input, and tentatively changes his answer. While I have focused on evidence of linguistic coherence seeking here, I do note that Chuck, Dunn, and Ms. H are connecting many kinds of information in this moment related to conceptual information, their framing of the task, tone and facial expressions, etc.

At low resolution, evidence of communication (speaking, listening, reading, etc.) is evidence of coherence seeking. As educators and researchers, it is important to at least acknowledge this “baseline” coherence seeking, even if other kinds of coherence seeking are more salient. (We might think of it as the cosmic microwave background radiation of the classroom).

4.5.3.2 Conversational sequencing.

When we hold a conversation, there is some expectation that what we say next should in some way hang together with what has been said before. Participating in a conversation therefore requires trying to build connections between speaking turns.

Sometimes, students make that work explicit, as when 5th grader Raphael tries to make space for a question about altitude and temperature during a discussion about lightning:

> Raphael: And also, I know this is kind of off our main question but, I just thought like since the the clouds are so high, high up and it's cold, and the sun, and they're closer to the sun than we are, why is it cold?

Here, Raphael points out an apparent inconsistency between the idea that clouds are cold/it is cold up high (a bit of information he constructed based on information from his teacher and a flight attendant), and his observation clouds are closer to the sun. In terms of conceptual reasoning, his comment is striking. However, the very first part of his utterance is important for other reasons. He uses a preliminary "And also, I know this is kind of off our…main question" to introduce his utterance, explicitly trying to make a connection between what has come before in the conversation, and the question that he wishes to introduce. Raphael's use of the preliminary indicates that he been keeping track of at least some of the prior moments in the conversation, that he thinks his comment might seem tangential to the teacher and his peers, and that he values his idea enough to share it despite the apparent disconnect.

In addition to being evidence of conversational coherence seeking, preliminaries might also tell us something about what social and cultural information students try to connect. Some districts, including the one in which the Learning Progressions data was collected, encourage teachers to establish the use of preliminaries as a classroom norm for gaining speaking rights. In Raphael's specific case, he appears to be connecting his ideas into the flow of the conversation, as well as possibly aligning his utterance with a classroom norm of "accountable talk." There are certainly situations in which a student might instantiate accountable talk without any clear evidence of having tried to connect her ideas substantively to those that came before. Thus, claims about what information that students are trying to connect when they use a preliminary must be grounded in the specifics of the episode.

Additional evidence of attention to conversational norms, beyond preliminaries already discussed, include turn-taking, repair, topical sequencing, shifts in gaze and body positioning, and speech volume normalization.

4.5.3.3 Story models and schemata.

Reading comprehension research models students' sense-making of text in terms of coherence seeking. Briefly, as students read or listen, they construct dynamic models of the text. How exactly that model is constructed (i.e. top down or bottom up) remains poorly understood, but evidence that readers seek coherence across a variety of levels of text is well-supported in a number of studies. Interestingly, coherence seeking occurs not only during initial reading of the text, but also in reconstructing that text from memory. In his studies of memory, Bartlett (1932/1995) asked participants to read a story called *The War of the Ghosts*, which contained a number of unexplained plot turns. In re-telling the story, Bartlett found that participants tended to omit "jerky, surprising, and apparently inconsequential" details, thus reducing a previously disjointed story to "an orderly narration" (p. 86). And even when explicit connections were described in the text, participants did not necessarily recite these connections verbatim, prompting Bartlett to distinguish between participants' tendency to seeking coherence, and their tendency to seeking (or recite) particular coherences:

> Any normal, educated observer strives after associative links, but whether the mode of connexion or the matter of such links, when they are supplied, is faithfully reproduced is another question altogether (p. 86)

Story models and the criterion of coherence in comprehension have also been applied to studies of juror decision making. Pennington and Hastie (1992) describe jury service as an "active, constructive comprehension process" during which jurors are expected to create coherent—defined as consistent, complete, and plausible—narratives from an unwieldy and often unorganized presentation of evidence during the trial (p. 190). A series of experiments demonstrate that jury verdicts may vary depending on the order in which evidence is introduced, suggesting that coherence seeking is in fact an ongoing process, and not something that occurs only at the end of the trial during deliberation.

4.5.3.4 Language as evidence of, and an act of, coherence seeking.

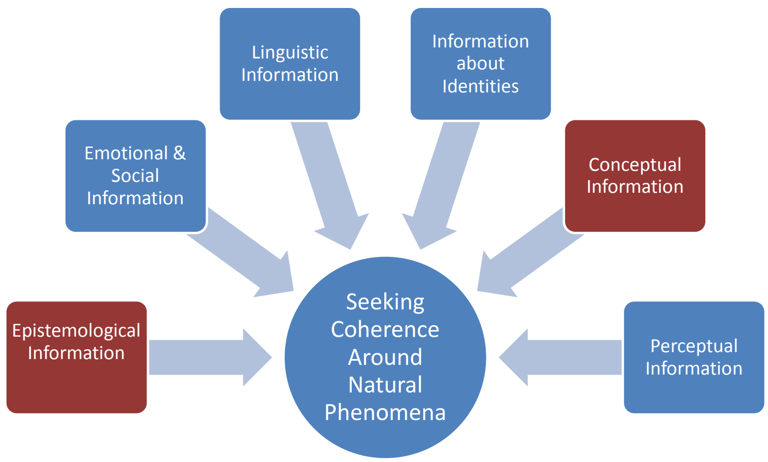
Work to understand student thinking in science from a cognitive perspective treats language as evidence of the inner workings of the mind. In other words, language serves as evidence of coherence seeking among conceptual and epistemological information. Drawing on Lindfors' (1999) language-act-framework, as well as the work on speech, conversational analysis, reading comprehension, I treat language as evidence of coherence seeking, but also as form of coherence seeking in and of itself.

To participate in classroom discourse, students must coordinate their ideas into words, their words together into thoughts. Furthermore, students must find ways to articulate their ideas in ways that align with the classroom norms and ways of speaking appropriate to school science:

> To operate the register of classroom physics successfully we must discern what goes with what else, what particular relationships are implied…every moment of the discourse during which a particular thematic system is in use is rich with implicit cues to the structure of that system and its connection to other systems. (Lemke, 1982, p. 264-265)

Thus, coherence seeking can be considered a cognitive act, as well as sociocultural activity residing in discourse.

Figure 4: "Information" in Coherence Seeking



4.5.4 Summary of Categories of Evidence

Within a framework that narrowly defines coherence seeking, evidence can be conveniently reduced to a list of behaviors or discourse patterns that apply across multiple contexts. But within a framework that broadly defines coherence seeking, identifying and keeping track of evidence of coherence seeking becomes quite difficult. Assuming that students are always seeking coherence does not solve the problem because that still leaves the challenge of finding evidence of that work they are presumably always doing. Thus, to orient my analyses and impose some organization on the perspective outlined in this work, I have developed multiple ways of slicing evidence of coherence seeking.

One categorization scheme distinguishes the *coherence seeking that students are always doing* from the *coherence seeking that they sometimes do*. I use perceptual processing, psychology, and studies of language and reading to illustrate examples of coherence seeking in which students are likely always engaged. But within making sense of phenomena, students may or may not try to reconcile conceptual inconsistencies, attend to experimental fairness, connect particular sets of information, etc.

Figure 4 demonstrates a second way to think about evidence of coherence seeking—according the kinds of information that students are trying to connect. When making sense of a physical phenomenon, for example how a bulb lights, students might seek coherence between epistemological, conceptual, linguistic, social, perceptual, affective, etc. information. The analytical challenge, then, lies in determining what kinds of information students are connecting and how.

A third way of organizing evidence of coherence seeking originates from the distinction between deductive and inductive approaches to analyzing data. The deductively-generated codes fall primarily from the working definition of coherence seeking, focus on conceptual information, and are described and illustrated in Appendix D. Examples include to: i) notice, draw attention to, or attempt to reconcile an inconsistency, ii) indicate that a result is unexpected, iii) attend to fairness of experimental conditions, iv) identify or construct a part-to-whole, causal, analogical, etc. relationship between ideas, v) notice or draw attention to an observation that is unaccounted for, and vi) question the relevance of a claim, observation, or piece of evidence. To inductively identify evidence of coherence seeking, I assume that students were always seeking coherence and considered how students' behaviors and speech might be evidence of that coherence seeking. Because such evidence is inherently context-dependent, keeping track of it all in a single table of evidence would be unwieldy and also of limited usefulness. However, some examples of evidence that appeared across multiple clips include: i) use of preliminaries, ii) breaks and restructuring of speech, iii) mirroring of vocabulary, and iv) shifting gaze.

Two final approaches involve distinguishing between evidence of *intentional* and *unconscious* coherence seeking, which I discuss at length in Chapter 6, and between evidence of *valuable/productive* and *other* coherence seeking, discussed primarily in Chapter 8.

4.5.5 Narrowing the Focus

Because I am primarily interested in understanding students' work to make sense of physical phenomena, I necessarily had to develop a way of narrowing the focus in analyzing data. Rather than narrow coherence seeking to mean particular kinds of connections between particular kinds of information, as Sandoval (2003), Ranney and Thagard (1988), and Vosniadou and Brewer for example do, I choose to focus on episodes that prominently involve students' sense-making around natural phenomena. For example, on the last day of the water cycle module in Ms. H's class, Molly and Ari have a conversation before science class about another student. They notice that this student changes her behavior depending who she is talking to. While Molly and Ari are seeking coherence in the sense of looking for consistency in their peer's behavior, I would not choose to analyze this episode in detail. Instead, I focus on moments when students are clearly engaged in making sense of natural phenomena. But *within* these clips, I might attend to students' coherence seeking with respect to social, affective, or other information that does not explicitly seem to be explicitly about the natural phenomena.

For example, on the first day of the water module, Ms. H's class created a list of ideas about what happened to the puddle water. Two of the ideas on the list were particularly contentious—that the water went into a crack or drain, or that it absorbed like a sponge into the ground. After a discussion of these and other ideas, Ms. H asks students to break into their small groups and create a "list of things [they] think would affect" the puddle.

Molly and Leah, along with their group mates John and Ari, spend a few minutes looking for dry erase markers, and then begin the discussion:

5.1 Ari: Okay. I wanna say something, that (*** ***)--
5.2 John: [*speaking loudly*] Okay, so questions.
5.3 Leah: Wait, [*to John*] what are we-questions?
5.4 John: These are questions.
5.5 Ari: Can I say one thing about the crack?
5.6 Leah: Yes.

During this transitional moment, there is tension among the students regarding what to do next. Ari makes two bids to continue an earlier discussion about the idea that the water went into a crack [5.1],[5.3]. John announces that this activity is about making "questions" [5.2]. Leah asks John what they are supposed to be doing [5.3], but also gives Ari permission to continue with the idea about the crack [5.6]. Molly is away from the group, sharpening her pencil.

By line [5.6], there are at least three different options for what the students will do next. One, they can follow Ms. H's directions and come up with factors that affect evaporation. Two, they can let Ari talk about the idea that the water went into the crack. Or three, they can follow John's lead and start coming up with "questions." These options roughly represent three different framings, or ways the students' might answer the question "What is it that's going on here?" (Hammer et al., 2005, p. 9). And, consequently, they also open up opportunities for different kinds of coherence seeking.

With Leah's permission [5.3], Ari takes the floor. He stops mentioning the crack, and instead talks about the idea that the water absorbed into the asphalt:

5.7 Ari: Even if let's say asphalt could absorb water-
5.8 John: Well I said wet asphalt. No one's mentioning that. (Ari: well but) I never said it was asphalt. I said it was wet asphalt.
5.9 Ari: But wet asphalt, sometimes let's say, you know sometimes if you put, let's say you put a spudge, sponge in water-
5.10 Leah: [*looking at Ari*] We need questions!
5.11 Ari: I'm just (thinking?). Um, if you put a sponge in water, [*Leah takes a paper from Ari*] it sometimes it's at a certain point where it can't absorb any more water.

The reason for Ari's change of topic is unclear. It could be that he sees the crack and the absorbing idea as related (the asphalt and the crack both have a limited capacity for holding water?). Or, he may have just misspoken in [5.5]. Either way, Ari's utterances in [5.1-5.11] indicate that Ari frames the activity as about considering ideas, rather than about generating questions.

But not only is Ari considering ideas, he is doing so in a particular kind of way—he tries to connect his knowledge of water and sponges to the idea that the asphalt absorbed the puddle. Ari suggests that a sponge has a limited capacity to absorb water [5.11]. Though Ari never completes the line of reasoning, the implication is that "even if" the asphalt could absorb the puddle water, maybe it would not be able to absorb it all. In a sense, he is pointing out that the sponge idea may not completely account for the observation that the puddle water completely disappears. Or similarly, Ari may be checking for consistency between his ideas of how a sponge absorbs water, and the idea that the asphalt absorbed water. If a sponge has a limited capacity to absorb water, than what does that mean about asphalt?

Two aspects of Ari's coherence seeking stand out. First, his comments occur at a transition between activities. Ari does not follow the teacher's directions, nor does he follow the lead of another student. Instead, he tries to make space for considering what appear to be problematic ideas—that the water went into a crack or absorbed into the asphalt. Secondly, Ari continues to pursue coherence between the sponge analogy and the puddle disappearance despite continued interruptions by John [5.8] and Leah [5.10, 5.11].

Leah, on the other hand, begins the episode apparently without a clear idea of what she should be doing. She turns to John (perhaps as a proxy for Ms. H) for input. She clearly latches onto his idea that the activity is about coming up with questions. And though Leah allows Ari to "say one thing about the crack", she soon interrupts him, both verbally and by taking his paper. Later, she also interrupts John:

5.12 John: Or, yeah. But or, if you were, if you were in a place like a few years ago, if there are, if there are fires where near where you live a lot, [*Leah taps the white board*] that would probably affect. Cuz it would probably be fairly warm in that area so that would affect. [*Leah writes "QUESTIONS" in big letters on the whiteboard*]

5.13 Ari: What! Leah...

5.14 Leah: [*hits her hands on the whiteboard, pointing to the word "questions*"]

Leah's use of the whiteboard indicates that she has an expectation about what the students should be doing, and that expectation is not being met. Both she and Ari exhibit persistence as they try to get the attention of the group. There is little evidence that Leah considered Ari or John's ideas, other than determining that they were not about coming up with questions. Surely Leah is seeking coherence with respect to *something*, but what? Certainly, as aforementioned, she is checking that the group's next activity should align with the teachers' directions. She shows some evidence of listening to John and Ari's statements (or perhaps intonation) to determine if they are asking questions. She works hard to find different ways to get the group back on task, including verbal reminders, written reminders, and gestural reminders. And we cannot rule out that she may be thinking about Ari's question. But in looking at her contributions to the inquiry taking place in this moment, her moves are clearly toward closing down, rather than opening up, the conversation around Ari's question.

Figure 5: Leah's Whiteboard

Thus, in the Questions! clip, the question of 'coherence with respect to what?' seems to be in part answered by distinguishing between Leah's "doing the lesson" and Ari's physical sense-making (Jimenez-Aleixandre, Rodriguez, & Duschl, 2000).

4.6 Challenges to Seeing Evidence of Coherence Seeking

So far in this theoretical and methodological chapter on evidence of coherence seeking, I have:

i) offered a working definition of coherence seeking,

ii) presented obvious and ambiguous examples of coherence seeking,

iii) justified the assumption that students are always seeking coherence with respect to something, and

iv) outlined various kinds of evidence of coherence seeking and how they inform my selection and analysis of classroom episodes.

But even with all of the groundwork laid in this chapter, challenges to seeing evidence of coherence seeking in the classroom remain. In the complex ecosystem of school, a number of distracters can draw our attention away from evidence of students' coherence seeking. Some of those distracters include:

- "incorrect" answers, or conversely, "correct" answers
- internal contradictions in students' work, from our perspective
- students' failure to draw on relevant experiences/information, from our perspective
- students' work primarily to understand the social world, rather than the physical world
- inarticulate or incomplete language
- lack of verbal communication

To illustrate some of these distracters, I draw on data from Davis (2003; n.d.). Davis's coding scheme for coherence ranks students' written work on a scale of 0 (incoherent) to 4 (coherent).

> Code 0 letters include a complete lack of coherence in their ideas. These letters are often **very brief or incomplete** (see, for example, S102 & S108). Students who write letters like this often rely heavily on everyday experiences (see S419 & S426), **to the exclusion of knowledge attained in science class**. These students say all the claims are valid (see S213 & S228), and often **cite no principles**. The letters may include critiques of the evidence or claims (see S312 & S329)—but those critiques are **not based on any scientific knowledge (normative or not)**. (Davis, n.d., p. 1; emphasis added)

In essence, the coding scheme rewards the coherences often valued or preferred by educators—display of classroom knowledge (including information, principles, and warrants) and assignment completion—and overlooks students' general attempts to make information "hang together." Applying that coding scheme to the following "letter to the editor", written in response to a fictitious news article with erroneous information about energy conversion, Davis finds no evidence of coherence and codes the letter a "0" (Davis, n.d., p. 1-2):

Dear Weekly World Science News,

Section 1: Introduction

Thank you for asking us for help in correcting and critiquing your artical. We had a fun time cratiquing you claims. We did some miner adjusting in some of your articles.

Section 2: The Claims and their Evidence

- For Bicyclists at Night we think that the evidence is not valid because it might not be true if the person had reflectors on his bike.

- We think that they could do some tests to prove that people get hot wereing black than white.

- We think that the evidence is not cradible because they do not have enough evidence to prove it is true.

- The evidence does not stay on the same topic.

Section 3: Evidence Guidelines for the Reporters

We think that they could do some tests on other things to prove their claim. The proof they have is not all substancial evidence. It's there, but it either doesn't make sense, or proves nothing.

Section 4: Conclusion

We think that they could do some tests not only to prove it to the readers but to themselves, and try to make sense of what they are writing.

Sincerely, 108 & 102

Clearly, the students did not randomly hit keys on the computer to generate this letter. The construction of the letter itself, as well as the ideas within it, involved coordinating all kinds of information together. First, students adopt a letter-writing tone, one that is tentative ("we think"), laudatory ("we had fun"), and polite ("thank you", "sincerely"). The students use pronouns to distinguish themselves ("we", the reviewers) from the fictitious reporters ("they", whose work they are reviewing) and from the editors ("you", the audience for the letter). And notably, the students use terminology (credibility, valid) they have likely learned to be important in school science. The coding scheme completely omits this task awareness as evidence of coherence seeking, and instead focuses on how well students articulate connections between conceptual knowledge learned in school.

Noticing students' task awareness matters not only for building a nuanced account of students' coherence seeking, but also for instructional decision making. In ignoring task awareness as part of the sense-making work that students do, educators may underestimate the influence that task awareness has on how students try to connect conceptual information. Students might see the letter writing task as sort of silly because no real editor exists, and thus write the bare minimum to complete the assignment. Or, students might see letter writing as an opportunity to share their ideas and imagine communication with a fictitious editor, rather than an opportunity to recite the details of energy conversion that they have used in class. The "incoherence" that Davis attributes to students' explanations in the letter may be as much an artifact of the students' interaction with the task as it is a reflection of the state of students' knowledge at the time they wrote the letter.

Secondly, the coding scheme is strikingly inconsistent. Part of the reason that Davis coded the letter a 0 was because the students "rely heavily on everyday experiences (see S419 & S426), to the exclusion of knowledge attained in science class." But if anything, the letter above illustrates the opposite. The students rely on knowledge attained in science class to the exclusion of their everyday knowledge. For example, the students suggest that editor "conduct some tests to prove that people get hot wereing black than white." A student who relies on everyday experience would certainly know that people feel warmer when they wear black clothing on a hot day. Thus, there would be no need to "prove" this to be true. But students learn in school to discount their everyday knowledge, i.e. the *epistemological knowledge* attained in science class says that knowledge must be proven experimentally. Thus, while the students may fail to incorporate conceptual knowledge related to energy transfer in the letters coded incoherent, they are likely incorporating epistemic knowledge that they have learned in school.

Certainly, Davis's coding scheme does not make any specific recommendations in terms of what teachers should do in cases where students earn a "0" /incoherent score on the writing assignment. And yet, we can easily imagine that a teacher who fails to take students' linguistic, social, epistemological, etc. coherence seeking into account might incorrectly presume that students' poor performance on a writing assignment purely reflects a lack of content knowledge. Thus, the failure to recognize evidence of students coherence seeking not only matters not only for research, but also has important implications for practice.

4.7 Conclusion

In overcoming the persistent urge to say that students are not seeking coherence, educators and researchers must recognize the myriad kinds of information that students connect continuously in science class, or as Buchmann and Floden (1992) write:

> Coherence allows for many kinds of connectedness, encompassing logic but also associations of ideas and feelings, intimations of resemblance, conflicts and tensions, previsagements and imaginative leaps. (p. 4)

Thus, in defining coherence seeking *as trying to form meaningful, mutually consistent relationships between information*, I hope to draw attention to the richness of students' coherence seeking in science class. Using examples from participant 4th and 5th grade classrooms, as well as data from other studies, I have already illustrated aspects of students' sense-making that other coding schemes miss. In general, these coding schemes focus on the conceptual content of students' sense-making and many of them judge that coherence from the perspective of the more knowledgeable expert. As a result, they miss the linguistic, social, cultural, affective, and epistemological coherence that students seek in science class, as well as fail to recognize the coherence seeking evident in students' non-canonical answers. I have also briefly touched on how noticing these aspects of students' sense-making matters for instructional decision-making.

In the next chapters, I set existing coding schemes aside and transition to detailing the strengths and weaknesses of my alternative perspective on coherence seeking. For example, in all of my analyses up to this point I have been intentionally vague about what constitutes "information" and "meaningful relationships" in the working definition. Chapter 5 explores these points in detail, with explicit attention to the researcher and student perspectives.

Chapter 5: Considering What Information Students Try to Connect—Examples from 5th Grade Experiments on Evaporation

"Thoughts are our way of connecting things up for ourselves. If others tell us about the connections they have made, we can only understand them to the extent that we do the work of making these connections ourselves."

–Eleanor Duckworth, The Having of Wonderful Ideas

5.1 Introduction

When students do science, they connect many different kinds of information in many different ways. But some aspects of students' coherence seeking have been studied much more extensively than others, largely due to their perceived importance in the scientific enterprise. Some work focuses on students' linking of particular concepts, for example, that *weight* is a kind of *force* acting on an object. Other work focuses more on the categories of relationships that students build between information. Studies of scientific argumentation for example explore how students form connections between data and claims via warrants and backing (Berland & Reiser, 2008; Driver, Newton, & Osborne, 1998; Kuhn & Udell, 2003).

In this chapter, I focus on students' coherence seeking within the context of another highly studied phenomenon in science class—students' response to anomalous data. Because so many ideas in science seem to contradict everyday intuitions, educators need to understand how students will respond to contradictory information. As outlined by Chinn and Brewer (1993), there are several different ways that students and scientists might respond to contradictory information, including ignore it, reject it, exclude it, reinterpret it, or change their ideas in response to it.

Drawing on data from Ms. H's 5th grade classroom during a water cycle unit, I analyze students' responses to unexpected observational data during experiments on evaporation. I show, analytically, that all of these responses can be thought of as evidence of coherence seeking with respect to different sets of information. Finally, I consider the analytical challenges of identifying precisely what information students try to connect, and in what kinds of relationships.

5.2 Anomalous Data in Science and in Science Class

Anomalous data, or data that does not fit expectation or theory, seems to be the perfect starting place for understanding how students try to fit information together in meaningful and mutually consistent ways. Anomalous data plays an important role both in students' experiences in science class, and also in the doing of science.

Karl Popper (1968) argued that falsifiability, or the possibility of contradictory evidence, demarcates science from other modes of thinking. Indeed, accounts of scientific progress are ripe with examples of anomalous data prompting acceptance, revision or tossing out of theories for those that better align with available evidence. General Relativity underwent a number of empirical tests before it gained widespread acceptance. Among those tests were i) explaining Mercury's shifting orbit, not accounted for by Newton's universal law of gravitation, and ii) predicting the bending of light by the massive objects like the sun, as demonstrated during a solar eclipse in 1919. The scientific community's acceptance of elliptical orbits, continental drift, and geomagnetic reversal all hinged on ability of these constructs to explain previously anomalous observational data.

Anomalous data has also come to play an important role in understanding how students learn science. After all, “encountering contradictory information is a very common occurrence when one is learning science” (Chinn & Brewer, 1993, p. 1). Anomalous data comes from a variety of sources in science class. Students may make predictions that do not hold up to observation. They may share ideas that contradict their peers’ ideas. Or, they may encounter explanations from the teacher or textbook counter their own intuitions about how the world works.

Misconceptions research has catalogued the myriad ways that students’ everyday intuitions might contradict scientific understandings, across a variety of topics in science (see for example Halloun & Hestenes, 1985). Within physics, students may express the idea that motion requires a sustaining force, or similarly that light dies out as it travels. While the ontological nature of these intuitions and their role in instruction has been debated, in general educators agree that part of learning science must necessarily involve students coming to reconcile their intuitions with the conceptual information made available to them in science class, whether that information be in the form of observations, experimental results, or authoritative knowledge from the teacher or textbook. Educators have also designed instructional programs, including laboratory tutorials and discrepant events, specifically aimed at students reconciling particular sets of observational, theoretical, and intuitive information.

5.3 Experimentation and Anomalous Data in the Ms. H's Year 1 Implementation of the Water Cycle Module

In the Learning Progressions water cycle module did not outline specific experiments or activities. Instead, as described in Chapter 4, the curriculum consisted of an opening question about what happens to puddle water that "disappears" over the course of the day, followed by a brief list of possible follow up activities, most of which involved further discussion of ideas.[19] In contrast to discrepant events and other learning sequences utilizing contradictory data, the source and role of anomalous data within the Learning Progression curricula emerge naturally, as students try to build accounts of phenomena that align with their intuitions, observations, and reason. In evaluating each other's ideas, students spontaneously generate counterevidence, offer competing interpretations of data, suggest possible experiments to test ideas, and identify possible flaws in those experimental designs. Experimentation was mentioned only once in the water cycle curriculum materials, in the context of students figuring out how to test their ideas. However, experimentation became an integral part of students' work on the water cycle in Ms. H's class during Year 1 of the project. Students used experiments to test their ideas about what happened to the puddle water, as well as to investigate various factors that might affect evaporation. In all, students conducted experiments on four of the nine days of the module (see Table 5).

[19] The Learning Progressions Water Cycle module is available online at http://cipstrends.sdsu.edu/water_module/

In the following sections, I explore a series of experiments conducted by the focus group of Leah, Molly, Ari, and John. Most of the experiments tested how one or more factors (size, shape, water temperature) affects the evaporation time of a puddle. Each experiment yielded unexpected results, from the students' perspective.

Though Ms. H's class conducted a number of different experiments over the course of the nine-day module, I focused on three of the focus group's experiments primarily because of data limitations. Two cameras were used to videotape the water cycle implementation in Ms. H's class. One camera followed Ms. H; the other camera focused on the focus group. Prior to the start of the module, Ms. H selected Leah, Molly, Ari, and John as the focus group. Thus, while I have access to bits and pieces of the other students' experiments through the camera that followed Ms. H, the focus group experiments are the only ones videotaped in their entirety—including brainstorming and design, conducting, reflection, and reporting on the experiment. To analyze the students' coherence seeking in the experiments, I draw on videotape data from these days, as well entries in the students' science journals. I present portions of that analysis here, focusing on moments when students comment on unexpected results.

Table 5: Summary of Water Module Implementation in Ms. H's Class

Day	Description and Clips Presented
1	Class discusses the Opening Question. **Clips: Questions! (Chapter 4)**
2	Focus group designs and conducts experiment to test how amount of water affects evaporation. **Clips:** · **Experiment 1a: Which evaporates faster—a "3 ounce" puddle or a "6 ounce" puddle? (Chapter 5)**

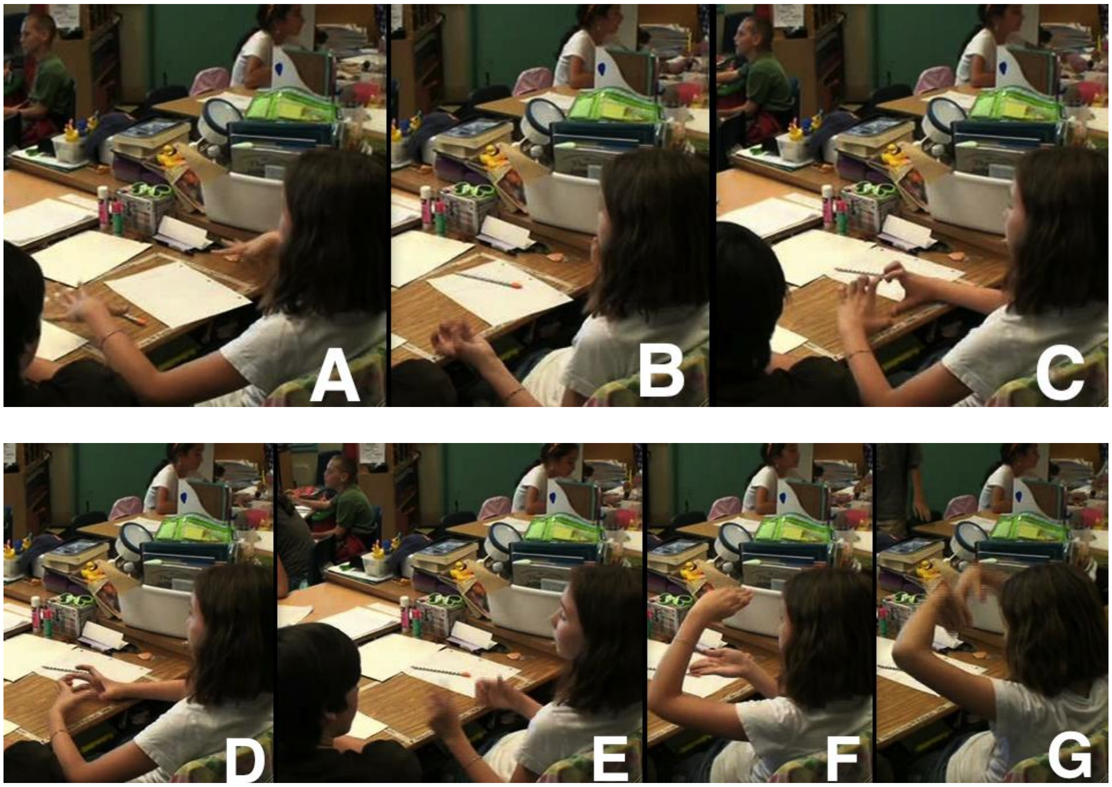
	· **Experiment 1b: Evaporating in double time (Chapter 5)**
3	Students debate what the “stuff” was that came off of the puddles while they were outside on Day 2.
4	The focus group tries to catch “evaporation” using plastic bins.
5	Students generate additional questions they have about evaporation; students work in groups to decide how they can answer their questions. **Clip: Nate’s question about evaporation in winter (Chapter 4)**
6	Students try to make clouds inside jars.
7	The focus group tests how temperature affects evaporation. **Clips:** · **Experiment 3a & 3b: Which evaporates faster—hot or cold water? (Chapter 5)** · **Jacuzzi analogy (Chapter 4)**
8	Class discussion about experimental results from Day 7.
9	Class discussion about weather, how they got from puddle to talking about weather, and how they feel about the module compared to other science they have done. Students research weather using books and the internet. **Clips:** **Annotated transcript of a focus group presentation about weather (Appendix B).**

5.3.1 Experiment 1a: Which Evaporates Faster—a “3 ounce” Puddle or a “6 ounce” Puddle?

Following the opening day discussion about the disappearance of the puddle, Ms. H asks students to work in small groups to decide what they want to explore next. John and Ari suggest running some experiments “to learn more about evaporation.” The focus group designs a 2 X 2 experiment to simultaneously test the effect of time of day and puddle size on evaporation time. But after sharing their plan with Ms. H and the rest of the class, they ultimately decide to just test amount of water. The next day, just before setting up the experiment, the students discuss their predictions:

1.1 John: Wait, so what do you think about it [*glancing around at each group member*]? Do you think a small puddle will evaporate faster or a bigger puddle?
1.2 Leah: I think a smaller puddle will.
1.3 John: ##Yeah.##
1.4 Ari: ##Yeah.## And also what I think that you never know. I wonder--
1.5 Leah: We should (*** ***)--
1.6 John: She said just put you think will happen.
1.7 Ari: Yeah.
1.8 Leah: Kind of like the science fair project, just, even if you already know the answer find out the scientific // ##the more scientific reason.##
1.9 John: ##Yeah find out the most logical one.## [*writing on paper*]
1.10 Leah: Yeah.
1.11 Ari: Um, what I'm guessing is let's say something is two feet but very very shallow, it might evaporate faster [*John gets up from the table*] than something [*Leah drinks from her water bottle*] // or two cups are all spread out might evaporate faster than two cups that are in a little vial straight up. I'm wondering if evaporation has to do // if the depth has something to do with how fast it evaporates. [*John returns*]
1.12 Leah: [*nodding head*] Yeah because if it was // like what Carl was saying if it was wider [*Fig. 6A*]. Like, if it was a wider space, [*Fig. 6B*] and the water spread out, then it would probably soak it up more [*Fig. 6C*]. But if it's // but if it's [*Fig. 6D*] depth and it's in a smaller area--
1.13 Ari: But--
1.14 Leah: But [*Fig. 6E*] Wait. Then it will probably take longer cuz the water's [*Fig. 6F*] on top of each other. And if it's spread out, then [*Fig. 6G*] all the different sun rays and heat could come on all of it at the same time.

Figure 6: Leah’s Gestures in Utterance [1.12]



Lines [1.1-1.8] reveal some information about how students view the task of designing an experiment. John, taking on a sort of group leader role, looks around at each student in [1.1] and asks which puddle they think will evaporate faster. He does not offer his own prediction, but Leah and Ari both predict the smaller puddle will evaporate faster. Perhaps recognizing the possible absurdity of running an experiment when they already know the outcome, Leah, Ari, and John begin to justify doing the experiment at all. Ari starts to express authentic uncertainty about the experiment in [1.4]. Leah also speaks, but her utterances are inaudible. Perhaps sensing the group moving off task, John refocuses students (“she just said put what you think will happen”). For John, the point of the task is to make predictions. It does not really matter what those predictions are or why—just make them.

In [1.8] and [1.9], Leah and John further explain that at school/science fair, the "scientific" or "logical" answers are those that are obtained through experimentation. In other words, even if you know the answer, that knowledge is not valid until it has been supported by an experiment. But then in [1.11], a shift occurs. Rather than explicitly comment on the rules of doing school science, Ari offers a scenario in which the experiment could plausibly yield unanticipated results. Ari's idea, briefly, is that more water could evaporate more quickly if that water is able to spread out.[20] Leah elaborates with a specific mechanism for how depth matters. First, in [1.12], she suggests that a puddle that spreads out could be soaked up more, presumably by the asphalt as her gestures show the water pulling down toward the ground, rather than up. And though John suggests in [1.1] that the students agree that the water evaporates, in fact, to this point the entire class has a number of options on the table for what happens to the puddle water, including absorption into the asphalt. Then, in [1.14], Leah adds that piled up water will not get as many sun rays and heat as water that spreads out. She seems to be so invested in her idea that when Ari tries to interrupt her in [1.13], she reprimands him.

After making predictions, the students set up the experiment. They create two puddles on the asphalt outside, one with "three ounces" and the other with "six ounces" of water. However, as the students have measured it, the term ounces refers to inches of water as measured from the bottom of the container to the top of the liquid.

[20] Ari's idea resembles one expressed by another student named Carl during a class discussion earlier that the day.

As the experiment proceeds, the students notice the water spreading out with the wind and also disappearing. Ari wonders whether the water is evaporating or disappearing some other way. In response to Ari's wonderings, John makes a prediction that focuses not on which puddle leaves faster, but rather, what causes the puddle to go away:

2.1 John: After our experiment is over we'll be able to tell if it's evaporation by touching it [*the asphalt*] and seeing if it's really hot. Then it probably would be evaporation (Ari: yeah). If it's not really hot then it's just sliding and probably drying on the asphalt.

Figure 7: Students Testing John's Hypothesis

John's prediction seems to be grounded in an idea that evaporation involves heat. If the water is evaporating, then the asphalt it was touching should be hot as well. Taking up John's prediction, Ari suggests touching the asphalt in a place where the puddle has already disappeared (see Figure 7).

2.2 Ari: Why don't we touch one of the areas like right around here. [*John, Ari, and Molly touch the asphalt where the puddle has already evaporated.*] Is it? Yeah that's pretty hot.
2.3 Leah: Well I think all the asphalt is hot.
2.4 John: [*standing*] Um, the part where it dried is cooler.
2.5 Molly: [*looking at John*] Yeah but if you put one hand one here

[*evaporated spot on asphalt*], one hand on here [*regular asphalt*], this part [*the regular asphalt*] is hotter.

2.6 John: ##Just by a little.##

2.7 Ari: ##You know what I think it is?## [*All the students stand up and start shifting around the puddle.*]

Ari suggests that rather than wait for the puddles to completely evaporate, they can just touch part of the asphalt where puddle has already evaporated [2.2]. His suggestion allows the group to immediately begin *looking for consistency* between John's prediction and the experimental results.

Ari touches just the place where the puddle evaporated and comments that it is hot. Leah implies that this information alone is not very helpful, saying "all the asphalt is hot" [2.5]. In other words, she *questions the relevance* of Ari's observation. John and Molly also touch the regular asphalt and evaporated spot. They find that the place where the puddle used to be is *cooler* than the surrounding area, even if "just by a little" [2.6]. The students immediately try to *explain and confirm this surprising result*:

2.8 Molly: ##Well yeah.##

2.9 Leah: ##Maybe it## // maybe it also um...

2.10 Ari: The water kind of is a little bit of a block

2.11 Leah: it...[*makes gesture with one hand as in Fig. 6D*] yeah

2.12 Ari: It blocks the ground a little bit but--

2.13 John: Let's try that with the other one. [*John and Molly go touch the other puddle*]

2.14 Leah: Maybe [*she touches the regular and then evaporated spot twice*]..maybe it's because it kind // ##it soaked in more.## [*repeat gesture Fig. 6D*]

2.15 Ari: ##yeah the water absorbed##

2.16 Leah: Maybe it soaked in so it's...[*Molly returns*]

2.17 Molly: yeah that--

2.18 Leah: soaked in a little also so it--

2.19 Ari: I think it also

2.20 Molly: that one's [*pointing to the other puddle*] a lot cooler than the ground

2.21 Ari: You know what I think it is. I think the water kind of acted like a

> cover for the asphalt for a few moments. So it // so that it // so this started to heat up, so it was like putting a cover over this so this doesn't heat up as fast as this. And then taking the cover off.

Ari wonders if the water may have “blocked” the asphalt like a “cover” [2.10, 2.21]. He does not specify what the water is blocking, but later in the experiment he reveals that the water might block sunlight sort of like “giant sunglasses.” Ari’s cover explanation accounts for at least three pieces of information: i) the water may have evaporated, ii) the asphalt under the puddle is cool, and iii) the asphalt warms up after the water is gone (Ari checks this himself). In Chinn and Brewer’s (1993) terms, Ari “reinterprets the data” and makes “peripheral changes” to his theory; that is, he maintains the idea that the water evaporated, but adds the idea that the water acts like a cover for the asphalt before it evaporates (p. 4).

Leah also tries to explain the discrepant result. She proposes that the water absorbed into the asphalt, causing the asphalt to feel cool. Her explanation is consistent with John’s original prediction that, if the spot is cooler, something other than evaporation must be occurring. In other words, she “accepts the data” and on the basis of that data, rejects evaporation as the cause of the water’s disappearance.

Rather than jump to explaining the anomalous data, Molly and John check to see that the result is repeatable [2.16, 2.23]. They find that even with the other puddle, the place where the water used to be is “a lot cooler” than the regular dry asphalt. No single category in Chinn and Brewer’s framework captures Molly’s and John’s attempt to confirm the result. The students do not outright reject the data or attribute it to methodological error, nor do they automatically accept the data. And, certainly they do not simply "hold the data in abeyance" trusting that it will be explained in the future.

The students never explicitly say that they expected the asphalt where the puddle was to be warmer. But it is easy to imagine that this was their expectation. The students tone and reaction to finding that the evaporated spot is cooler is some evidence of their initial expectations. The students likely associate evaporation with heat or with heat sources like sunlight or the stove. If evaporation involves heat, then it is reasonable to think that the place where water evaporated should be hotter than everywhere else. Or, perhaps the students thought of the asphalt as something like a stovetop, where the burner feels warmer than the surrounding area. While I cannot for certain identify the origin of each student's idea that the spot under the puddle will be warmer, the exercise of identifying everyday experiences (or cognitive resources) that students might draw on in thinking about the puddle experiments is an important part of how I analyze what information they are trying to connect. I elaborate on other aspects of that analysis in the next section.

5.3.2 Identifying the "Information" That Students are Trying to Connect

At a low resolution analysis of the coherence seeking, the students are connecting many kinds of information while they conduct this experiment. They communicate, thus fitting together ideas and phrases into semantically and substantively meaningful thoughts. They process perceptual information from the world around them, including the feeling of coolness of the asphalt where the puddle evaporated. They recognize the work they are doing as "an experiment" and thus take on particular roles that they associate with doing experimental work, including time keeping and taking notes. They notice an anomalous experimental result and try to make sense of it. These general statements paint an overall picture of students' coherence seeking, but they do not really answer a more specific question: What information are these students trying to connect? I would like to have some more nuanced sense of the "ideas in play" for these students.

But narrowing down a word as vague as "information" into something analytically useful is not trivial. First, there is the question of the ontological nature of this information, i.e. are we talking about the information in students' minds or information that lives in discourse? Ranney and Thagard (1988), for example, attempt to model the network of information in students' minds. Characteristic of work on students' cognition more generally, they uses interviews as a way to glean evidence of what happens cognitively for a student as she encounters anomalous data. The nodes and connections in their diagrams (see for example, Ranney & Thagard, 1998, p. 6) represent information and links thought to reside in some form *inside the students' minds*. Lindfors' (1999) work, on the other hand, situates coherence seeking as an act of language. In her approach to parsing discourse, the utterances are units of conversational meaning, and not necessarily indicative of units of meaning inside the mind. Surely, seeking coherence involves both coherence seeking in the mind and in discourse, and so it worth considering both.

There are many different ways of linking coherence seeking in the mind with coherence seeking as living in interaction. Lindfors argues that Vygotsky's notion of internalization allows for ways of speaking to become ways of thinking. Abrahamson's (2009) work considers how students appropriate and re-interpret semiotic tools (language, diagrams, symbols, etc.) of mathematics to support their own intuitive ideas about, for example, probability. And embodied and distributed cognition blur the distinction between the individual mind and the external world. An account of coherence seeking built on Hutchins' (1995) work, for example, might speak of a classroom (physical space and equipment included) as seeking coherence, with individual students playing specific roles within that larger system. While such complex views of cognition are certainly worth exploring in future work, for the purposes of this dissertation I have chosen to focus on coherence seeking as attributable to individual students. In other words, while student's coherence seeking might be influenced by their interactions with others, by the physical environment, and even their physical location in space, I treat all of these as pieces of information that are ultimately connected within the individual's mind.[21]

Additional issues surrounding the development of a more specific account what information students are connecting are best illustrated through an examples of existing methods for doing this kind of work. In their analysis of students' ideas about seasons, for example, Sherin, Krakowski, and Lee (2012) develop a system for isolating two kinds of cognitive units of information in students' interview responses: nodes and modes. The nodes are elements of knowledge of all kinds (and at all levels of abstraction), whereas the modes are a set of interconnected nodes. To explain their

[21] Hutchins argued that in some systems, the "outcomes of interest are not determined entirely by the information processing properties of the individual", in which case the system should become the unit of analysis. For example, landing a plane requires the coordination of two pilots and multiple artifacts, making the cockpit a sensible unit of analysis. Because my focus in this work is not on outcomes, per say, it is not methodologically imperative that I inform my unit of analysis based on the data. However, if I were to try to characterize, for example, the focus group's progress in developing an account of evaporation through the lens of coherence seeking, then most certainly I would need to more carefully consider whether the individual mind is really the unit of interest.

coding scheme, they present a snippet from an interview with a student named Leslie, who tries to explain the causes of the seasons:

> 3.1 Leslie Um::: well, um, you know times savings? / / you know? Like in the summer, when you have –
> 3.2 Interv. // mm-hmm
> 3.3 Interv. – Daylight Savings time?
> 3.4 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. (Sherin et al., 2012, p. 176)

Sherin et al. identify the following nodes in Leslie's utterances: i) *sun is a source of heat*, ii) *daylight savings*, iii) *days are longer in summer and shorter in the winter*, and iv) *the earth moves* (p. 11). But what do these units really tell us about the information that *Leslie* is trying to connect, from her perspective? It seems they tell us more about how the researcher makes sense of Leslie's ideas than how Leslie herself makes sense of them.

For example, in [3.4], Leslie comments on "the circulation of the earth and like the axis that it's on." Sherin et al. collapse this statement into the node *the earth moves*. As the authors acknowledge, what exactly Leslie imagines with respect to earth's circulation and the axis is not clear. But when the researchers combine the idea of circulation and earth's axis into one node, that choice reflects their own understanding, and not necessarily the connection Leslie sees between these ideas. While to an expert the idea of Earth having an axis might be subsumed by the idea that Earth moves (i.e. the Earth rotates around an axis), even in the structuring of her language (circulation of the earth AND like the axis), it seems that Leslie distinguishes these in some way.

Sherin et al.'s analysis also favors researcher perspective in that it focuses only on the conceptual aspects of Leslie's reasoning. But Leslie clearly attends to more than just the conceptual knowledge inside her mind during the interview. For one, she responds to verbal information from the interviewer. When the interviewer suggests the phrase "Daylight Savings time" in [3.3], Leslie incorporates this phrase into her response in [3.4], meaning that she is not only making sense of the Earth's seasons, but possibly also the cues and hints that the interviewer provides. And while the authors do not provide the necessary evidence to make such claims, including gestures, gaze, and facial expressions, it is very likely that Leslie is also responding to nonverbal cues from the interviewer, including signals about her performance. All of this is to say that understanding the information that Leslie is trying to connect, from her perspective, requires de-centering and trying to see the physical and social world from her point of view (Donaldson, 1979).

Returning to the transcript from Ms. H's class, in line [2.1], for example, what information was John trying to connect? John's statement sets up the conditions for anomalous data to arise in the first place, and so understanding his ideas in [2.1] are a necessary part of understanding the students' later response to the anomalous data. Akin to Sherin et al's approach, one of the approaches I have tried in analyzing classroom data is to leverage students' phrases and terms to isolate key conceptual components. For example:

> [2.2] John: After our experiment is over we'll be able to tell if it's evaporation by touching it *[the asphalt*] and seeing if it's really hot. Then it probably would be evaporation (Ari: yeah). If it's not really hot then it's just sliding and probably drying on the asphalt.
>
> 2a) The puddle evaporates or slides and dries.

2b) Evaporation involves heat.

2c) If the puddle evaporated, the asphalt should be hot.

2d) If the asphalt is not hot, the puddle might have slid and dried on the asphalt.

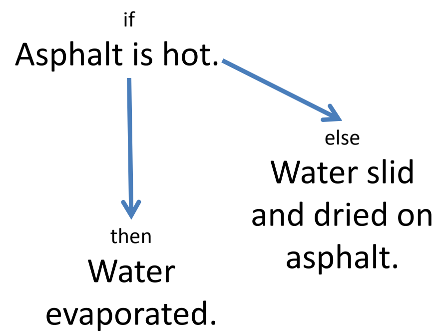
2e) He can check the hotness of the asphalt by touching it.

2f) The check must be done when the experiment is over.

Certainly, John may be drawing on information in this moment not explicitly represented in his language. However, as a starting point in analyzing data, I parse students' utterances into potential units of meaning, and those units might focus on the physical or social world. Like Sherin et al. (2012), I am drawn to the information that students express about the physical world. However, the list of information 2a-2f might suggest that for John, the experiment is primarily about physical sense-making, when actually, social and other dynamics might be more important or prominent to John in this moment. To deal with such ambiguity, I consider scale. In looking at the experiment as a whole, clearly, social and school norms play an important role for John. He conducts an experiment in accordance with procedures and rules he has learned at school, and he has also built up an interactional history with each of the students in his group. However, in looking at utterance [2.2] specifically, these dynamics seem to run in the background, even for John, as he works to articulate a prediction based on his everyday sensibilities about how the world works. In other utterances, for example [1.6] ("She just said to put down what you think will happen") social dynamics seem to be important locally.

In analyzing the Puddle Experiment clips, I also tried mapping the units of meaning and relationships in the form of diagrams, akin to the work that Sandoval (2003) and Ranney and Thagard (1988) did in their analyses of students' explanations. For example, in trying to map John's statement in [2.1], I interpreted it as an if/then/else statement (see Figure 5).

Figure 8: Diagram of John's Utterance in [2.1]



The benefit of these diagrams, as opposed to lists of information, is that they start to show potential relationships that John tries to make between that information. For example, John's use of if/then language suggests a branching structure as indicated in Fig. 8.

But the lists and diagrams above, while clearly representative of how I make sense of John's statement, may not necessarily represent the units and relationships that John sees as important. Thus, in trying to think more from John's perspective, I also try parsing his language according to natural breaks for him, as indicated by pauses in his speech. Pauses can be indicative of distinctions between ideas, for example:

[2.2] After our experiment is over we'll be able to tell if it's evaporation [*gestures towards puddle*]

[*pause*]

by touching it [*the asphalt*] and seeing if it's really hot. Then it probably would be evaporation

[*pause*] (Ari: yeah).

If it's not really hot then it's just sliding and probably drying on the asphalt.

The first pause in John's statement, lasting just over a tenth of a second, occurs after the first instance of evaporation. The purpose of the pause might be to think about what he is going to say next, to take a breath, or to signify the beginning of a new thought. The second pause occurs after the second instance of evaporation, while Ari is looking down at the puddle. Ari uses the pause as a moment to give feedback and express his agreement with John ("yeah"). Ari's agreement appears to encourage John to continue talking, and thus he introduces the second half of his hypothesis about sliding and drying. In essence then, the bit about sliding and drying might be an add-on to John's initial idea, rather than part of a formal if-then-else relationship. In addition, John utters the words "seeing if it's really hot. Then" without any pauses at all. In the structure of John's speech, 1c and 1e are uttered as though they are one thought, rather than distinct ideas.

There are other reasons, besides attention to the pacing of John's language, to question the way I have delineated the units of information in the list and diagram above. For example, John identifies "evaporation" as one thing that could be happening to the water. But the second option "sliding and probably drying on the asphalt" is more confusing. Does the puddle slide, and then dry? Or is the sliding part of the drying processes, to John? To answer these questions, I looked at Leah and Ari's utterances that came just before John's [2.1]:

> 2.0 Ari: One thing I'm wondering is, is it, is it actually evaporation or is the water just kind of sliding, eh the water over there—
>
> Leah?: I think it's both. (Ari: yeah) It's sliding so there's less water and um (Ari: yeah, so there's) and it's easier for it, it's faster. Yeah.
>
> Ari: Yeah. I think that's the depth now. How deep it is. Even if nothing's, if most um, two cups, it might if one is three inches deep and one is one inch deep. The one inch cup might evaporate faster.
>
> 2.1 John: After our experiment is over we'll be able to tell if it's evaporation by touching it [*the asphalt*] and seeing if it's really hot. Then it probably would be evaporation (Ari: yeah). If it's not really hot then it's just sliding and probably drying on the asphalt.

Both the terms evaporation and sliding were introduced by Ari in [2.0], and the term sliding was echoed by Leah [2.0]. Thus, in terms of coherence, John may be seeking to mirror the terminology introduced by Ari and Leah. Sliding, as a unit of information for John, may represent both a possible outcome for the puddle, but also represents information about the students' conversation. That is, the item 1d in my list might be revised to say something like "If the asphalt is not hot, the puddle might have slid like Ari/Leah said, and dried on the asphalt."

But the bit about "drying on the asphalt" is unique to John. Perhaps John agrees that the puddle slides, but also thinks that sliding alone does not account for the water's disappearance, i.e. the puddle must slide *and* dry. Or, he might see sliding and drying as part of a single process. He subsequently refers the puddles as drying during the rest of the experiment, and does not mention sliding again, suggesting that the term "sliding" did not hold much conceptual value for John. Rather, he may have used that term primarily as a tool for conversational coherence (to link his ideas to what has come before in the conversation), and also possibly to acknowledge Ari's contributions. Like John's comment in [2.1], Ari's explanation in [2.10] is relatively articulate:

> I think it also. (Molly: [*joining group*] that one's [*6 oz puddle*] a lot cooler than the ground) You know what I think it is. I think the water kind of acted like a cover for the asphalt for a few moments. So it, so that it, so this started to heat up, so it was like putting a cover over this so this doesn't heat up as fast as this. And then taking the cover off.

While John's statement in [2.1] helped define what counts as anomalous data, Ari's comment in [2.10] is an attempt to account for anomalous data. Again, trying to break Ari's idea into units of information:

> 10a) The water kind of acted like a cover for the asphalt for a few moments.
>
> 10b) The [covered asphalt] doesn't heat up as fast as the [uncovered asphalt].
>
> 10c) [When the water leaves] it is like taking the cover off.

Items 10a)-10c) represent explicit units of conceptual meaning in Ari's statement. However, there are additional pieces of information contained in his utterance that are not represented in 10a)-10c). That is, there is additional meaning both explicitly in the Ari's discourse, and also ideas that we can infer are in his mind.

First, conceptually, there seems to be more meaning in the word "cover" than what Ari explicitly states here. He talks about water acting like a cover, as though water can "block" sunlight, or whatever is heating up the asphalt. Maybe this is as far as Ari's gone with the idea—he has drawn on some intuitive idea of blocking sunlight with objects, without necessarily elaborating for himself the mechanism by which that cover works. Or Ari could be imagining a specific kind of cover, like an umbrella or a sheet, and comparing the water to that. From my perspective, that water is transparent seems to be a confounding factor that Ari needs to account for in his story; however, there is no evidence that transparency is a relevant part of the story for Ari.

There are a few linguistic and conversational markers that indicate Ari may be connecting more than just conceptual information in his statement. He uses a series of preliminaries to make space for the introduction of his idea: “I think it also”, “You know what I think it is”, “I think…” According to Schegloff (1980), preliminaries, or “self-referential feature[s] of the utterance” can serve many different purposes in speech, including to summon audience attention, to establish a point before moving forward, to mark something as a delicate topic, or to request permission to speak (p. 104). Rather than requesting permission to speak, Ari appears to use a series of preliminaries to draw attention to or gain space for his idea. The timing of his preliminaries supports this observation. In line [2.9], Leah starts to share an idea, but trails off with the word “also.” Ari, perhaps mirroring her language, uses his first preliminary “I think it also.” The preliminary suggests that he not only recognizes that his idea is different than Leah’s, but also that he needs to use conversational norms to transition to his idea. He uses his second preliminary “You know what I think it is” just after Molly has joined the group and shared her observation about the temperature. Ari also faces the two girls directly, indicating that he wants to share his idea specifically with them. The preliminary serves to unite the two girls into a single audience for Ari’s idea. In terms of information that Ari is connecting, the preliminaries are evidence that he is attending to the flow of the conversation or some sort of conversational norms, Leah’s idea, Molly’s joining the group, and possibly even the gaze or other indicators of whether or not Molly and Leah are listening to him. In other words, Ari's statement in 2.10 suggests that he is connecting not only conceptual information related to anomalous data, but also social and perceptual information as well.

It is easy to get lost in these nuanced considerations of what counts as "information" and lose sight of the purpose: to understand how John, Ari, and the others students are trying to make sense of a strange observation. But what can be gleaned from a careful exploration of lines 2.1 and 2.10 is that if we are really to interpret students' search for coherence in terms of the information they are trying to connect, what counts as information must be flexible, so that it can represent the students' perspective to the fullest extent possible given the available data. In addition, the analysis may need to attend to social, linguistic, cultural, affective, and epistemological information, as these may strongly interact with students connecting of information about the physical world.

In terms of the more specific issue in this analysis—students' response to unexpected findings—all four students address the unexpected observation by confirming the data, accepting it, or developing new explanations for it. Once the students move inside to write down their reflections on the experiment, however, their noticing and treatment of the anomalous data diverge.

5.3.3 Experiment 1b: Evaporating in Double Time

After completing the puddle experiment, the group goes back inside. In a moment of transition, John sets the stage for the next activity:

4.1 John: Okay, everyone. Write down your theories. Okay so, here's what we were at. Three ounces, three ounces equals one and a half, one and a half inches. Six ounces equals three inches [*referring to the height of each amount of water in a graduated cylinder*]. Both of them, both of them go where the wind goes. (Ari: wait d'ya wanna) About thirty-five degrees Celsius (***).

Again, taking on the role of group leader, John instructs everyone to “write down [their] theories.” But, rather than write himself, John begins reading back the list of data they collected during the experiment. Ari interrupts once with a preliminary (“wait d’ya wanna”), and then again:

4.2 Ari: But do you know what I thought was really interesting? Is that you would think that, let's say that three inches evaporated in five minutes. Then wouldn't you think that the six inches would evaporate in ten minutes?
4.3 John: Yeah. (Molly: what, what was it-)
4.4 Ari: But they really evaporated, is not double time in—I don't think.

Ari interrupts John to point out what he believes is a surprising result: that twice the water does not take twice the time to evaporate. Not only does Ari find this result to be surprising, but he expects that everyone else will find it surprising too (“wouldn’t you think that…”) [4.2]. His use of the pronoun “you” and the phrase “wouldn’t you think that” may also indicate his taking a “reaching stance” and conveying to his partners that he is framing the activity as about making sense of the data, and inviting them to join (Lindfors, 1999, p. 106). The stance is not only towards the students, but also towards the topic. For example, lines [4.2] and [4.4] suggest that Ari is holding the experimental results accountable to common sense. He thinks it makes sense that twice the water should take twice as long to evaporate, but almost takes an accusatory tone towards the results that suggest otherwise (“not double time”). Leah briefly responds to Ari’s comment:

4.5 Leah: Uh I think it's because it's ground.
4.6 John: Depends on location, I think.
4.7 Ari: I think how fast it's spread out and how fast it can (move?) out.
4.8 John: Yeah the big one got so spread out so much that it got thin

and evaporated quickly.

Leah and John do respond to Ari [4.5, 4.6] but is not clear how their answers explain the result Ari has pointed out. Leah and Ari may be providing short answers to mollify Ari and get back to "writing theories." They might not find the result particularly surprising, and so they do not engage with it. Or maybe they do find it surprising, but they have reconciled the idea in their minds and do not feel compelled to discuss it further. For whatever reason, this result clearly fails to spark the relatively unified flutter of activity that surrounded the anomalous data while they were conducting the experiment outside.

In [4.7], Ari provides a slightly more detailed explanation, suggesting that maybe evaporation time is related to how quickly the puddles "spread out." John elaborates, providing a sort of mechanistic description of how a big puddle quickly spreads out, gets thin, and so can evaporate relatively quickly [4.8]. John's elaborated explanation is rather clear evidence that at least part of the information he is making sense of in that moment are the conceptual ideas Ari has put on the table. However, John quickly shifts back to reading data after elaborating on Ari's explanation:

4.9 John: Okay, so three minutes for the six ounce to get to steam. Three minutes. You can just look at this [*the paper*] later.
4.10 Leah: Can I see?
4.11 John: Just look at all the stuff on it, and I'm gonna write theories.
4.12 Leah: So it's three minutes for um, the three

John appears to give up on reading the paper, and decides to just "write theories", though precisely what he means by this is not clear. He seems to distinguish between the "stuff" or data written on the paper, and the "theories" that should be written down after the experiment [4.11]. Leah focuses on copying the data from the paper, as indicated in [4.10] and [4.12]. Ari again interrupts, returning to the problem of evaporation times:

4.13 Ari: I think they probably both evaporated in the same time. But the big one was more visible because it was um.
4.14 Leah: I can't read anymore.
4.15 John: Can you read this, Ari?
4.16 Ari: Yeah I can read that.
4.17 Molly: I wanna see.
4.18 Ari: Um, uhhh, I'll read it out loud. Three ounces equals one and a half inches. Six inches. [*writing and speaking to himself*] Three O Z equals

In comparing [4.2] to [4.23], Ari's ideas about the experimental results seem to change. In [4.2], Ari suggests that the puddle with twice the water should have taken twice as long to evaporate. But in [4.23], he says that he thinks the puddles probably evaporated "in the same time." However, these distinct ideas, and almost contradictory senses, might actually be part of the same line of reasoning for Ari. First, clearly Ari does not trust the experimental finding that the larger puddle took only one minute longer to evaporate, as indicated in both [4.2] and [4.23]. Secondly, Ari suggests a sort of causal explanation for why the relationship between amount of water and evaporation time is not linear—the larger puddles spread out more quickly, allowing them to evaporate faster. Then, in [4.23], Ari suggests that maybe the big puddle was "more visible", i.e. when they were collecting data, it was easier to see the big puddle than the small puddle. Because Ari does not finish his thought, we cannot be sure what he was thinking here. However, the students used the water marks on the asphalt as an indicator of evaporation, and perhaps Ari thought the bigger puddle left more visible water marks leading to an overestimate of the time it took that puddle to evaporate.

In fact, there are reasons to question the reliability of the data. The criteria the students use to determine when a puddle "evaporated" varies over the course of the experiment. Whereas the smaller puddle was considered "evaporated" when the water and most of the water marks on the asphalt were gone, the bigger puddle was deemed evaporated with water marks still evident on the asphalt.

However, why Ari specifically states that the puddles probably evaporated at the *same* time (as opposed to just any time other than what they recorded) is not clear. He might have been thinking that spreading cancels out the effect of volume so that both puddles evaporate in the same time. That interpretation is supported by a comment Ari wrote in his science journal that day: "Volume doesn't matter but depth does." Or, he might have been reflecting on the groups' data collection methods when they were outside.

Regardless, throughout this episode, Ari appears to be trying to make sense of the experimental data that the group collected outside. All the while that he tries to make sense of this information, he also attends to the signals and comments from his group mates, most of whom are asking him to focus on writing down theories and copying the data. Leah, on the other hand, seems stably engaged in copying the data [4.10, 4.12, 4.14], and, in the conversation, there is less evidence of her trying to deal with the anomalous data Ari has pointed out. From Leah's perspective, and looking at the information she is trying to connect, her response to Ari makes sense: task is to write down observations and theories, not discuss them. John switches back and forth between these two modes, while Molly is relatively silent and writing.

5.3.4 Experiments 2a and 2b: Does Temperature of the Water Matter?

In the first experiment, the focus group encountered an unexpected result (that the spot where the puddle was is cooler than surrounding areas) and tried to confirm and explain it. While they were inside discussing the experiment, Ari pointed out another unexpected result (that twice as much water does not take twice as long to evaporate), but was only able to draw John in briefly to discuss it. However, in both of these cases, the students' findings did not violate scientifically accepted understandings of evaporation. Cold water would cool the asphalt on contact and evaporating is a cooling process, so the formerly wet asphalt should be cooler than the surrounding area. And, though the students' data collection process is questionable, as Ari describes, a non-linear relationship between amount of water and evaporation time is plausible, given variations in how much the puddles spread out.

But on Day 7 of the module, the focus group makes a jarring experimental observation—that cold water evaporates faster than warm water. If that observation were to be confirmed by scientists, then it would certainly require a change in our current understanding of evaporation and phase change which predicts that warmer substances contain particles with higher kinetic energy, resulting in faster evaporation. In addition, the finding that cold water evaporates faster than warm water would require new explanations for any observable phenomena that suggest warm water evaporates faster than cold.

According to Ari, the point of the experiments on Day 7 was to test if the temperature of the water affects evaporation. The students attempt to heat two beakers, each with "6 ounces" of water, to different temperatures using a microwave. (Previously, the students used ounces to refer to inches of water; however, the measurement process for this experiment was not captured on video, so I am not sure what ounces means here.) The students use the time heated in a microwave as a proxy for temperature:

Puddle A: 15 seconds in the microwave

Puddle B: 0 seconds in the microwave, “room temperature” water

Puddle C: 20 seconds in the microwave

They do not use a thermometer to confirm the different temperatures of the water, and there are numerous interruptions, technical difficulties with the microwave, re-heatings, and arguments during the microwaving process.

Once outside, the students pour the beakers onto the asphalt outside, and time how long it takes them to evaporate (see Fig. 9).

Figure 9: John Labels the Puddles

The students first claim that the hot water evaporates faster than the cold approximately three minutes into the experiment. At this point, Molly is sitting on the down recording data on a piece of paper. John is drawing chalk boxes around the puddles and labeling them. Ari and Leah are walking back and forth between the puddles (see Table 6):

5.1 Ari: Um..B has spread out the most.[*Ari walks around the puddle and Leah.*]

[*8 seconds of silence*]

5.2 Molly: Which one evaporated most? Probably B. B or A?

5.3 Leah: What? I think B is.

5.4 John: This one [*C*] is probably the thickest. It's still spreading out really over there.

5.5 Leah: That's weird cuz that's the 20 second one.
[*John draws a box around the puddle*]

5.6 Leah: Okay, it's been three minutes.

Table 6: Puddle Information for Experiment 2a

	Puddle A	**Puddle B**	**Puddle C**
Temperature	15 seconds in the microwave	0 seconds in the microwave/room temperature	20 seconds in the microwave
Ari's Opinion of Testing Surface	In a dent	No dent	In a dent
Students' Decision on Evaporation Order	Second	First	Third

The students express different relationships between evaporation and "spreading out" in this exchange. Ari seems to think that how much the puddle spread out is important for the experiment. He comments that Puddle B spread out the most in [5.1]. And on previous days, including the volume experiment already discussed, Ari contemplated that thickness or how much a puddle spreads out might affect its evaporation time. For example, he wrote in his journal: "I think the more spread out/less depth the faster it evaporates…Volume doesn't matter but depth does." John does not specifically relate evaporation and thickness in this exchange, but in previous conversations he has also agreed with Ari that thickness might affect evaporation.

Leah, on the other hand, seems to use thickness as an indicator of, or measure of, evaporation. When John points out that Puddle C is the thickest and still spreading out, Leah comments on the observation as "weird" [5.5]. What is weird about that, to her? As she makes the comment in [5.5], she looks down at one of the puddles in front of her (not visible to the camera), and then points and glances over to the 20 second puddle. Perhaps, as indicating by her shifting gaze, she makes some sort of comparison between the puddles. If she sees thickness as a measure of evaporation, for example, then she might find it strange that the warmest puddle is also the thickest, i.e. least evaporated.

Molly, acting as record keeper, has made some judgment about which puddle has evaporated first ("Probably B. B or A?"). However, her judgment could be grounded in observations of the puddles' shape or thickness, the water marks on the asphalt, or other students' comments; there is no evidence that the relationship between evaporation and thickness is meaningful for her in this moment.

As the experiment continues, and John and Leah begin to settle on the idea that the hot water is evaporating the slowest, Ari raises concerns about the testing conditions:

5.7 Ari: I think we found um a problem with the experiment. Is B and kind of it's a flat ground. C and A are both on a dent in the ground.

According to Ari, the testing surface is not level. Rather than make a generalized appeal for fair experimental conditions, Ari focuses on a problem with the experiment that could specifically affect thickness of the puddle. If C and A lie in dents in the ground, then they cannot spread out as far, and presumably cannot evaporate as quickly. Leah, Molly, and John do not take up Ari on his comment about the testing conditions. After a brief pause, Leah continues with her observations about the puddles:

> 5.8 Leah: Oh, is there water vapor on all of them. Like I only see water vapor on that one.
> 5.9 Molly: That one, B still has some water vapor at 5 minutes?
> 5.10 Leah: Yeah. No, um, 6 minutes.
> 5.11 John: No it has a little.
> 5.12 Leah: C has a little.
> 5.13 John: I don't see any on B.
> 5.14 Leah: They all are drying up quickly.
> 5.15 John: That one's [*C*] probably gonna go last.
> 5.16 Leah: Six and a half minutes.

By water vapor, the students seem to mean the water stain left on the asphalt after the water disappears from the puddle. Leah, Molly, and John check each other's observations for consistency, to determine which puddles have "water vapor" left and at what time periods. John makes a prediction that Puddle C, the warmest one, will evaporate last.

As the experiment continues, Ari and his ideas become even more isolated from the sense-making of the rest of the group:

> 5.17 John: Here, here's what I think. First-second-third. [*B*-*A*-*C*]. First-second-third. This one's [*B*] less thick.
> 5.18 Ari: No that's the thickest [*A*].
> 5.19 John: First-what do you think? Leah, what do you think? I think it's going first, second, third.

John predicts that Puddle C will evaporate last. He also invokes a linguistic structure for making these predictions (first-second-third) that the group continues to throughout the rest of the experiment. Ari responds "no" to John, indicating disagreement, and claims that Puddle A is the thickest. Rather than elaborate on the details of their disagreement, John brings in a third party, Leah, to settle the debate.

Leah and John finally settle on an agreed order, B-A-C, while Ari continues to worry about the dent in Puddle A.

5.20 Leah: I think first [*A*]--
5.21 Ari: I think first, second, third [*C*,*B*,*A*].
5.22 John: I think that's going first.
5.23 Ari: It looks like there's a dent there [*A*].
5.24 John: (***) they all do.
5.25 Ari: That one's [*A*] the deepest.
5.26 Leah: Seven and a half minutes. Well, no I think that one's going first, so it's B, A, C.
5.27 Ari: I don't-that one [*A*] definitely is deeper than all of the other ones cuz it's in a dent.
4.28 Molly: It's gonna go B, A, C.
4.29 John: Yeah.

The exchange in [5.20-5.29] demonstrates the continuing marginalization of Ari and his ideas. Leah begins by offering a prediction, again in the form first introduced by John in [5.17]. She also places emphasis on which puddle she “think[s]” will be “first.” Ari uses the same language structure in [5.21] (“I think first…”) to show his disagreement with Leah’s prediction. John then chimes in and confirms that he also thinks A will be the first to evaporate. Perhaps realizing that his group mates are moving towards consensus, and his opportunities for voicing his concern are growing more limited, Ari again refers to a dent under puddle A [5.23]. This time, John does respond to the dent comment [5.24]. He says that “they all” have dents, but he does not continue to make the case that the testing conditions are therefore fair. Rather, he seems to be trying to discount Ari’s concern about the dent. Again, Ari tries to point out that puddle A is the deepest, i.e. that it is in a dent. Thus, puddle A is thicker than the other puddles, extending its evaporation time.

Leah, playing time keeper as she usually does during these puddle experiments, announces that at seven and a half minutes into the experiment, she now thinks that puddle B is evaporating first. However, her change in ideas is not in response to Ari's comment, but rather, her observations of the puddles. Molly and John agree, whereas Ari still tries to voice his dissent and draw attention to the depth/dent of puddle A.

Though Ari adapts the linguistic structures of the group in order to voice his ideas, he fails to get the group to take the dent/depth issue seriously. In other words, his linguistic and conversational coherence seeking does not lead to alignment among the conceptual information the group tries to connect. The dent remains an important bit of information for Ari, but John specifically sets the issue aside as irrelevant in [5.24]. Ari continues to worry about the testing conditions, perhaps sparked by his distrust of the experimental result that cold water would evaporate faster than hot water. Leah and John do not seem to worry about testing conditions at all; rather, their focus is on determining the order of the puddles' evaporation, while apparently suspending their intuitive sense of what a reasonable order might be.

At the completion of the experiment, John reports to Ms. H that they found that cold water evaporates faster than warm water. After talking with Ms. H, the students choose to repeat the experiment to test different "cold" temperatures. Expanding the temperature range could serve as a confirmation of the results of the first experiment. Or, it might allow students to refine the apparent inverse relationship between temperature and evaporation rate. But part of the reason John suggests testing colder temperatures appears to be driven by his need to satisfy Ms. H's requirements.

[*Ms. H stands up on a ramp with the students below her*.]
6.1 John: Ms. H, the hottest one evaporated last.

6.2 Ms. H: Hottest water evaporated last...
6.3 Molly: Yeah the room temperature one evaporated first.
6.4 Ari: I think- -
6.5 Ms. H: So what's going on with that?
6.6 John: Uhh, the cooler it is the more heat it's exposed to [*sotto voce*].
6.7 Ms. H: So you think it'll absorb more heat just because it's cold?
6.8 John: Yeah.
6.9 Ms. H: I don't know. I'm *asking*.
6.10 Ari: But I also think-
6.11 John: [*smiling*] Right now that's what I think.
6.12 Ari: But I also think--
6.13 Ms. H: So how can you figure out if that's it?
6.14 Ari: I also think it (***) because that one--
6.15 John: We could test colder temperatures instead of hotter ones.
6.16 Ms. H: True, cuz now you're already saying it's not the hot one.
[*4 seconds of silence*]
6.17 John: *[turning toward group*] Okay, so now that we've figured out the hottest will evaporate last, the coldest will evaporate first we could try different temperatures that are colder than the three we did.

When Ms. H asks John to explain why colder water evaporates faster, he suggests that cooler water is somehow exposed to more heat, as if it reacts more because it is cold. But when pressed, John expresses a lack of commitment to that idea [6.11].

Again adopting the role of group leader, John suggests that the group test colder temperatures [6.17]. The students conduct a second experiment with one puddle consisting of six ounces of room temperature water and another puddle with 4 ounces of room temperature water and two ounces of ice. But, the students allow the cup with ice to melt before conducting the experiment, perhaps explaining their finding that, again, the coldest water evaporates first:

7.1 Molly: Coldest evaporates first. The warmer it is, the slower than the cold.
7.2 Leah: That's weird.
7.3 Molly: Yeah that is weird.
7.4 Leah: Ooh! It's kinda like when you go in a pool and a jacuzzi.
7.5 Leah: You go in the pool and then you go-you go in the pool then it's cold then you in the jacuzzi and it's hot.

7.6 Leah: And it's even hotter than usual. So it's kinda like when-you know what I mean?
7.7 Molly: [*shakes her head no*]
7.8 Ari: Yeah

This time, Leah does comment on the strange experimental finding intellectually, socially, and emotionally, as discussed in the Jacuzzi analogy episode from Chapter 4.

5.3.5 "Meaningful Relationships" in Students' Search for Coherence

I suggest as a working definition for coherence, students' trying to form meaningful, mutually consistent relationships between information. In the context of the first experiment, I explored in more detail some analytical approaches and challenges determining the information that students are connecting. And, parallel challenges exist for understanding the kinds of relationships students build between information.

In Chapter 4, I identified some of the relationships that have disciplinary meaning in science, including causal, analogical, and systemic. As a starting point, these kinds of relationships can guide our exploration of students' coherence seeking. Sandoval's (2003) work explored the causal connections that students build between information to explain the decline in population of particular Finch species in the Galapagos in 1977. Much of the work on explanatory coherence considers how students align theory and evidence, with sometimes elaborate diagrams to indicate the relationships between these bits of information (see for example Ranney & Thagard, 1988).

However, that the pursuit of particular relationships between information is meaningful in a disciplinary sense does necessarily translate to meaning (or, at least, the same meaning) for students, and vice versa (Hutchison, 2008). Thus, considering the pursuit of meaningful relationships from the students' perspective is not as straightforward as looking for the kinds of relationships we as educators would like them to make in that moment.

During Experiments 2a and 2b, for example, Leah and John continuously work to reach a consensus on the order in which the puddles evaporate, i.e. the meaningful relationship they seek is alignment between observations. There are many reasons why this relationship might be meaningful for them. The students might expect that an experiment should have a clear result. Or, Leah and John might have some social reason for trying to reach a consensus together, i.e. if they are developing a friendship. Through conversational techniques such as directing comments to each other, and talking past Ari, Leah and John succeed in completing the experiment and collecting data without too much interference from Ari. Thus they develop relationships not only between their observational data, but also among themselves to the exclusion of Ari.

But within science, consensus is not usually valued as an end in and of itself, especially when that consensus seems to contradict commonsense ideas without explanation. And existing coding schemes for coherence do not include *consensus* as a kind of relationship between information, perhaps because it is not considered an important kind of coherence to seek in science. (Though, it is important to note that sociocultural accounts of science recognize pursuing consensus in its own right as characteristic of the discipline). However, in conceptualizing coherence seeking as perspective-dependent, rather than objective and defined by the discipline of science, we cannot ignore that social consensus plays a prominent role in Leah's and John's work.

Reaching a consensus seems less important to Ari, in some ways making him seem more in line with objectivist or post-positivist accounts of science. He interrupts John and Leah's attempts to reach consensus in order to introduce his own concerns about the testing condition and the reliability of their experimental results. Ari's concern for the reliability of the observations may rest at least in part on the causal relationship he sees between thickness/spreading and evaporation over the course of the experiments. He does not pursue fair testing conditions as a goal in and of itself; rather, he sees a mechanism by which the unfair conditions could affect the experimental result. However, there may be other social and affective factors guiding his concern for the testing conditions. If he feels that Leah and John are ignoring him, he might continue to press on the point about the dent for social recognition.

My evidence that consensus and fair testing conditions are particularly meaningful for these students consists of both how often the students refer to these ideas, and the forcefulness by which they do so. In other words, they are somewhat persistent in seeking these particular coherences, as compared to others that they could possibly purse in the moment. Molly does not really provide clear evidence of if and how the consensus and fair testing relationships are meaningful to her; however, the lack of evidence does not imply a lack of meaning. One of the aspects of the framework that could be further developed in the future is articulating exactly what role meaning plays in students' coherence seeking, how to conceptualize meaning from the students' perspective (especially in a dynamic way), and what counts as empirical evidence of meaning for students.

5.4 Discussion

5.4.1 Contextualizing Students' Treatment of Anomalous Data Within Their Broader Coherence Seeking

Approaching students' treatment of anomalous data with the assumption that the students are always seeking coherence with respect to something proves to be very useful in making sense of Leah, John, Molly, and Ari's discourse in the puddle experiments. Consistent with Chinn and Brewer's findings, the students respond to anomalous data in a variety of ways. In the first experiment, when the students find that the asphalt under the puddle is cool, they try to explain the result. Inside, when Ari notices that the relationship between volume of water and evaporation time is not linear, he again tries to explain it; Leah either does not recognize the finding as anomalous, or ignores it. In Experiment 2a, when the students find that cold water evaporates faster than hot water, Ari suggests that the testing conditions are problematic. John, Leah, and Molly accept the anomalous finding as truth, without explaining it. Following the second water temperature experiment 2b, Leah comments on the strange result and tries to explain it.

While some of these responses appear to be a failure to seek coherence, in my analysis I have also demonstrated that even when students seem to ignore anomalous data, they are doing so in service of other kinds of coherences. In other words, different ways of treating anomalous data are equivalent to seeking coherence between different sets of information.

That finding raises important questions about how we characterize and evaluate students' responses to anomalous data in science class. First, students' attempts to reconcile dissonant information might lead them even farther from the canonically accepted answer, as was clearly the case in the hot/cold water experiments. I argue, drawing on similar findings from other studies, that this might be a feature, rather than a design flaw, of science curricula. Many studies have attempted to show that students' development of non-canonical explanations for phenomena can be a valuable part of their learning to do science. Likewise, I have shown that, despite (or perhaps because of) issues in their experimental design, many aspects of the focus group's attempt to explain the anomalous data in their experiments in fact aligns with characterizations of expert science.

Secondly, and not surprisingly, students respond to anomalous data in ways that are highly context-dependent; information about the task at hand, peer relationships, etc. intersect with students' work to make sense of observational data. One of the ways Leah and John dealt with anomalous data, for example, was to defer to rules of school science. Ari often appeared to deviate from the rules of school science and his peers' wishes in order to reconcile anomalous data with his intuitions about the physical world. Neither of these responses is inherently "good" or "bad", but certainly they imply different criteria for coherence which we would ultimately like students to be able to evaluate and negotiate as they make sense of physical phenomena.

5.4.2 Pinning Down "Information" and "Meaningful Relationships" in the Working Definition

In trying to make information "hang together" in science class, students pursue consistency between information and meaningful relationships between information. Vosniadou and Brewer (1992), Driver, Guesne, and Tiberghien (1985), and others have demonstrated consistency depends on perspective, i.e. what students see as consistent may look inconsistent to educators, and vice versa. Likewise, I argue through analysis of data that the "information" and "meaningful relationship" aspects of coherence may also differ in the students' and educators' perspectives. A growing body of research has suggested that affect, identity, and social dynamics, for example, are inextricably intertwined with students' conceptual sense-making (Engle & Conant, 2002; Girod & Wong, 2002). Though construction of a complete analytical framework for these entanglements is well beyond the scope of this work, these analyses warrant additional exploration of how students' sense-making of the physical world intersects with their sense-making of the social word.

5.4.3 Comments on Normative Claims about Students' Coherence Seeking

Finally, analysis of the focus groups' responses to anomalous data in the context of experiment suggest that, even when students are ignoring some information, they are doing so in service of seeking coherence with respect to other information. However, students' coherence seeking differs in terms of the information they are trying to connect, how they are trying to connect it, and possibly, as will be discussed in the next chapter, why they are trying to connect it.

The perspective on coherence I have described and illustrated thus far theoretically distinguishes between what counts as *evidence of coherence seeking* in the science classroom, from our ideas about what counts as "good", "productive", or “sophisticated” coherence seeking in science class. But it is tempting to make whole-scale generalizations about certain kinds of responses to anomalous data being more sophisticated than others. Something about Ari’s work in the puddle experiments just seems more productive for coming to understand evaporation than what Leah and John do. We might base these judgments of sophistication by comparing the students’ work to that of practicing scientists; however, Chinn & Brewer (1993) make a compelling case that in their work to build accounts of natural phenomena, scientists respond to anomalous data in many ways, including reject or ignore it. And yet, while rejecting contradictory data might prove productive in particular contexts and grain sizes, certainly we do not want students to complete their education with “untrammeled authority to construct any response to a problem in a discipline and declare it resolved” (Engle & Conant, 2002, p. 409).

We might look at the effects of students’ coherence seeking within the bigger picture of trying to understand what happens to puddle water. However, even with that approach, complications arise because we must consider how social and other ways of seeking coherence might support or limit students’ connecting of conceptual ideas. For example, seeking consensus for social reasons might be detrimental to students’ physical sense-making in the short term, but once students develop strong social ties, they might be more willing to challenge each other’s ideas later.

I do not mean to hopelessly complicate matters by suggesting that assessing students’ coherence seeking involves a seemingly infinite number of entangled dimensions. Rather, I use the puddle experiment data to reinforce Engle and Conant’s suggestion that dynamic, nested judgments of students’ collaborative work might better align with our conceptions of productive disciplinary engagement than the predominantly static, locally-based judgments of individual students' work currently employed in education research and practice.

Chapter 6: Intent and Coherence Seeking—Examples from a 4th Grade Class Arguing About the Contents of a Battery

"…there is a secret tie or union among particular ideas, which causes the mind to conjoin them more frequently together, and makes the one, upon its appearance, introduce the other…" *-Hume*

6.1 Introduction

An account of students' coherence seeking—their *trying to build meaningful, mutually consistent relationships between information*—must in some way address the issue of intent. That is, are students really "trying" to make connections, or are the connections the result of coincidence, chance, or unconscious cognitive processes?

There are pedagogically important reasons for drawing a distinction between purposefully seeking coherence and accidentally supporting or happening upon coherence. While accidental or coincidentally discovery has played an important role in the progress of science, as educators, we would like our students' work to be more than just pure happenstance. Among the many goals of science education and education more broadly, we would like students to develop a meta-cognitive awareness about their thinking, wherein they intentionally checking for certain kinds of consistencies, or work to develop certain kinds of explanations. We would further like students to search for particular coherences because they see it as valuable and useful in their work to understand natural phenomena, and not just because the lesson sets them up to do so. In other words, not just for descriptive purposes, but also for evaluative ones, educators need to have a grasp on what information students are trying to connect, and why they are trying to make those connections.

A theme recurring throughout this dissertation is the importance of distinguishing *what we value or would like to see*, from *what is*, with respect to coherence seeking in science class. Students often rely on superficial aspects of a problem that educators find irrelevant, and they ignore information that educators find important, but in both cases students are still connecting some set of information together. Continuing along that line of thinking, in this chapter I explore if and how questions of intent are relevant for building an account of students' coherence seeking in science class. Specifically, I consider:

- Is evidence of intent required to claim that students are seeking coherence?
- Do conceptions of "authentic scientific practice" require that students seek coherence for particular reasons?
- Does my interpretation of students' intent affect my understanding of what information students are trying to connect, and in what ways they try to connect it?

Drawing on episodes of student thinking from elementary, post-secondary, and teacher professional development science classrooms, I argue that intent certainly matters for thinking about coherence seeking, but not for reasons often identified in the literature. To be internally consistent, the perspective on coherence seeking set forth in this dissertation seeking cannot require that students work to connect information on purpose, or even for particular reasons, in order for their work to count as evidence of coherence seeking. Furthermore, definitions of "sophisticated", "authentic", or "disciplinary" coherence seeking cannot rely on intent or purpose alone, for educators' interpretations of *why* students are seeking coherence are intertwined with interpretations of *what information* they are trying to connect.

In the following sections, I explore each of these claims in more detail, beginning with an account of why the word "trying" appears in the definition of coherence seeking in the first place. Then, I present a series of examples to show how intent matters for thinking about what information students are trying to connect. Finally, I conclude with a theoretical case for re-framing the debate around "pseudo" and "authentic" disciplinary engagement away from intent and purpose, and towards more careful consideration of what information students are trying to connect.

6.2 The Importance of "Trying" in the Working Definition of Coherence Seeking

Research on student thinking in science has expanded from merely categorizing students' ideas along dimensions of correctness to considering more fully the substance of those ideas, as well as the dynamic processes by which students construct them (see for example Cavicchi, 1997; Engle & Conant, 2002; Hammer, 1997; Smith, Maclin, Houghton & Hennessey, 2000; Varelas, Pappas, & Rife, 2006). However, work that focuses specifically on coherence continues to take a more static approach, using coherence as a way to characterize the state of students' knowledge and explanations, rather than an aspect of their dynamic reasoning.

Hammer et al. (2008) characterize scientific inquiry as "the pursuit of coherent, mechanistic accounts of natural phenomena" (p. 150). In characterizing inquiry as a pursuit, Hammer et al. re-frame the work of the teacher from about getting students to particular answers, to about facilitating students to refine their everyday intuitions about natural phenomena—i.e. allowing students to do science. Likewise, attaching the word "seeking" to coherence, I hope to emphasize the moment-to-moment work that students do to try to connect ideas and information together, even if in the end those connections do not pan out, from the students or educators' perspective.

Emphasizing coherence seeking as an activity complements current work aiming to characterize "the nature and quality of students' participation in exploration, invention, and discourse" (Hammer, 1997, p. 488). Furthermore, "shifts in attention from finished products to discovery processes" within education mirror a similar shift within philosophy of science:

> Within traditional philosophy of science, the role of inconsistencies has largely been ignored. As best, inconsistencies were seen as a hindrance for good scientific reasoning…Today, it is generally recognized that almost all scientific theories at some point in their developments were either internally inconsistent or incompatible with other accepted findings (empirical or theoretical)… Whereas finished theories usually seem to satisfy the consistency requirement, developing theories do not. (Meheus, 2002, vii)

Though perhaps not an apt way to describe science in general, the process/product distinction suggests at least two goals for science education: i) that students' develop coherent understandings or explanations, and ii) that students refine their abilities to attend to, seek, and value different kinds of coherence. While the first goal has been the focus of many studies, the second has received far less attention. Thus, initially, I chose to think in terms of coherence seeking, and not coherence, in order to capture the dynamic nature of students' reasoning. What I did not anticipate was the linguistic and theoretical baggage that comes with the use of the word "trying" in my working definition. Thus, in the context of refining the perspective on coherence seeking, one of the important tasks was to clarify what exactly "trying" means, and how that relates to evidence of coherence seeking.

6.3 Evidence of Coherence Seeking Does Not Necessitate Evidence of Intent

In an everyday sense, the word trying denotes a conscious or purposeful attempt to act. In other words, if someone "tries" to do something, they are thought to be intentional, conscious, or purposeful in that trying.[22] Thus, coherence seeking, defined in Chapter 3 as *trying to form meaningful, mutually consistent relationships between information*, seems to necessitate intent. Certainly, there are moments when people are clearly intentionally working to fit ideas together, for example, when we make predictions about how a movie will end, when make guesses about the criminal's identity while reading a mystery novel, or when we suggest a compromise for disagreeing peers.

However, in laying out evidence for coherence seeking in Chapter 4, I referred to theories of psychology and perceptual processing which suggest that individuals "try" to connect information together subconsciously, outside of their awareness. We see evidence of this subconscious processing for example in conversation, when people mirror each other's tone, gesture, and body positioning without even recognizing that they are doing so. Subconscious coherence seeking can manifest in more insidious ways as well, for example, in the form of stereotype induction:

> In one study, Leichtman & Ceci (1995) provided animated descriptions of their "clumsy" friend Sam Stone to preschool children. On a number of occasions, these children were told of Sam's exploits, which included accidently breaking Barbie dolls or ripping sweaters. Later, the children met Sam Stone, who came to their classroom for a short, accident-free visit. The

[22] Notably, in everyday conversation, we also sometimes distinguish trying from intentionality. For example, in saying someone "intentionally tried" to hurt another, we imply that the intention and the trying are separate but related aspects of a person's behavior.

> next day, the teacher showed the children a torn book and a soiled teddy bear. Several weeks later, a number of three- and four-year-old children reported that Sam Stone had been responsible, with some even claiming that they had seen him do this. (Bruck & Ceci,1999, p. 428).

One might argue that these "unconscious" processes while important more generally, are too generic or broad to be useful evidence of students' reasoning in science. The criticism is warranted. Characterizing every gaze, change in body position, facial expression, or utterance of speech as an act of coherence seeking is unwieldy analytically, and even if feasible or interesting from a researcher's standpoint, certainly will not be of much use to an educator trying to make decisions about where to go next with her students. Even in the analyses presented in this dissertation, I have chosen to highlight certain kinds of evidence of coherence seeking in each clip; rarely do I specifically point out that students' object recognition can be conceptualized as a form of coherence-seeking.

However, in some episodes, unconscious attempts to connect information were clearly pivotal for students' sense-making about natural phenomena. For example, in Chapter 5, John predicted that after a puddle evaporates from the asphalt, the asphalt will feel cool. That prediction was based on a variety of experiences: objects can "feel" hot or cold, evaporation involves heat, when something touches a hotter object the cooler object warms, etc. How exactly these different experiences are stored and called upon are not yet understood, but clearly John's making of such a prediction indicates that he has coordinated these kinds of experiences, and much of that coordination likely occurred outside of his direct awareness in the past and in the moment. Likewise, when Leah and the other students touch the asphalt, they coordinate a variety of sensory information to conclude that the asphalt feels warm.

Leah did not need to *try* to feel if the asphalt was warm; she just sensed it. Thus, while not always salient, “unconscious” coherence seeking—moments without clear evidence of intent to connect information—can indeed play an important role in educators’ understanding of students’ sense-making.

Furthermore, attempts to restrict coherence seeking to intentional work would require an understanding of the human consciousness that as yet we do not possess:

> Although consciousness is the only way we know about the world within and around us—shades of the famous Cartesian deduction cogito, ergo sum—there is no agreement about what it is, how it relates to highly organized matter or what its role in life is. (Koch, 2009, n.p.)

Requiring evidence of intent to call students’ work coherence seeking means developing analytical tools to distinguish what students do intentionally and with awareness from what they do accidentally, coincidentally, unknowingly, etc. But clinical studies suggest that the line between conscious and unconscious thought is blurred. Humans often do not even know why we do things; when asked, we post-rationalize our decisions without actually understanding our intent at the time we made those decisions. In one hallmark study, Nisbett and Wilson (1977) asked consumers to select a pair of stockings from a row of four. While consumers generally picked the pair of stockings farthest to the right, when asked to explain their decision-making, consumers came up with a variety of reasons (softness, etc.), none of which included the location. Split-brain studies have also brought into question the degree to which humans understand the reasons for their behavior (Wolman, 2012). Michael Gazzaniga exposed a split-brain patient to two stimuli—the word ‘smile’ to the right hemisphere and the word ‘face’ to the left—and asked the patient to draw what he had seen. The patient drew a smiling face, even though he was unaware that he had seen the word smile due to the separation of his right and left hemispheres. When asked why he drew a smiling face, the patient responded: “What do you want, a sad face? Who wants a sad face around?” According to Gazzaniga:

> The left hemisphere made up a post hoc answer that fit the situation…The left-brain interpreter…is what everyone uses to seek explanations for events, triage the barrage of incoming information and construct narratives that help to make sense of the world. (Wolman, 2012, p. 262)

Given i) our limited understanding of human consciousness, and ii) evidence that humans often operate outside of, or despite their articulated intent, I think it premature, and possibly unnecessary from an analytical standpoint, to demarcate what counts as evidence of coherence seeking from what does not solely on the basis of conscious awareness or intent. Thus, while perhaps linguistically awkward, I maintain that individuals do seek coherence both consciously and unconsciously, and I maintain the use of the phrase “unconscious coherence seeking” throughout the dissertation.

So, why talk about intent at all? At the start of this chapter, I suggested that intent does matter for coherence seeking, just not in the ways that the field of science education has previously identified. But none of the work on coherence reviewed in Chapter 2 tries to make a strong case about students’ intent. Sandoval (2003) talks about students’ epistemic criteria for coherence, but does not state whether these epistemic criteria operate on the level of students’ awareness. Vosniadou and Brewer (1992) suggest that the consistency of students’ answers reflects the consistency of knowledge structures in their minds, in some sense taking intent out of the question altogether. And Thagard, Ranney, and Schank approach coherence as a criterion for theory selection, but their claims do not require that scientists *consciously* select theories because of their increased alignment with data. As far as Thagard and Nowak's (1988) study is concerned, scientists might 'prefer' certain coherences in the same way that Nisbett and Wilson's consumers 'prefer' the stocking to the right.[23]

While science educators have not appeared to have taken a strong position regarding whether evidence conscious intent is required for evidence of coherence seeking specifically, they have suggested that the units of information that students try to connect can be identified without any serious consideration of students' intent or perceived purposes of the activity in which they are engaged.

However, in analyzing classroom data, I found it quite difficult to separate my answer to "what information are students trying to connect, and in what ways?" from the second half of my research question: "to what ends?" In other words, my claims about what information students were trying to connect, and how, was intertwined with my perceptions of students' intent.

6.4 Intent As Intertwined With the "What" of Coherence Seeking

To illustrate how interpretations of students' intent might influence claims about what information students try to connect and how, I draw on an example from an undergraduate University of Maryland introductory physics tutorial. Briefly, in these tutorials, students work together in small groups to complete a series of questions and laboratory activities. The tutorials encourage students to think of physics as a refinement of their everyday intuitions about the physical world. For

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[23] That is not to suggest that scientists never seek particular coherences purposefully; certainly they do. Rather, Thagard and Nowak (1988) showed only that that scientists' eventual selection of the Theory of Plate Tectonics over Contraction Theory can be postdicted on the basis of increased alignment with evidence. The study does not conclusively suggest that the scientists intentionally or consciously preferred Plate Tectonics for those reasons.

example, one part of a tutorial for Newton's Third Law explicitly asks students to reconcile their understanding of Newton's Third Law with their intuition that small objects react more:

> Suppose the truck's mass is 2000 kg while the care's mass is 1000 kg. And suppose the truck slows down by 5 m/s during the collision. Intuitively, how much speed does the car gain during the collision? (Conlin, Gupta, & Hammer, 2010, p. 279)

As written, the tutorial encourages students to draw on particular pieces of information, including: i) the masses of the truck and the car, ii) the ratio of the mass difference between the vehicles, iii) the change in speed of the truck, and iv) their intuition that smaller objects react more (an intuition which the tutorial writers predict students will activate based on other findings from education research). But transcript from one group's conversation about the tutorial question reveals they are bringing all kinds of information to the table, beyond what the tutorial specifies:

1.1 Molly[24]: The car is half as heavy, so it'll gain twice as much.
1.2 Camille: Ah shoot [*laughs*]
1.3 Dianna: Or something, I dunno
1.4 Molly: That's what they want us to think, but this is not the real answer.
1.5 Bridget: This is not the right /one/. Apparently, I think that's what they want us to say.
[*about ten seconds of silence*]
1.6 Dianna: This is going…five…five meters per second, that's it's what? Acceleration or velocity?
1.7 Camille: Speed. ##Velocity##
1.8 Molly: ##velocity##
1.9 Bridget: Slows down by…??
1.10 Dianna: Velocity?
1.11 Camille: Mm hmm. [*pause*] So the car gains ten meters per second?
1.12 Bridget: I guess.
1.13 Dianna: Didn't he say something about how like somebody in class, like—if something's touched a velocity, or something was changed…what was he talking about in class, something, the masses?

[24] *Not* the same Molly from Ms. H's 5th grade class.

(Conlin, Gupta, & Hammer, 2010, p. 279-280)

In [1.1], Molly seems to draw on her sort of common sense expectation that a lighter object will gain proportionally more, in line with the expectations of the tutorial designers. But then in [1.4], Molly shifts the focus of her inquiry from the car/truck question to the intentions of the tutorial writers. She suggests that the tutorial sets up students to say the wrong ("not real") answer. Bridget confirms, "That's what they want us to say" [1.5]. Both of the students appear to be drawing on an experience or idea that "teachers/science/tutorials try to trick us." The source of that idea might be in the history of these students' experiences in school or in tutorials more generally; or it might be triggered by the phrasing of the specific tutorial they are working on. In a published analysis of this clip, for example, Conlin, Gupta, & Hammer (2010) point out that immediately after the previous excerpt, Dianna hears another group use the word "intuitively" (a word also used in the tutorial question), and says to her group, "I hate that word, 'intuitively.'" Dianna does not elaborate, but her comment suggests that the word "intuitively" is at least ambiguous to her, perhaps explaining her uncertainty about the answers the tutorial expects.

Following Bridget and Molly's comment about the intentions of the tutorial writers, Dianna asks whether 5 meters per second denotes the truck's acceleration or velocity [1.6]. Most simply, Dianna may be trying to coordinate the following pieces of information: i) the phrase "five meters per second", ii) the terms "velocity" and "acceleration", iii) some sort of expectation or idea that using the correct term matters. In other words, Dianna may be *trying* to complete the worksheet, and part of doing that successfully requires her to use correct units. However, Dianna may be working with more information than she explicitly states in [1.6]. If I assume that Dianna is doing more than searching for correct terminology, I can start to see other information she might be trying to connect in the service of physical sense-making. As worded, the tutorial question is a bit ambiguous. Meters per second are units of speed or velocity (see Camille and Molly's responses in [1.7] and [1.8]), but the tutorial asks about a change in speed (see Bridgette's comment in [1.9]) which, as Dianna points out, is called acceleration. What the tutorial means to say is that the initial and final speeds of the truck differ by 5 meters per second. However, this point might be confusing for Dianna. Though she does not specifically refer to it in [1.6], Dianna may be also trying to fit together the previously identified information (i-iii) with iv) "the truck slows down by", making her coherence seeking seem more about physical sense-making than just using correct terminology, i.e. *what is this change the truck experiences ("that's it's what?).* Identifying which information Dianna is trying to connect is intimately related to my interpretation of what she is trying to do in this moment.

In [1.11], Camille sort of resolves the problem of what quantity 5 meters per second represents by omitting a label for her answer entirely ("so the car gains ten meters per second?). Bridget still seems uncertain, either about the answer the worksheet wants, or the truck/car problem itself. Finally, Dianna begins "shopping for ideas" from physics class lectures related to velocity, change, and mass (van Zee et al., 2005, p. 1019).

So, what information are Dianna and her classmates *trying* to connect in meaningful, mutually consistent ways? The snippet illustrates a few ways to view “trying” in the context of students’ sense-making. Dianna, for example, is trying to connect information about quantities and their units with the wording of the question; however, she may be trying to make these connections in the service of physical sense-making, to generate an answer for the worksheet, or both. Likewise, Camille is trying to unite Molly’s answer (the car gains twice as much) with the concerns Diana raised about units, and she does this by omitting quantity labels. In this case, she is not trying to ease Diana’s and Bridgette’s uncertainty so much as she is trying to get the group to agree on a sanctioned answer for the worksheet.

Attention to the nestedness or multiple levels of purpose to students’ activity (from their perspective) has become increasingly important in science education, especially in work aiming to reform science education toward more “authentic” scientific practice. In reaction to findings that students can appear to engage in disciplinary practices like argumentation and modeling, but without the genuine purposes of science, the community has undertaken defining authentic scientific practices in a way that necessitates evidence of intent. In other words, students must not only argue in the form that scientists argue, but also for the reasons that scientists argue.

Though coherence seeking cuts across scientific practices, and is not a practice unto itself, it serves as a useful construct for exploring the developing role of intent in scientific practices more generally. Specifically, analyses of students’ coherence seeking reveal that perhaps our concerns about the authenticity or productiveness of students’ sense-making stem not just from our perception of their intent (why they are doing what they are doing), but more fundamentally, from our perception *of what it is that the students are doing.*

6.5 Re-considering "Pseudo-inquiries" in Terms of What Information Students are Trying to Connect

In the push to make school science more like scientific practice, standards documents, education research, and in some instances teaching practice have moved away from presenting science purely has a collection of facts, and towards science as a way of thinking and knowing as exemplified in scientific practices. According to the 2012 Frameworks:

> Science is not just a body of knowledge that reflects current understanding of the world; it is also a set of practices used to establish, extend, and refine that knowledge. (NRC, 2012, p. 27)

But as the frameworks and a host of research studies point out, students are extremely adaptive; they can quickly master the game of a disciplinary practice and implement it as a rote procedure, rather than as a tool for making sense of the physical world. In their study of argumentation in a high school genetics class, for example, Jimenez-Aleixandre, Rodriguez, and Duchl (2000) identify two different patterns of participation—'doing science' and 'doing school.' The students who are doing school focus on completing tasks for the sake of school, or to meet the teachers demands, whereas in moments of doing science, "students are evaluating knowledge clams, discussing with each other, offering justifications for the different hypotheses, and trying to support them with analogies and metaphors" (p. 771). Other researchers have referred to doing school as 'procedural display' (Bloome, Puro, & Theodorou, 1989) or 'pseudoinquiries' (Lindfors, 1999). Lindfors in particular criticizes reciprocal teaching and other modes of instruction that emphasize students' execution of procedures to the detriment of their genuine wondering about a topic. She recounts an anecdote from her experience visiting a third grade social studies class, when the teacher asked the class to come up with questions about Eskimos:

> Over time there came to be a sanctioned set, and the task was to think of a missing member and suggest it. I'd look up at the board and say to myself, "Let's see now. Which ones aren't up there yet? We still don't have 'What are their customs? Or 'What's their religion?'" We gave Mrs. McKenzie the "questions" she was after. There was purpose in our utterances, but it was not inquiry's purpose. We were engaging in a teacher-pleasing exercise. (Lindfors, 1999, p. 52).

In Lindfors' view, authentic engagement in inquiry requires that the participants' intent, purpose, or desire be to truly wonder and find something out about the world.

6.5.1 What 'Doing School' Means in Terms of Seeking Coherence

In analyzing classroom data for evidence of coherence seeking, I shared Lindfors' view. During the first summer of the Learning Progressions project, the participant teachers completed the battery and bulbs module under the teachers participated in a summer workshop, during which they completed the battery and bulbs module. Working in groups of four or five, the teachers found multiple ways to make the bulb light, and also ways that do not work. As a collective, the teachers recognized that all of the ways that work require "two points of connection," i.e. that the wire touch two points on both the bulb and the battery. After the discovery, the facilitator, David, asked the teachers to come up with some sort of analogy to explain why there need to be two points of connection. The idea for the analogy as a next move stems in part from an historical precedent in professional science, namely, that scientists generate analogies in their work to make sense of new and unfamiliar phenomena (Holyoak & Thagard, 1995). In addition, both directed and spontaneously analogies appear to play a pivotal role in students' science learning (May, Hammer, & Roy, 2006). One group of teachers share with David their train analogy to explain the two points of connection, in which the power box represents the battery, the track represents the wire, and the train moving represents the bulb lighting. David probes the analogy:

2.1 David: What in this story makes the train move?

[*2 second pause*]

2.2 Patty: The battery source connect to the...wire.

2.3 David: how --

2.4 Wendy: Something moves from the battery when you turn it on and everything is connected, something is moving from this power source through the tracks to that connection between the wheel and the track.

2.5 David: So that part of your story is still sort of intangible it sounds like.

David points out the analogy does not account for what makes the train move, and suggests that the teachers think about *flow* as a way of refining their analogy:

2.6 David: …[*lines omitted*] And in fact, in fact // So I want to give you, I want to give you a little bit of a nudge of a place to go shopping..Look in your mind around things that you know about that *flow*.

2.7 Wendy: [*pointing to Patty*] Water.

2.8 David: Because you // electricity flows. People always talk about electricity flowing from the battery to the bulb. That kind of thing. Look for things you know about that flow. And think about things that flow that might be a basis for thinking more about what the electricity is like and what it's doing and and what it's doing in the bulb...[*David leaves*]

2.9 Trish: So it goes back to the water wheel or canal or aqueduct.

2.10 Wendy: The paddle wheel on a..boat.

[*4 second pause*]

2.11 Patty: What about a possible connection to what we were talking about yesterday with air flows, right, wind creating the high and the low across the areas. That's also // or the water cycle, the actual water cycle itself // that's still not tangible. That's not tangible.

2.12 Trish: Is there a toy boat, is there a boat, I mean is there something with a boat that we can use, that they've seen.

2.13 Patty: But it doesn't ##depend on (the wind?)##// the water's just the surface that you're putting it on.

2.14 Wendy: ##It // flow. He wants something that flows.##

2.15 Patty: But that water flows. [*9 second pause*]

One of the prominent aspects of Patty, Wendy, and Trish‗s work in this moment is that they appear to be searching for ideas about flow primarily because David has asked them to do so, and not because they see it as essential in refining their account of how circuits work. For example, in [2.11] Patty starts to suggest a connection to air and the water cycle, but retracts it on the basis of it not being tangible. David had explicitly stated in the beginning of the activity that the analogies should be tangible, everyday, and familiar (i.e. not like teleportation). Thus, in [2.10] Patty struggles to coordinate two criteria for the analogy—flow and tangible—both of which originate from David. Trish, in [2.11] suggests a toy boat as an analogy. Toy boats are tangible, involves water (which flows), and have the added benefit of being something with which students are familiar. Patty points out that in order for the boat to move, it needs wind, and that water is just a surface for the boat. Wendy re-iterates the instructions: "he wants something that flows" [2.14].

An experienced science facilitator, David was quite aware of the possibility that the teachers would try to do what he asks, instead of focus on making sense of the circuits. Thus, he repeatedly reminded the teachers:

> The "what am I supposed to do" kind of thing is not thinking about the world. It's thinking about the boss. So, I want to stay thinking about the world…Don't think about what I want. Well what I want is you thinking about the world.

But simply cataloging the teachers' work in lines [2.1-2.10] as an instance of 'doing school' or "thinking about the boss" makes ambiguous precisely what about their work we find troubling. The issue, I think, lies in what information the teachers are really connecting. In outlining the task, David asked the teachers to make analogies that are "tangible" and later, to try to draw on examples of things that "flow." These words hold particular meanings for David, both as physicists and an educator. The word tangible, as David describes it, means:

> …connected to what people know about the world and not other than. Not distant. Not something weird. I mean cognitively tangible. Not necessarily that you can actually touch it with your hands, but that it is // it's not something that you think // it's not like teleportation. It's like kicking.

And the unit of information represented in the word flow, for David, includes the ways that people use the word flow, and flow as a way of thinking about movement [2.8], among other things. But the teachers take up 'flow' and 'tangible,' as units of information, in ways different than what David meant. First, tangible and flow are tied to "what David wants," i.e. criteria for a correct answer. The teachers also associate flow with some of the water system analogies they generated earlier in the morning. And tangible, as Stacey uses it, is intimately tied to something that her students would have access to, like a toy. Thus, setting aside for a moment why the teachers take up flow the way they do in the episode, clearly, the term 'flow' denotes at least two different units of information, one for David and one for the teachers (though, there are likely differences between the teachers, as well). Certainly, as Lemke (1982) notes, these meanings are determined by David and the teachers dynamically in interaction with each other and the classroom space, but importantly, the meanings are not universal. Or, as Jimenez-Aleixandre, Rodgriguez, and Duschl (2000) put it:

> …students and teachers often do not share the same "purpose" for a lesson or activity. Sometimes teachers and students are assigning (constructing) different meanings for the same concept; other times the confusion surrounds

> what counts as evidence, what counts as data, or what counts as explanation. (p. 762)

And sometimes, our failure to consider students' intent can lead to possible misinterpretations of what information they are really trying to connect, particularly when we mistake adeptness at using classroom vocabulary or completing assignments for coherence seeking with respect to ideas about physical phenomena.

6.5.2 What 'Winning' Means in Terms of Seeking Coherence

Sometimes, learners take up a disciplinary practice like generating analogies as a moment to display procedural knowledge or create a teacher-pleasing answer. Another "pseudo-inquiry" drawing the attention of education research involves students' participation in disciplinary practices primarily for social or affective purposes, i.e. "to win." The concern here is that disciplinary practices are primarily tools for knowledge construction in science, but in science class, these practices sometimes become sources of entertainment for students, or tools for negotiating their social status, etc. (Hutchison, 2008). Engle and Conant (2002) found that students may align themselves with a position in order to avoid confrontation, or employ discourse moves to shut down the opponent and "win" the argument. Berland and Hammer (2012) showed how students will marshal evidence in sophisticated ways that both allow students to "win" a debate, but at the same time lead to progress in the accounts of predator-prey models. Notably, these findings challenge the notion that "authentic inquiry is motivated in the sense that the process is driven by an explicit intention to find out" (Kuhn & Pease, 2008, p. 513). On the contrary, students' desire to win a debate, to gain approval from others, or to get an 'A' on an exam might be the very thing that drives their efforts to find out about the natural world.

But my focus here is not to argue whether the desire to win, to hurt or support others, or to gain the teacher's attention ought to be considered a valuable or productive aspect of school. Rather, I aim to show that these perceptions of students' intent again may be tied into what I believe is a more fundamental disagreement in the community about the nature of students' sense-making—that is, what information students are trying to connect and in what ways. To explore in more detail the social and affective dynamics of students' sense-making, I turn to a clip from fourth grade class also working on the batteries and bulbs module—the same module that we saw teachers working on in the last clip.

Ms. F's class, like the teachers, found different ways to make a bulb light, and also generated analogies to explain why certain arrangements work. Ms. F asked each group of students to share their analogies (called "models" in this class), and during the presentations students were encouraged to ask questions and challenge each other. During these presentations, the students begin to unite around the idea that the battery contains two ingredients—positive and negative energy—which interact in some way to make the light bulb light. At one point, a student named Baxter suggests that these two kinds of energy leave the battery and meet in the light bulb, where they "fight" and "kill" each other and make the bulb light. A student named Phoebe challenges Baxter:

3.1 Phoebe: I don't believe that because ##(***)##--
3.2 Shaye: ##So so so but## where does --
3.3 Ms. F: Shaye, let Phoebe say something please.
3.4 Phoebe: Yes, Shaye. Well, I don't think that that's possible because the negative side still has to have energy in it --
3.5 Baxter: ##Yeah## it has a little energy, like ##the negative's##
3.6 Phoebe: ##cuz they## ##but## they have to be different kinds of energy to form a reaction.

3.7 Baxter: Yeah, like the negative side has different liquid that like, kills the positive and the positive kills the negative. ##That's why their separated.##

In what still resembles Lindfors' (1999) description of collaborative inquiry, Phoebe and Baxter debate the plausibility of negative and positive energy killing each other to make the bulb light. Phoebe begins with an appeal to ideas the class has already established—that both kinds of energy are needed for a "reaction." She does not elaborate on this argument, but she might be thinking that if one kind of energy kills the other, then only one energy remains and that is not sufficient for a reaction. But her approach in [3.8] changes, and she stops referring to other ideas that the class has already established:

3.8 Phoebe: [*facing Baxter*] ##Energy trying## to kill each other?
3.9 Baxter: Yeah. [*Phoebe scrunches her eyebrows together*]
[*Many students speaking at once*]
3.10 Delia: Wait but -- (***)
3.11 Student: I think (***)
3.12 Brad: Then why would they have a negative if the positive kills [*moves right hand into his left hand*] the negative? ==
3.13 Baxter: ##They have a##
3.14 Brad: ##And lights it?##
3.15 Baxter: They, because they would have to separate them or when you get a battery it wouldn't like // You know how there's juice in a battery. Well, um, they kill each other [*moves hands together and apart rapidly*] --
3.16 Brad: ##Electric-electricity can go through metal.##
3.17 Baxter: ##Well, when##
3.18 Brad: ##Electricity can go through metal.##
3.19 Phoebe: ##You're talking about energy and electricity trying to kill each other! <Where is that from?!>##
3.20 Baxter: ##Yeah## Yeah, when you try to light something up, the positive [*drops right hand*] and the negative [*drops left hand*] are killing each other [*shakes both hands*] and then light something up [*moves hands apart*] and that's how it loses juice [*drops hands*] because uh ==
3.21 Phoebe: Are you trying to (*** ***)[25] [*slightly smiling and raising*

[25] I transcribed her utterance as "Are you trying to act like a teacher (***) in earlier analyses.

and then raising her eyebrows]
3.22 Baxter: ##No## [*giggles*]
3.22 Student: ##Either, I think the negative wins## or something like that.

Phoebe's three comments in this exchange are a bit more confrontational, and less like the kinds of exchanges Lindfors (1999) describes in collaborative inquiry. In terms of coherence seeking, Phoebe no longer tries to fit Baxter's idea into the class's agreed upon knowledge. In fact, in asking "where is that from?!" Phoebe indicates Baxter's "killing" idea does not fit with *any* of her ideas about energy and electricity.

Of course, the aforementioned interpretation represents Phoebe's treatment of Baxter's idea as grounded in highly logical, rational, and conscious processes. It might be that Phoebe does not *like* the idea of energy killing each other, and so she becomes increasingly unwilling to entertain this idea. And further, Phoebe's response might not even be completely grounded in conceptual the ideas. The exchanges above suggest a volatile relationship between Phoebe and Baxter. For example, Phoebe turns around and makes faces at Baxter when she speaks, and she changes her intonation with each utterance. In interviewing Ms. F about this clip, I asked her to discuss in more detail the relationship between the students in her class (see Appendix F). She commented that Phoebe is a "lawyer in training" and "can hold her own" in a conversation, and that Baxter's ideas are often a target. She also suspected that the relationship between Baxter and Phoebe is contentious. Thus, Phoebe's resistance to Baxter's ideas, and Baxter's persistence in defending them, are likely part of a complex social dynamic. While these two students may in part be trying to make sense of electricity, they are also (perhaps primarily) trying to engage in social negotiations as well.

Ife Phoebe is taking on the role of a lawyer, trying to win a case, what is Baxter doing? Initially, Baxter's reason for bringing up the idea that positive and energy kill each other might be grounded in his work to understand why wires sometimes get hot, and why the batteries do not blow up. Earlier in the conversation, Baxter suggested positive energy is dangerous, and left unchecked, can heat up the wire or explode the battery. Just like subtraction reduces a positive number (which the students learned that morning in math class), he reasoned, the negative energy "minuses" the positive energy, making it less dangerous. The introduction of killing, an embellishment but also an anthromorphism, seems to be a refinement of this "negative reduces positive" idea. From the perspective of coherence seeing, Baxter's idea contains many conceptual elements (positives, negatives, energy, killing/cancelling) that he has combined into an analogy for understanding how circuits work. In other words, part of the answer to "what information Baxter is trying to connect" seems to be resources related to his experience with opposites and cancelling. But as the students, notably Phoebe, strongly disagree with him, Baxter's facial expressions and tone start to indicate a shift in the information he is trying to connect. The "killing" idea morphs from an explanation for how the bulb lights into an idea that must be defended against Phoebe, and also becomes tied into his reading of the social and emotional tone of the class. Erin, who at the time was standing at the front of the class trying to share her group's idea, fights for space to respond to Baxter's killing idea. However, unlike Phoebe, she responds to Baxter in a calm and somewhat understanding tone:

[*37 lines omitted*]

3.59 Baxter: Well, my strategy is sort of confusing but if I could draw it [*looking towards Ms. F*] that'd be easier.

3.60 Erin: I know what you're saying. You're saying like, um, when cuz you're saying that it's too dangerous if there's // if all if the positive goes wherever and then this [*the bump*] lowers it down because it's a minus and plus. I don't think that's true.

3.61 Larry: I kind of disagree with that because, again, if you put the po // if you connect the wires to the positive side and you put it to // if you put it to the same spot on the light bulb, nothing's gonna happen.

3.62 Baxter: Yeah, because like um ==

3.63 Erin: You have to connect both sides to it um if you want it to light cuz it has [*moves hands in a 'U' shape upward*] ==

3.64 Shaye: [*facing Erin*] ##Well that's why you need both types of energy for it to light##

But when Baxter again tries to interject his idea that energies kill each other, the class immediately and loudly tries to shut him down:

3.65 Baxter: ##Well since, like, Larry## [*Larry looks towards Baxter*] I'm answering your question. Well, you know how they kill each other?

[*Many students speaking at once, and loudly*]

[*Alyssa and Phoebe turn around to face Baxter*]

3.66 Phoebe: They don't --

3.67 Student: They do not kill each other!

3.68 Ms. F: Stop! Stop! Stop!

3.69 Brad: Shhhhh.

3.70 Erin: You need the negative side --

3.71 Ms. F: ##Guys, stop yelling. Remember, we're all just expressing## --

3.72 Tony: ##Baxter, how does energy kill each other?##

3.73 Baxter: ##I dunno [*giggles*] I just said it##.

3.74 Ms. F: Anthony and Ari. Stop for a moment. Remember, we're all just expressing some ideas, k? --

3.75 Baxter: Well, maybe ==

3.76 Ms. F: We're gonna try to get out our ideas. Other people can hear our ideas. They can add to it. They can offer some counter examples. But we need to stop drowning out each other. And we're not arguing, we're trying to make some understanding from this. Baxter.

As Ms. F states in [3.76], the students talk over each other loudly in a way that might inhibit careful consideration of ideas. The students appear to be trying to shut Baxter down, or win, rather (or perhaps in addition to) trying to "make some understanding."

Intent becomes relevant in these exchanges because students' may not be trying to connect the *substance* of Baxter's idea to the conversation. Instead, they begin to associate the killing idea with something silly or wrong that needs to be squashed. In terms of Baxter's coherence seeking, he might be "just saying" [3.73] the killing analogy to attract attention; for example, he often smiles or giggles when Phoebe yells at him. But Baxter successively modifies his killing analogy in substantive ways throughout the class, suggesting that at least part of his coherence seeking indeed involves substantive ideas about the ingredients in a battery.

6.6 Discussion

6.6.1 The Importance of Students' Trying to Make Connections

There are many ways of making sense of the world, and science has arguably come to represent an amazingly influential, but also narrowly defined set of tools, practices, and knowledge for sense-making about natural phenomena. By recognizing the myriad ways that students try to make sense of their experiences in science class, we are better prepared as researchers and educators to support their ongoing refinement of their ideas about natural phenomena, even if those sense-making practices appear to deviate drastically from accepted scientific practice. The idea that the battery contains two ingredients indeed proved to be a useful idea for students in Ms. F's class. They not only refined the model over successive days in the module, but also used that model to explain other observations, for example the differing brightness of bulbs in a series and parallel circuit. And Baxter's use of anthropomorphism raised questions about whether energy in a battery has "agency" and how the kinds of energies in a battery might interact. I use these examples to reiterate a point already made, but unfortunately under acknowledged, in the science education literature: that a primary goal of educators and researchers ought to be to consider sincerely the sense that students are trying to make (see for example Duckworth, 1996; Hammer, Goldberg, & Fargason, in press; Lindfors, 1999).

6.6.2 How Intent Matters for Coherence Seeking

Philosophical and cognitive accounts of humans' work to connect perceptual, epistemological, conceptual, social, linguistic, cultural and other information together distinguish between those connections which are achieved on purpose, consciously, and those which occur without any apparent conscious intent.

I have argued in this chapter i) that students seek coherence both consciously and unconsciously, and ii) that our perceptions of students' intent affects our interpretations of what information students are trying to connect. However, I have remained relatively agnostic concerning normative judgments about students' coherence seeking, especially in regard to intent. In their review of conceptualizations of argumentation in studies of science and science education research, Bricker and Bell (2008) advocate for a broader perspective on what constitutes authentic engagement in that practice:

> We have used the scientific practice of argumentation as a model for our argument that the field of science education's attempts to integrate conceptualizations of scientific practice deeply into the work of science education have been hampered by arguably *narrow theoretical considerations of the forms and purposes of those practices*—and that many of the specific theoretical conceptualizations like the kinds presented in the previous sections can be used to further inform important aspects of the endeavor. (Bricker & Bell, 2008, p.495, emphasis added)

Likewise, I suspect that *a priori* limiting "authentic" coherence seeking to those moments in which students are purposefully trying to search for connections among conceptual ideas will not serve the interests of researchers or educators. Whether students are trying to win, trying to do well in school, or are just curious, our focus as educators really centers on what those purposes tell us about the substance of students' reasoning, and in what ways students' criteria for coherence differ or align with ours.

Chapter 7: Reflections on Defining and Seeing Evidence of Coherence Seeking

"Yet even if too broad and vague, this classification of life at least points us in the right direction..." *-James Lovelock, on the Gaia Hypothesis*

7.1 Introduction

In constructing and refining a perspective on coherence seeking, I studied classroom videos and transcripts from the Learning Progressions project carefully and considered, "How are the students' utterances, movements, expressions, gazes, etc. evidence of coherence seeking in this moment?" In other words, rather than ask if or when students seek coherence, I asked, "What information are they trying to connect?"

In purposefully stretching the construct of coherence to its limit, I illustrated how students' attention to classroom norms, peers' and teachers' expressions, instructions, their sense of what a task is about, their acts of language, etc. can be construed as kinds of coherence seeking, along with the more often recognized forms of coherence seeking related to connecting conceptual information. It is only partly facetious to say that according to the perspective laid out in this dissertation, everything is coherence seeking. Some might argue that a construct which can be construed so as to include every aspect of the classroom ecosystem is meaningless, and also useless. The usefulness of any construct in education research, they might add, stems from the ability to reliably distinguish what does and does not fall into the categories defined by that construct.

In response to such concerns, I first point out that the emphasis of this work is not so much to create a valid and reliable definition of a construct, but to create a perspective, or way of looking at, students' reasoning in the classroom. Certainly, perspectives can hold important cultural, emotional, and spiritual consequences for individuals and their communities. The mantra that "music is everywhere" for example, plays an important role in Tanzanian communities (Paladino, 2008), as does the principle of interdependence in some Native American cultures (Cajete, 1999).

Without minimizing these sorts of meaning stemming from expansive worldviews or perspectives, I appeal to evidence that the development of these ambiguous perspectives can be important tools for discovery and may significantly impact practice. Working under the assumption that any sound (or lack thereof) can be called music, post-modernists have explored music as a social construct, leading to recognition of forms of musicality previously unknown to Western culture (Kramer, 1999). Within the field of education, educators' shift from a deficit model to the view that students enter the classroom with myriad resources for reasoning about the world has a profound impact on their assessment practices and instructional decision-making, and may also impact many aspects of students' performance in school, including retention and self-efficacy. Though the mechanisms by which educators' perspectives on learning impact the classroom are not completely understood, evidence for the impact is well-documented (see for example Ball, 1993; Hammer, 1997).

Beyond the demonstrated practical implications, an expansive view of coherence seeking might appeal to researchers' and teachers' intuitive sense. Rosch's

(1973) work on prototype theory suggests that for many natural categories, humans view category membership as a matter of degree, rather than a matter of fitting (or not fitting) a definition. In other words, when asked to identify members of a particular set ("birds", "furniture", "colors") participants demonstrate a gradation—i.e. a robin is more like a bird than a penguin. In terms of coherence seeking, existing work appears to identify prototypical examples (causal relations, explanatory coherence, non-contradiction from the expert's perspective), without acknowledging the possibility of gradation in membership (i.e. to some degree, everything is coherence seeking). The perspective outlined in this dissertation treats coherence seeking as a sort of natural category of which all classroom activity is a part; however, in doing so, I have possibly understated the importance of centrality—i.e. is "finding inconsistencies among ideas" more like coherence seeking (or more valuable) in science than "aligning one's behavior with social norms" or "recognizing an object as a chair"? Since issues of centrality become salient in conceptualizing students' progress in science, I discuss that issue in more detail in Chapter 8.

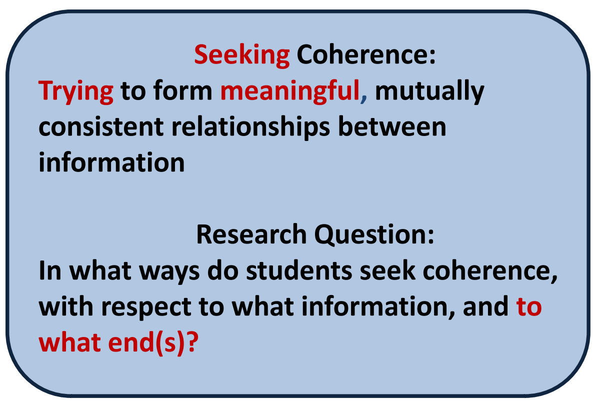
While there are reasons to value a perspective that essentially tags everything in the classroom as evidence of coherence seeking, certainly, in stretching the construct of coherence seeking to its limits, aspects of that perspective have become ambiguous or ill-defined. Components of the perspective that require further refinement include the definition of coherence seeking, the fluid boundary between research and student coherence seeking, and the emphasis on verbal over non-verbal evidence. I discuss each of these in turn in the following sections.

7.2 Refining the Definition

Three aspects of the working definition and research questions (see Fig. 10) proved inextricably intertwined, and problematic: ‘trying’, ‘meaningful’, and ‘to what end.’ While not initially conceptualized that way, all three of these terms ended up intersecting at the idea of purpose of students’ coherence seeking, from their perspective, i.e. what are students trying to do in science class, and why are they trying to do that?

Figure 10: Ambiguous Terms in the Definition and Research Questions

Aspects of the framework that need to be elaborated, specifically along the dimension of purpose, intent, or meaning of coherence seeking are highlighted in red.



The word ‘trying’ proved potentially problematic in analyzing student work that lacked clear evidence of intent. For example, students in Ms. F’s and Ms. H’s class often shared grammatical structures in a sort of coherence seeking that operated beyond their awareness. In making sense of phenomena, students’ appealed to intuitive ideas that likewise are the result of coherence seeking operating outside of their awareness. For example, John expected that the asphalt where the water evaporated should be hot; Raphael expects it to be warmer closer to the sun. These types of intuitive knowledge are built from experience in the world, and yet, students do not seem to "try" to put those experiences together, it just happens. The concept of trying also needed to be bifurcated in data analyses to distinguish between local goals of connecting information, and broader goals related to the framing of the task at large; though, clearly, these two goals might reflexively inform each other. For example, Dianna in Chapter 6 tried to connect a vocabulary word to the quantity *five meters per second*, but she did that perhaps in service of the broader goal of completing a tutorial worksheet. (And her recognition that the tutorial worksheet should be completed is likewise the result of even more coherence seeking on her part, with respect to her experiences in school.) The initial reason for using the word trying into the working definition was the same reason for using "coherence seeking" instead of coherence—to mark coherence seeking as something that students' do, rather than as just a static characteristic of the products of their reasoning. To that end, the language of trying and seeking has been useful. However, future refinement of the definition might include alternative ways of expressing that dynamism without the added baggage of intent.

Vosniadou and Brewer's (1992) work provided some guidelines for thinking about 'consistency' from the students' perspective; thus, that aspect of the definition was relatively unproblematic in analysis. However, the term 'meaningful' was both theoretically and analytically challenging. First, I quickly realized that while I could relatively easily distinguish consistency from my own and the student's perspective, it was far more difficult to step outside my own views on what relationships are meaningful. Raphael's Cloud Story, for example, included a chronological account of how fog forms. There is some evidence that Raphael found the story meaningful. He was excited to share it with Ms. M, and he exclaimed "Oh I know!" when he thought of it. At least one reason why he found it meaningful, from his words, is that the story connec[ed] clouds, evaporation, and the sun together. But when watched Raphael share his story, I saw meaning in its cyclical-ness and causality. In other words, the relationships in that story that are meaningful to me may not be the same relationships that are meaningful to Raphael, or at least not meaningful for the same reasons.

I originally opted to include the word 'meaningful' in the working definition in order to distinguish coherence seeking from a random listing of information. However, in analyzing data, I never found it necessary to invoke that boundary; students are rarely if ever truly random in their behavior or speech in science class. Rather, the word meaningful became a sort of stumbling block for analysis because it suggests that not all relationships are meaningful, and thus not all connecting of information is coherence seeking. (Theoretically, it must be the case that all relationships are meaningful for the students, otherwise the assumption that students are always seeking coherence does not hold.) I found in trying to address meaning, I really was addressing the "to what end" research question defined at the outset of my study. In other words, in analyzing data, the use of meaning, trying, and to what end became redundant; all three of these words are different ways of articulating the reasons that students do what they do.

7.3 Distinguishing Researcher Coherence Seeking from Students' Coherence Seeking

Ironically, seeing evidence of coherence seeking in students' thinking requires the researcher to seek coherence on multiple levels. And often, I found it difficult to distinguish between my attempts to connect information, and the students attempt to do so. In analyzing a transcript, I had the benefit of being able to trace students' ideas over many minutes, hours, or even days to construct claims about the information they were trying to connect. However, in constructing these claims, I may have seen connections that the students were not actually making. In making sense of this methodological challenge, I used the analogy of the word association game. In the game, players alternate saying the first word that comes to mind. For example:

Player 1: apple

Player 2: orange

Player 1: Florida

Player 2: sunburn

Player 1: red

Player 2: apple

In looking at these turns, I might make guesses about how the players came up with their words, i.e. an orange is a kind of fruit, like an apple. Florida exports oranges. Sunburns happen in Florida. Red is the color of burned skin. Apples are red. But, I might also assume that Player 2 has sought some sort of coherence over the entire exchange, trying to bring the conversation back to apples. In other words, I, like the players constantly seek coherence; and one of the coherences I see is this cyclical pattern in the data, starting and coming back to apples. But when Player 2 said 'apple' was he actually connecting (consciously or intentionally) back to the opening word, or was the reappearance of the word apple the result of coherence seeking with respect to the word ‘red’ or some other unarticulated information?

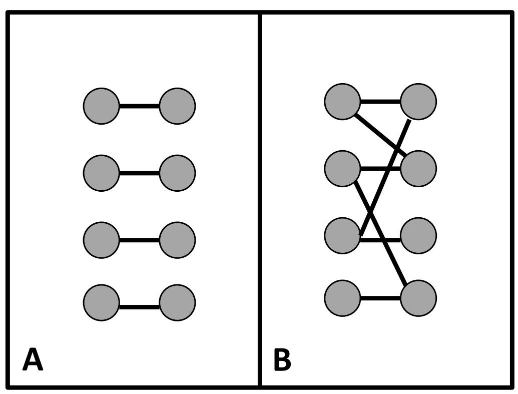
The word association game is a simplified version of the methodological challenge I faced in analyzing classroom data. For example, in discussing how a bulb lights in Ms. F’s 4th grade class, Baxter puts forth a series of ideas involving a reaction between “positive” and “negative” energies. Baxter’s ideas appear to evolve throughout the conversation, and I struggled to make sense of whether successive versions of Baxter’s ideas were connected, for him, or whether I was imposing these connections as an outside observer. I have arranged a small portion of these utterances chronologically (noted by timestamp), and extracted from the surrounding conversation:

> [8:16] Baxter: ##I'm starting to think## now that --Well, they're, they're probably can't be a chemical reaction because, like if there's a chemical reaction, in chemical reactions, doesn't like something explode inside or –
>
> [8:31] Baxter: You gotta get a sign of the chemical reaction // Well, um now I'm starting to think Ari's way because when you were holding the wires, if you were holding the metal, then it would get really hot, and then it would burn your fingers for a second. Well I think that would be the positive and negative energy mixing. --
>
> [9:57] Baxter: Wait. Wait, now I sorta think they go together because I'm sorta thinking about math now, and how // let's just say you add 20 plus 20. Well a way to um check that is uh // you could get your answers by 20 minus twe-uh 40 and what would that ##equal##? It'd be // yeah.
>
> [10:19] Baxter: Yeah, it'd be 20. So you'd have two 20's and one 40. ##They go together as a fraction.##
>
> [10:42] Baxter: Or, or maybe ##the positive side## // Maybe the positive side has more like um, more like power and the negative side takes away power. So like, ##Like adding builds## it up and minusing takes it down. So maybe uh the plus // well the positive side um has a lot more energy, like a lot of energy so the negative has to take some away or like it will be ##dangerous##.

> [11.19] Baxter: Yeah, but like maybe one liquid is a negative liquid and like it takes away power. And the positive uh adds power so when they combined it's just neutral. And it stays the same so it, it doesn't become dangerous and it won't, and it // like it will make it so it won't light up. So it's right in the middle. Like if you use one battery and two lights, the lights will only light up a little bit. Maybe the minus, well the negative takes away a lot of the power because if you took all the positive it would like make, make it really uh light up. And like, it would be like, dangerous like, it could burn your hands if you touched it or something. (See Appendix G for omitted portions of the transcript.)

The challenge, analytically, was to determine whether Baxter was trying to connect all of these ideas over the course of the conversation together, or whether he shared each of his within a local moment of conversation, i.e. if we were to diagram the coherence seeking, would it look more like Figure 11A or 11B?

Figure 11: Two Possible Diagrams for Baxter's Utterances



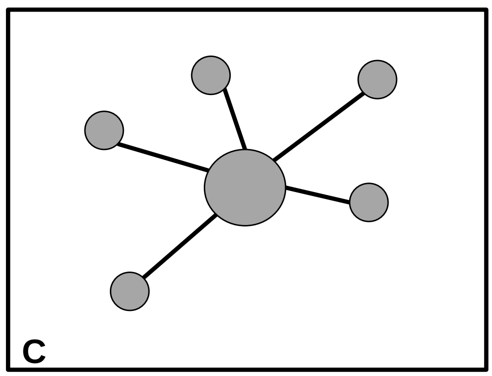
The circles represent the conceptual ideas Baxter shared in class. (A) Baxter tries to connect the circles together over the scale of the whole conversation, i.e. a sort of global coherence seeking. (B) Baxter tries to connect his ideas together to other information, locally, but not necessarily globally.

Importantly, I did not pick these quotes in such a way as to suggest a pattern; rather, I selected a few minutes of transcript, and modified it only by removing all of the speakers besides Baxter. In reading the transcript, I cannot help but see patterns and connections in Baxter's utterances. In [8:16] he posits that a chemical reaction cannot occur between the positive and negative energies because that would lead to an explosion inside the battery. In his next utterance, Baxter changes his mind based on his observation that the wire sometimes heats up. Here, he uses a linguistic marker to specifically highlight his changing view ("Well, um now I'm starting to think"). In [9:57], Baxter again uses a linguistic marker ("Wait, now I sorta think") to indicate shifts in his idea. He brings an idea he just heard in the math lesson prior to science class—that a way to check the result of an addition problem (20 +20 = 40) is to turn it into a subtraction problem (40-20 = 20). Baxter does not fully articulate the connection he is trying to make here between math and science, but he does say ("I'm sorta thinking about math now") indicating that he is seeking some sort of connection here. The next time Baxter speaks, he elaborates that the positive side might have "more power" which is reduced by the "negative side." Further, that without the negative "minusing down" the positive, it would be dangerous. He seems to be referring to two ideas that he has already introduced previously: i) that a chemical reaction in the battery would be dangerous, ii) that addition and subtraction might be useful for thinking about how negative and positive energy interact. Finally, in his last utterance of the three minute episode [11:19], Baxter suggests that when the negative and positive combine, they are "neutral" and not dangerous. Again, he labels the positive energy as the stronger or more powerful ingredient, and the negative energy as the calming or reducing ingredient.

Over the course of the utterances, Baxter appears to construct and refine a model of the circuit based on an idea from math class—that the positive adds power to the bulb, and the negative takes it away. The opposing relationship between these two kinds of energies accounts for why the wire sometimes gets hot [11.19], why two bulbs are dimmer than one in a certain circuit [11.19], why both positive and negative energy are needed for the bulb to light, and why the reaction between the negative and the positive energies does not result in a dangerous explosion [8.16, 11.19] Baxter seems to attribute certain properties, like strength and effect, to the negative and positive energy relatively consistently (to me) throughout the three minute episode. He also continuously refers back to a concern he stated in [8:16]—that the battery might explode if the positive and negative energies undergo a chemical reaction. Finally, he sometimes verbalizes the connections he is trying to form between his ideas ("Wait, now I sorta think..", "I'm sorta thinking about math now"). These aspects of his utterances seem to indicate that Baxter's work in the presented sections looks more like Figure 11B than Figure 11A.

One of the dangers of such an analysis arises from the assumption that consistency from the researcher's perspective equates to the consistency (or the same consistency) to the student. Part of the reason that Baxter's ideas seem to "hang together" is that he uses the same terminology throughout the three minute episode, even if the ideas behind these words change. Each moment of speech is a reconstruction of an idea; and yet, as researchers, we can scan over an entire set of utterances as though they existed simultaneously in time, making the mistake of choosing Figure 11B over Figure 11A more likely. Finally, there is the possibility of weighting particular elements of information more strongly than they would be weighted for the student. For example, in my analysis, I have highlighted how Baxter's utterances seem to describe the successive refinement of an idea; there is little evidence that Baxter himself sees his work in this way. Rather, there is ample evidence that the issue of dangerous explosions is of central importance to him, and so perhaps a better way to depict his coherence seeking might be something like Figure C:

Figure 12: A Third Diagram for Baxter's Utterances



The details of the diagram itself are not so important, and I argued in Chapter 2 that in fact they may serve to de-contextualize students' reasoning in problematic ways. But in attempting to construct these diagrams, researchers might become more aware of the fluid boundary between their own coherence seeking and the students.

The challenges discussed here relate strictly to if and how Baxter seeks coherence between the conceptual information he himself shared in class. The challenge of distinguishing researcher coherence seeking from Baxter's becomes seemingly insurmountable considering all of the different information that Baxter (and the researcher!) try to connect throughout the three minute episode, or during the entire class.

In the analyses presented in this dissertation, I have tried to denote clearly how my own coherence seeking intersects with my analyses of students' coherence seeking. However, future work must continue to articulate this distinction, and I suspect one aspect of that work will be considering not only individual's coherence seeking, but also the group or class as the unit that seeks coherence.

7.4 Unpacking Linguistic and Non-Verbal Evidence of Coherence Seeking.

Linguistic and conversational coherence remains one of the understudied aspects of coherence in science education. Many of the existing coding schemes for coherence, including Davis (2003), Sandoval (2003), and Ranney and Thagard (1988) implicitly rely on linguistic structures and explicit articulation of relationships. However, little work has been done within education research to consider how students' work to articulate their ideas is an act of coherence seeking in and of itself. I have drawn on aspects of conversational analysis, linguistics, reading comprehension, as well as Judith Wells Lindfors' language-act-framework to begin to outline evidence of coherence seeking located specifically in students' language. However, future work might unpack that evidence further and more systematically, especially in conceptualizing the relationship between conceptual and linguistic coherence seeking. For example, while teaching a unit on weather to high school freshman, I asked students to read an excerpt from *James and the Giant Peach* (Dahl, 1961) that describes how hail forms. According to the story, Cloud Men in the sky mold clouds into hail, and then once they have a big pile of hail stones, they use a shovel to spread the hail onto the earth below. I asked students if they believe the story about how hail forms. One student said no, and when I asked her why, she said, "Because it sounds like it's written for little kids." In that moment, I realized that her sense-making around the explanation for how hail forms was intimately tied to her sense-making around language of the story. And that coherence seeking was based not necessarily on the denotation of words, but rather her experiences with the language of children's books and the language of science class. In Lemke's (1982) terms, the student recognized the language in *James and the Giant Peach* as a thematic structure from children's books, and not science class. (I cannot help but wonder, had I re-written the story using more technical vocabulary, might she have believed it?) Work on science and literacy connections abound; and yet, even recent work focuses on literacy as a way to convey science content, rather than literacy as another aspect of students' coherence seeking within sense-making about natural phenomena (see for example Barber, 2009). Future work might unpack more specifically the linguistic, conceptual, and epistemic aspects of students' coherence seeking in service of refining the framework and in extending current work on the science/literacy connection.

Finally, one notable shortcoming of this work is the lack of focused attention on non-verbal evidence of coherence seeking. While I did incorporate non-verbal evidence such as gaze, length of gaze, body position and movement into my analysis of highly verbal interactions like those in Ms. F's class, I chose not to focus in this study on episodes that were totally quiet. However, in the batteries and bulbs unit, students spent a significant amount of time quietly constructing circuits. In watching these students, I could see evidence of violation of expectations, drawing on intuitive ideas about how electricity should work, and refinement of ideas (see Fig. 13). A more extensive study of moments of quiet sense-making, perhaps in engineering, experimentation, or among listeners in science discussions, and drawing on for example studies of infant cognition, would extend the perspective presented here in important ways.

Figure 13: An Example of Non-Verbal Evidence of Coherence Seeking

Anne tries to make a bulb light. (A) She straightens the wire. (B) She checks the bulb, which does not light. (C) She turns bulb over to check connection at the bottom. (D) She looks back to battery, adjusts connection between battery and wire.

7.5 Conclusion

In suggesting ways to refine the perspective on coherence seeking described in this dissertation, I have focused primarily on the needs and interests of the education research community. Indeed, when I first decided to create an alternative framework for coherence seeking, I did so specifically in response to coding schemes and ideas circulating among researchers. But, I am a teacher at heart, so in the next and final chapter, I discuss implications of the perspective lying at the intersection of research and practice: student progress and curriculum design.

Chapter 8: Discussion and Implications for Pedagogy

"A proper account of coherence must not start from some partial intuitions, but should pay attention to the role that this notion is supposed to play within a particular context." *-Bovens and Hartmann (2003)*

8.1 Introduction

The focus of this dissertation was to create and refine a perspective on coherence seeking, with a focus on the following research question: What information do students try to connect, in what ways, and to what end?

Starting with the assumption that students are always seeking coherence with respect to *something* turned out to be a useful way to notice previously hidden aspects of coherence seeking science class. In particular, the approach revealed that even in moments of reasoning in which students ignore discrepant evidence, create non-normative accounts, or make seemingly off-task comments, we can still conceptualize their work meaningfully in terms of trying to form meaningful, mutually consistent relationships between information.

But claiming that students are trying to make ideas fit together says nothing of whether educators see those connections as valuable or desirable. Rather, I have painstakingly distinguished *evidence of coherence seeking* from *evidence of coherence seeking that we usually value in science class*. But in the practice of teaching, we must make decisions about what reasoning and ideas to support in working towards our educational goals.

Thus, finally, in this chapter, I outline what a dynamic, broadly construed, student-centered conceptualization of coherence seeking means for two key aspects of science pedagogy: student progress and curriculum design. I argue first that coherence seeking may serve as a useful construct for characterizing students' progress in science in that it cuts across disciplinary practices and lends itself to a context-sensitive notion of sophistication. Secondly, I argue that the perspective on coherence seeking presented in this dissertation is fundamentally at odds with efforts to build coherence into the science curriculum.

8.2 Rethinking Learners' Progress in Science in Terms of Coherence Seeking

As mentioned in the introduction, this dissertation painstakingly distinguishes evidence of coherence seeking from the evidence of things educators would like to see in the science classroom. In my analyses, I have remained relatively agnostic about whether or not the work that students do is "scientific" or "sophisticated" or "desirable" from the educators' point of view, not because all coherence seeking is the same or equally valuable, but because the rulers by which we measure "goodness" of students' reasoning depending on one's educational philosophy, goals, and decision-making in the moment, and an elaboration of all of these contextual factors is beyond the scope of this work.

However, I do suspect that coherence seeking might serve as a productive way for educators to think about students' progress in science. First, coherence seeking cuts across and is embedded in all disciplinary practices, and as such, has the potential to reunite the strands of scientific proficiency that have become increasingly disparate in research and curriculum as of late. Secondly, coherence seeking is something that both students and scientists do, though perhaps in different ways, with respect to different information, and for different reasons. Thus, coherence seeking allows educators to imagine bridges between novice and expert practice, in ways that value each in their own right (rather than cast one as deficient, and the other as "sophisticated" or desirable).

8.2.1 Bridging Disciplinary Practices

Much of the data presented in this dissertation (see Appendix C) comes from a larger project to develop learning progressions for scientific inquiry. As defined by the National Research Council, learning progressions are the "successively more sophisticated ways of thinking about a topic that can follow one another over broad spans of time" (NRC, 2007, p. 214).

After developing a litany of learning progressions for various content areas and disciplinary practices, researchers began to recognize the growing and problematic separation of practices from content, and practices from each other. Some learning progressions focus on the development of concepts of force, without any discussion of the role disciplinary practices play in students' building accounts of motion. Other progressions focus on the development of students' evidence-based explanations, without any meaningful connection to the role those explanations play in students' coming to understand natural phenomena. Thus, learning progressions research has resulted in curriculum materials and assessments that separate practices from content, and practices from each other, which we know does not characterize expert scientific practice, nor does it foster students' meaning making and sense-making in class (Lehrer & Schauble, 2009).

Part of the reason that disciplinary practices resist unification, I believe, is that they are, in Bricker and Bell's words (2008), often narrowly defined in both form and function. An attempt to unify the disciplines need not start with specific practices, but rather, with the general orientation toward making sense of natural phenomena that underlies them. Coherence seeking is well-suited for that work.

Thinking in terms of what information students are trying to connect and why gets at the heart of any educative aim, whether that be in science, poetry, performance, or any other mode of sense-making. With coherence seeking as the starting point for a conceptualization of progress in science, disciplinary practices are re-cast as tools for making particular kinds of connections, for particular reasons, in particular moments. Mechanistic reasoning entails forming relationships between "entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions" (Russ & Hutchison, 2006, p. 642). Models are "a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena" (Schwarz et al., 2009, p. 633). And scientific argumentation is the process of connecting data and claims via warrants and backing. But all three of these disciplinary practices are more generally an attempt to connect information together in meaningful, mutually consistent ways. In other words, coherence seeking highlights what all of the disciplinary practices have in common, while at the same time recognizing the context-specificity of the connections that each practice values.

Another challenge to learning progressions research has been to bridge disciplinary practices and students' learning of scientifically accepted explanations for phenomena. Certainly, one of the concerns teachers expressed in the LP project was the possibility that students could develop complex, well-thought-out explanations that are, to put it bluntly, wrong. In Ms. H's class, for example, the focus group wanted to find out if temperature affects evaporation time for water. They tested three different water temperatures and found that the coldest water evaporated the fastest. Then, to confirm or extend the findings, they repeated the experiment with room temperature and ice water. Again, they found that ice water evaporates faster. To explain the unexpected results, Leah and John suggest that ambient temperature somehow matters. The students design an experiment to test that idea:

> John: So we wanted to do the hot vs. cold thing. And see like if on a hot day cold water will evaporate faster // well we know that. Or if on a cold day warm water will evaporate faster [*comment from Ms. H omitted*]. And we're going to test four temperatures and one will have colder water and one will have hotter water to see what'll evaporate faster.

The module (and school year) ends before the students are able to conduct the experiment, meaning that they leave 5th grade thinking that cold water evaporates faster than warm water.

Likewise, in Ms. F's class, the students generate an idea that positive and negative energy somehow interact to make a bulb light. The students clarified various components of this idea, including the nature of the interaction between the positive and negative energy, the interior of the battery, and what sorts of materials allow the two energies to travel. Later, Ms. F said in an interview (see Appendix G) that after the LP electricity module, she exposed the students to the correct answer in the textbook and many students refused to accept it. They continued to argue for the idea that current flows in two directions and from both ends of the battery.

Students' apparent failure to reach the canonically accepted explanations in Ms. H's and Ms. F's class does not reflect a failure to seek coherence. On the contrary, the students were connecting a variety of information in class, and often in ways that epistemologically-speaking, resembled portrayals of expert science. The two ingredient model proved quite versatile in Ms. F's class; they were able to explain many observations using that model, including why some arrangements light the bulb and others do not. In Ms. H's class, the students did not just accept the strange finding that cold water evaporates faster than hot water; rather, they tried to confirm that relationship for a range of temperatures, and identify other factors (i.e. testing conditions, ambient temperature) that could explain the finding. Thus, though the students did not reach the canonically accepted answers, they certainly 'got somewhere' in their work much in the same way that scientists make progress in refining their own theories and models (Engle & Conant, 2002).

8.2.2 Bridging Novice and Expert Practice via the Notion of Context-Sensitive Sophistication

Progress, as defined by the Oxford English Dictionary, is "forward or onward movement towards a destination." In conceptualizing students' progress in science, then, we must necessarily answer the question, *progress toward what*? Because children's education lies at the intersection of political, social, and historical tensions, clearly no simple answer exists. Some argue that education ought to empower students to work toward a more just and democratic society; others argue that education ought to prepare students to compete in a capitalist economy. These goals may have very different implications for science education, as Calabrese-Barton, Ermer, Burkett, and Osborne (2003), Labaree (1997) and others have discussed. Within the United States, science education has also become a tool for imparting worldviews around controversial topics such as climate change and evolution, for which entrenched and competing worldviews exist. Thus, progress in science is associated with the learning of particular knowledge and skills, as well as the adoption of particular worldviews. For the purposes of argument, I will focus in this section on the commonly accepted goal of science education as expressed in the frameworks for science education (NRC, 2012) and other standards documents: students' coming to engage in the work that scientists do.[26] I argue that if we take seriously students' developing expertise in the doing of science, our conceptualizations of their progress must necessarily involve a context-sensitive notion of sophistication. Finally, I present coherence seeking as a construct that lends itself to such notions.

8.2.2.1 What does a static notion of sophistication look like?

A static notion of sophistication labels some forms of thinking, or some ideas, as absolutely better than others, regardless of circumstance or context. Often, learning progressions focus on conceptual knowledge, and so the idea labeled as "most sophisticated" is the one that aligns with current accepted scientific understandings, regardless of how well-developed students' alternative explanations are. There are also learning progressions and classroom rubrics that label particular ways of connecting evidence as absolutely more "scientific" than others, for example Gotwals and Songer's (2008) progression for generating scientific explanations (see Fig. 14).

[26] I intentionally phrase this goal as students' engagement in "work that scientists do" rather than "thinking like scientists" or "acting like scientists." In doing so, I hope to emphasize that it is the practice of science itself, and not just the students, that might change as a result of science education. Also, for students to engage in the work that scientists do they need not literally work alongside scientists; rather, I use the phrase figuratively to mean that students are engaged in making sense of natural phenomena.

Figure 14: A Static Notion of Sophistication as Represented in a Learning Progression for Scientific Explanation

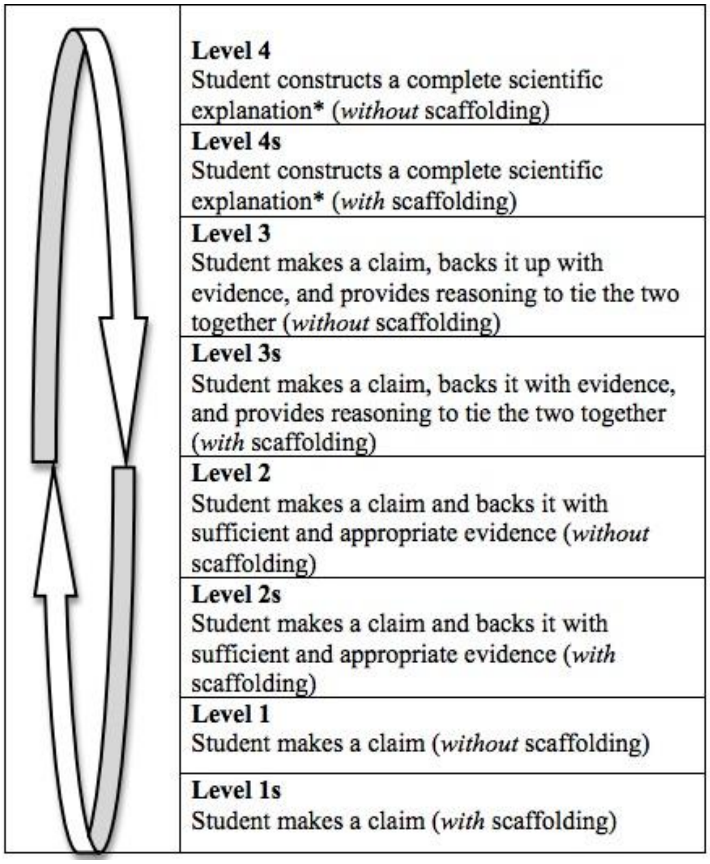


Image courtesy Songer, Kelcey, and Gotwals (2009, p. 49).

Similarly, for coherence seeking, potential candidates for the slot of "most sophisticated" (and their least sophisticated counterparts) include:

- Intentionally searching for inconsistencies or counterevidence for an explanation vs. actively avoiding or ignoring counterevidence
- Seeking reconciliation between competing explanations vs. accepting disagreement as merely a matter of opinion
- Developing causal mechanisms vs. generating lists of factors, patterns or correlations

- Evaluating ideas based on their alignment with observational data vs. evaluating ideas based on personal preferences, principles of fairness, or their spiritual, aesthetic or entertainment value
- Bounding a data set on physical grounds vs. bounding a data set so as only to include confirming (or disconfirming) evidence

8.2.2.2 Why the construct of coherence seeking suggests a context-sensitive notion of sophistication.

The perspective on coherence seeking outlined in this work demands a context-sensitive notion of sophistication. Coherence, as Buchmann and Floden (1992) state, carries "positive implications of value" (p. 4). So, in frameworks that treat coherence as a dichotomous characteristic of students' work or reasoning, calling a students' work "coherent" is in and of itself a normative claim. And further, when narrowly defined, these frameworks specify which kinds of coherence are sophisticated and which are not.

I have argued for approaching classroom data with the assumption that students are always seeking coherence. In doing so, I have essentially applied the positive connotation of coherence to all classroom activity, meaning that construct of coherence seeking alone no longer distinguishes productive classroom work from everything else. Instead, judgments about the productiveness of students' sense-making must be determined by what that sense-making allows to happen in the moment, and what opportunities it opens up for future knowledge construction. Such judgments are inherently context-sensitive.

Beyond the direct implications of the construct as presented in this dissertation, studies of expertise also suggest a context-sensitive notion of sophistication. Though some experts certainly possess exceptional skill in executing specific procedures, more generally a hallmark indicator of expertise in and out of science is cognitive flexibility, or adaptive expertise (Hatano & Inagaki, 1986). That is, experts are able to resolve novel problems through coordination of various material, social, and reasoning tools, and their use of those tools depends sensitively on context; no tools are universally better than others.

Disciplinary practices unfortunately do not easily lend themselves to that context-sensitive view of sophistication because they are rather narrowly focused on particular kinds of connections and defined in isolation from one another. When broadly defined as suggested in this work, coherence seeking allows, and in fact demands, malleability in terms of what information and what connections we view as potentially most productive in students' sense-making of physical phenomena.

8.2.2.3 An example of evaluating the sophistication of coherence seeking within context

To illustrate what that context-sensitive view of sophistication might look like in practice, I present a clip from a professional development meeting, during which the learning progressions participants and staff worked on the question, "Why doesn't it rain more often in San Diego?" The group included 3 university professors, 2 graduate students (including the author), and 7 elementary teachers. I participated in the workshop as a learner, a researcher, and occasionally a co-facilitator, allowing me to comment on conceptualizations of progress from all three of these perspectives.

San Diego, where the workshop takes place, is a large, urban, ocean front city. San Diego's low rainfall amounts, given its proximity to the ocean, troubled staff members and teachers alike. Over the first two days of the workshop, we brainstorm possible factors that could explain the lack of rainfall, including topography, latitude, ocean currents, and average temperature. We also began to consider mechanisms for what makes rain, but by the third day we had multiple threads of conversation going and no consensus. To reignite our inquiry intellectually and emotionally, the facilitator of the discussion, S4, suggested that we make a list of upon which we all agree. S1, another staff member and a biologist by training, offered two possible items of consensus, namely i) that heat rises, and ii) that it is colder at the top of the atmosphere. As one of the San Diego teachers eventually points out, these two ideas seem to contradict, i.e. how can heat rise and it also be colder at the top of the atmosphere? But in the moment, neither S1 nor any of the other participants (including myself) appear to notice the contradiction, or if they do, they do not mention it:

[*T = San Diego Teacher; S = Learning Progressions staff member*]

1.1 S1: I have a contribution. I think..we all agree..that heat from the ground or the water is rising up to [*gestures upward*] // toward the atmosphere. Like, heat's going in an upward direction [*repeats gesture*]. Can we agree with that?

1.2 T8: Heat rises?

1.3 S1: No, not just that heat rises. But we either have land or water, and so we have heat going up in our atmosphere.

1.4 S2: So what do you mean by heat?

1.5 S1: I dunno. Warm? Temperature? Warmth?

1.6 S2: Warm?

1.7 T3: Oh, hot air goes // hot air rises.

1.8 S1: Warmth. Hot air rises. Not like a physics[27] thing of heat, but like [*gesture*]

---

[27] perhaps uttered in response to S2's training in physics.

1.9 T1: Warm air rises.
1.10 S1: Yeah, warm, warm goes up. [*laughter*]
1.11 T3: Well warm goes this way or that way too [*gestures left and right*].
1.12 S1: Would a second thing we agree on is that it's colder up there [*pointing up*], whatever up there is, than it is down here? [*pointing toward the floor*]
1.13 S3: Gotta be careful with that one because of a // mar // uh inversion layer thing.
1.14 S1: How bout way up there?
1.15 S3: K, super high up there, okay, that's cold.
1.16 S1: ##Top of the atmosphere?##
1.17 S2: ##Outter space##
1.18 T5: ##Where clouds form?##
1.19 T3: How about just higher--
1.20 S1: Top of the atmosphere
1.21 T1: What about top of the atmosphere? What?
1.22 S1: It's colder at the top of the atmosphere than it is down there.
1.23 T1: Oh yes, yes, yes it is.
1.24 S1: Can we agree with that?
1.25 T3: Top of the mountain is colder than the bottom, right.
1.26 S1: So we got two things. We got two things. That's two things. I got no more.

Working to reach consensus represents a particular kind of coherence seeking, where the objective is to find alignment between differing viewpoints. In lines [1.1-1.26], S1 suggests two items for consensus. First, she says that heat goes in an upward direction. T8 generalizes the idea to “heat rises”, but S1 clarifies that she is referring specifically to the case of heat rising in the atmosphere. S2 asks for a clarification of the term heat, and T1 responds as though she is using the term “heat” in the everyday (and not physics) sense of the term. And T3 says that “warm” can also move left and right, or sideways. In other words, perhaps heat/warmth does not *always* rise. S1 looks directly at T3 during [1.11], but then looks away as if to intentionally ignore the contribution. Possibly, S1 wanted to avoid T3’s confounding evidence in order to continue with the process of reaching consensus.

S1's second item of consensus is that "it's colder up there…than down here." S3 expresses concern over the second item because she had recently read about inversion layers, or areas in the atmosphere where the air is warmer than that below it. S3 modifies her statement to say that the air "super high up there" in the atmosphere is colder than the ground, and S1 accepts that modification. Additional points of comparison suggested are outer space [1.17], where clouds form [1.18], and the top of the atmosphere [1.20]. With the suggestion of the top of the atmosphere, T1 seems to suddenly "tune in" and subsequently agrees with S1. T3 also agrees, apparently in part because that idea aligns with her knowledge about temperature change on mountains.

As a collective then, we evaluate the evidence to support the claims (i) that hot air rises and (ii) that it is colder at the top of the atmosphere, but do so in a piece-meal fashion. We connect (i) and (ii) together via *consensus*, but at least initially we do not apparently check that (i) and (ii) fit together in any other way. Agreeing on ideas without checking for internal consistency seems to be at odds with the scientific enterprise. In other words, according to static notions, perhaps our failure to address a logical inconsistency [1.1-1.26] was rather unsophisticated.

Remembering that coherence is always a matter of perspective, one could argue that perhaps most of us saw (i) and (ii) as consistent; or alternatively, we had already resolved any inconsistency ourselves or put it in abeyance. But a few lines later, T1 decides she does not support the idea that it is colder at the top of the atmosphere because it contradicts the claim that heat rises:

> T1: Yeah, I don't want to say that because then that doesn't // that doesn't match with warm air rises. You can't just say warm air rises, but it's colder at the top of the troposphere. That doesn't make any sense. [*laughter*]

The group erupts in laughter following T1's comment, indicating that suddenly we all became aware of the tension between (i) and (ii).

Even though we agreed on two contradictory ideas, a case can be made for the locally sophisticated nature our coherence seeking in [1.1-1.26]. To put the moment in context, we had been working for three days to understand why it rarely rains in San Diego. We tried coming up with mechanisms for what causes rain, as well as generating lists of relevant factors. We "went micro" to consider how rain drops form within a cloud. And we also looked macroscopically at global wind patterns and water transport. We were trying, but emotionally and intellectually struggling, to fit all of these different ideas together. Thus, the establishment of a few "foothold idea[s]" that we definitely agree on (even if they contradict), held promise for helping us move forward in our thinking at a time when we increasingly felt stuck (van Zee, Hammer, Bell, Roy, & Peter, 2005, p. 1015).

Indeed, part of our assessment of the quality of coherence seeking might reasonably rest in what follows students' attempts to make particular connections. For example, following line [1.26], T1 does point out that ideas (i) and (ii) contradict. Immediately, members of the group articulate ways to fit these ideas together, speaking rapidly and often overlapping each other. One teacher suggests that as the warm air rises, it hits into the cooler air and cools down. Another teacher suggests that the air rises as it cools, without suggesting a particular mechanism for that cooling. The establishment of foothold ideas opened up another line of inquiry to understand precisely what happens to the temperature of air as it rises. (Perhaps conveniently, that rising and cooling process is absolutely central to the modern understanding of cloud formation, meaning that our agreement on two contradictory ideas actually opened a path toward the canonically accepted answer.)

8.2.2.4 Clouds weren't made that way.

A natural question to ask, following the last analysis, is: "Are there examples of reasoning that, regardless of the context, just do not belong in science?" Gieryn (1983) argues that "science is no single thing" and that attempts to absolutely demarcate science from other forms of knowledge construction are futile and misguided. And yet, there are certainly examples in the history of science where ideas are cast aside as non-Western-scientific. For example, phrenologists, who studied personality and character via the shape of one's skull, were once viewed as legitimate scientists. But following a series of disputes in the mid-19th century, phrenology and anatomists diverged over issues of measurement methods and objectivity, their perceived connection to religion, and their standards for establishing truth. Anatomists maintained their status as scientists, and phrenologists lost theirs as a result of these highly politicized disputes.

What might non-Western-scientific thinking look like in science class? On the second day of the workshop about rain in San Diego, discussed in the previous section, we discussed why rain falls from clouds in droplets, as opposed to "dumping" all at once like water out of a bucket. One teacher, T2, suggests that perhaps the reason the water does not fall all at once is because clouds are not *made* that way:

1.1 T2: Can I throw something out I was thinking about last night?
1.2 Unknown: Please do.
1.3 T2: Cuz I know T4 was stuck with why doesn't it just dump, or I think we talked about that last time in our whatever discussion. Can't we just say that the cloud's not capable of dumping? That it, the way it rains, or the way it releases itself, it just comes down. That it's not..it's not capable of dumping. It's not *made* that way?
1.4 T4: ##(*** ***)##
1.5 T3: ##You mean like a bucket?##
1.6 T2: Yeah. [*slightly glancing back at T3, who sits behind her*]
1.7 S4: When you say // when you say "can't we just say" what is // what are you asking?
1.8 T2: ##Well--##
1.9 T4: ##It's cooling at different rates.##
1.10 Ms. F: ##It's not all gonna cool instantly.##
1.11 T4: Yeah. It doesn't all cool at the same time.
1.12 Ms. F: We were thinking as it's swirling around here [*pointing to drawing*] it's not all gonna cool instantly at the same *time* so as it's cooling that's the reason it doesn't ##all dump [*gestures hand downward]* immediately.##
1.13 T2: ##Okay, so there is a (***) behind this.##
1.14 T4: Well that makes sense with what you're saying [*pointing to T2*].
1.15 T2: Yeah, because I just // it // it's not capable of just dumping. It's never just gonna // why doesn't it just dump like a bucket? // Well because it's not *made*.
1.16 Ms. H: And get rid of all of it at once.
1.17 T2: Yeah because it's // the cloud doesn't work that way type // type thing.
1.18 Ms. F: Think about too when you in a crowd, the people on the outside of the crowd are going to get colder first, so it's almost like in that swirling the stuff on the outside is gonna kinda cool down first and stuff.[28]

Though brief, the excerpt contains an incredible amount of epistemological complexity, and speaks directly to the question of whether there are certain forms of coherence seeking that just do not belong in science class. In [1.2], T2 opens up a conversation around what constitutes a viable explanation:

[28] See Chapters 5 and 6 for more information about Ms. H's and Ms. F's participation in the Learning Progressions project

> Can't we just say that the cloud's not capable of dumping? That it, the way it rains, or the way it releases itself, it just comes down. That it's not..it's not capable of dumping. It's not *made* that way.

T2 suggests that clouds rain, rather than dump water, because they were made that way. Though she phrases her statement as a question ("can't we just say"), T2's tone drops, not rises, when she says "not capable of dumping." She seems to challenge to the group to develop a reason why her answer is not acceptable, in effect positioning her explanation as the dominant and satisfactory one.

Multiple people respond to T2's comment, but no one directly challenges her comfort with the "clouds were made that way"-type explanation. Instead, T4 and Ms. F refer back to an idea they just shared about cloud formation to show that they have a possible mechanism for how droplets form [1.12]. They suggest that when air rises, it cools at different rates. Since the air rises and cools at different rates, then the liquid water in the cloud must also form at different rates, resulting in droplets rather than a massive dump of water. By constructing a mechanism on the spot for what might explain rain droplets, T4 and Ms. F offer a sort of epistemological response to T2, i.e. *we can do better than the "clouds aren't made that way" story*. In [1.13], T2 acknowledges their effort, but does not verbalize whether she has accepted their mechanistic story.

A few minutes later, T3 again brings up the question of why rain does not fall in buckets:

2.1 T3: So going back to T2's question about why doesn't it just drop, do you think you could uh design an experiment to show a way that water doesn't just drop.
2.2 S1: Good challenge. That's a good challenge.
2.3 T2: But, see, I'm not stuck on that. I'm saying that I don't ever //

I've never thought that the cloud just dumped. Why? Cuz I've never seen the cloud just open up, pour a bucket on her head [gesturing to Sharon], and close up. So I'm saying, I've never seen any evidence of this // sorry S2 // [*S2 and T2 laughing*]. I've never seen that // I mean I've seen--

2.4 T3: Haven't you got rained on though by I mean *huge* amounts, like like like--

2.5 T2: Yeah, but not // but a bucket, I mean literally it's just gonna // its gonna to soak you like I jumped in the pool and it's, I've never seen it. And I'm from the east so I've been through my share of storms. I've never seen it. So I'm just saying, as a student, I would never ever ever go there that saying that it just dumps as a bucket. So I would automatically try to explain the phenomena of all of that stuff and like you said the colder water and separate all that stuff cuz I would have never // it would have never been an issue for me.

2.6 S4: I do think it's // I do think it's something that we have to account for. I just // and you're question is [*gaze in T2's direction*]..what would // how could we account for that?

T2 disregards the droplet/dumping distinction because she has never seen any evidence to suggest that rain ever would dump all at once. In other words, in this moment T2 identifies the presence of, and not the lack of, an event as something to be explained. S4 pushes T2, saying that we do need to develop an satisfactory explanation for why rain does not dump, even though what that explanation might look like has yet to be agreed upon.

In terms of coherence seeking with respect to conceptual information, the distinction between T2, T3, and Ms. F and T4 lies both in what information they would like to connect and how. T3, T4, and Ms. F identify *rain does not dump* as a phenomenon to be explained; T2 does not. T4 and Ms. F seek an explanation that aligns with components of their model for cloud formation [1.12]; Donna seeks an explanation that includes experimental data [2.1]. Finally, and importantly, T3, T4, and Ms. F all express that the question of why rain does not dump is connected to more general questions about rainfall rates. T2 specifically separates the dumping rain question (a phenomenon which she has never observed) from other questions about downpours, etc., which she has observed. And, while scientists might employ teleological reasoning or place phenomena or data in abeyance at times, as a collective they are unlikely to settle on these kinds of explanations as satisfactory end goals of their inquiry, as S2 is apparently willing to do in [1.3, 1.15, 2.3, and 2.5].

Even so, as educators, there are reasons to value S2's work. Among other things, S2's comments indicate a healthy skepticism about the group's inquiry, and her comments forced some of us to consider more carefully our own patterns of thinking. Is the fact that rain occurs in drops rather than all at once really a phenomenon that needs to be explained? If so, what might that explanation do for us, in terms of answering the question why it does not rain often in San Diego? And, finally, what are the criteria for a satisfactory explanation? In our specific discussion, the presence of a competing set of epistemological resources introduced by S2 had resulted in our coming to distinguish two different cloud models: one in which the cloud is a container that fills up with water, and the other in which the cloud is merely a collection of different sized water droplets.

More generally, Bang and Medin (2010) suggest that the presences of "conflicting and sometimes aligning epistemologies" may facilitate learners' "distinguishing, and navigating epistemological resources and their applications" (p. 15). In other words, even if we choose to demarcate some modes of coherence seeking as non-scientific, they might still prove to be fruitful in students' coming to seek other kinds of coherence in science class and serve as a bridge to more commonly accepted forms of reasoning in science.

8.2.3 Thoughts on What Kinds of Coherence Seeking to Foster (or Not) in Science Class

I have argued in the previous sections that a static assessment of coherence seeking will not satisfy educators' needs for understanding and supporting students' progress in science. To briefly recap, the arguments against a static assessment of coherence seeking emerge along three dimensions: i) the multiple and competing goals for science education, ii) our understanding of coherence seeking in expert science, and iii) our understanding of science learning as a complex phenomenon. Based on these arguments, I tentatively concluded that there are no forms of coherence seeking which are absolutely more sophisticated, or uniformly more productive for students' science learning, than others. However, that does not mean that all forms of coherence seeking are equal, or that science teachers ought to allow students to pursue whatever connections they fancy in the moment. Some kinds of coherence seeking are, generally speaking, more likely to be useful for certain educational purposes.

8.2.3.1 Allowing learners to experience the kind of work that scientists do

Consider the opening question that S2 and the rest of the Learning Progressions teachers worked on during the summer workshop: Why doesn't it rain very often in San Diego? In working on this question, one of our educational goals among the project staff was to allow teachers the opportunity to experience the kind of work that scientists do. In other words, we were not planning to write vivid fairy tales to explain how rain forms, nor use drought as a metaphor for difficult periods in one's life. We did not refer to San Diego's agricultural policy documents as part of our inquiry, nor did we express our ideas in the form of a song or interpretive dance. Rather, we hoped that our work on the rain question would 'look like science' in that it would involve the "use of evidence to construct testable explanations and predictions of natural phenomena" (National Academy of Sciences, 2008, p. 10).

So what kinds of coherence seeking must we encourage, if our goal is for students to generate testable, evidence-based explanations with predictive power? In previous chapters, I explained that we might not want to emphasize scientific vocabulary, task instructions, or authoritative sources of information because each of these can distract students from the sources of evidence upon which scientists generally rely (observational data and intuition) and obscure the nature of students' reasoning.

But within the classroom where students are generating and refining explanations based on observational data and intuition, the educator must recognize which kinds of reasoning are likely to ultimately lead to evidence-based, testable, explanations with predictive power, and which are not. The key here is "ultimately lead to"—in other words, while science is ultimately concerned with evidence-based, testable explanations with predictive power—scientific practice need not adhere to all three of these criteria at all times.

For example, a list of factors or patterns, without an underlying understanding of their cause, will not usually have robust predictive power. But identifying patterns can nonetheless be a very productive part of scientific practice. Meteorologist Dean Blake's (1933) early work to understand the origin of San Diego's rainfall was almost exclusively focused on finding patterns in empirical data. Blake collected data from three weather stations in San Diego County: one near the coast, one near the mountains, and one in a valley. By coordinating rainfall data from each of these weather stations, Blake attempted to track the path of storms across the county. He determined that the rain in San Diego generally originates in one of four locations: North Pacific, the South Pacific, the Interior/Great Basin, and western Mexico. Blake was further able to coordinate these empirical findings with Thomas Reed's (1932) system for classifying Pacific Coast storms based on direction and flow of air masses. In other words, in leading the field of meteorology toward evidence-based, testable explanations with predictive power, Blake relied on two key forms of coherence seeking, 1) identifying patterns in rainfall amounts across various geographical locations, and 2) coordinating his empirical findings about rainfall with Thomas Reed's empirical work on air masses. Blake's work demonstrates that searching for patterns in empirical data can be a productive, or sophisticated, form of coherence seeking in science, even though on their own such patterns do not produce robust predictions.

Likewise, in science, we often think of quantitative relationships as more sophisticated or useful than qualitative relationships. It is not enough merely to know that a force applied to a stationary object will cause it to start moving; we would like to know how quickly the object will speed up, and what its final speed will be. So intuitively, it seems that a student who is trying to express quantitative relationships between variables must be engaged in a more sophisticated form of coherence seeking than a student trying to build qualitative relationships; however, that is not necessarily the case.

First, qualitative reasoning can be very useful in developing explanations with predictive power. J.R. Humphrey's work on the origins of San Diego's rain relied heavily on qualitative reasoning. He describes how for example, how the Coriolis Effect determines the direction of prevailing winds, the location of high pressure zones at various latitudes, and the subsidence inversion in San Diego. And perhaps more importantly, his attempts to qualitatively relate temperature, humidity, and rainfall amounts foreshadowed future work on modeling weather as a chaotic system:

> In short, the entire circulation of the atmosphere and of the ocean and the distribution of temperature, humidity, and rainfall are so intimately woven together into one complex interdependent whole that no change could be made in any one without producing a reaction upon all the others." (Carpenter, 1913, p. 74, citing W.J. Humphreys of the United States Weather Bureau)

Again, Humphrey's work demonstrates that while we might ultimately prefer an account of weather that relates temperature, humidity and rainfall quantitatively, our work towards that end goal might necessarily involve qualitative reasoning.

If history of science alone fails to convince educators to evaluate the sophistication of students qualitative reasoning locally, Russ (2006) provides additional evidence. Russ studies a group of college students trying to predict the difference in pressure between the top and bottom of a room. Initially, the students articulate a sensible, qualitative prediction: the pressure at the bottom of the room will be higher than at the top. But as the students turn to equations to solve the problem, they apparently lose all sense of physical reality. They try using the Ideal Gas Law to calculate pressure, and in doing so, they get stuck trying to calculate the volume of the room. The students' use of equations was locally unsophisticated in that it worked against the explicit goal of the curriculum: to foster students' sense-making about the physical world.

In meeting the goal of having students experience the work of science, educators will likely want to at some point support students' causal reasoning, coordination of theory and evidence, quantitative reasoning, reconciliation of inconsistencies, etc. But, in addition, educators must be able to recognize moments when pattern matching, qualitative reasoning, process of elimination, and a host of other forms of reasoning might be evidence of students' locally sophisticated engagement in science. (Or conversely, recognize when students' quantitative reasoning, attention to inconsistencies, etc. is actually inhibiting progress, as in Russ's work). Such dynamic assessments of students' work require careful attention to students' ideas and reasoning in the moment, as well as an eye for where these ideas might lead. The Learning Progressions project attempted to facilitate teachers' growth along these two dimensions via professional development and an associated curriculum. The results of that work are described in Lineback (2012) and in Hammer, Goldberg, and Fargason (in press).

8.2.3.2 The complexities of school science.

Even a simplistic account of science suggests a context-sensitive notion of sophistication, as demonstrated in the previous sections. However, within a science classroom, issues of what constitutes productive or sophisticated coherence seeking become even more complex.

First, educators need to recognize that students' seemingly "non-scientific" ways of thinking can lend themselves to "scientific" ways of thinking later. For example, in Ms. F's class, Baxton's anthropomorphizing of energy (that energy kills each other) led to an argument about the nature of the interaction between positive and negative energy—a piece of their model which had not yet been fully fleshed out. Similarly, Warren et al. (2001) showed how a student improved the design of an experiment to determine whether ants prefer darkness by imagining himself as an ant. And in the rain workshop, S2's claim that clouds do not dump water all at once because they "aren't made that way" led to the articulation of two different cloud models, as previously discussed. Indeed, students bring a range of experiences and ways of thinking into the classroom, many of which have been shown to play a productive role in science class. And the fruitfulness of some resources, including fantasy, narration, and spirituality, have yet to be carefully explored in the context of science class.

A second reason to make space for a variety of forms of coherence seeking in science class is that students may come to better understand one way of thinking by seeing it in contrast to, or in harmony with, another. While working on the San Diego rain question, for example, we recognized that identifying lists of factors could only get us so far, and that at some point we needed to develop an account of what makes rain. Similarly, S2's suggestion that clouds do not dump rain all at once because "they aren't made that way" led to a discussion of what that explanation gets us in terms of understanding why it does not rain very often in San Diego. I do not mean to suggest here that all forms of thinking should be given equal time in science class, or that we ought to present scientific and other (for example, religious) accounts on equal footing. Rather, I suggest that educators and researchers reconsider for example the National Science Teachers Association's (NSTA) position that:

> There is no comparing science and religion because they explain different realms. Students bring many and varied beliefs into the classroom that are neither theories nor testable, and science does not emphasize questions that cannot be tested. (NSTA, 2012, n.p.)

On the contrary, future research might consider if and how students' epistemological awareness of science is actually enhanced, rather than inhibited, by the presence of competing epistemologies in science class.

Finally, school science has many goals, some of which are in apparent tension with each other. In her seminal work on the dilemmas of mathematics teaching, for example, Ball (1993) explains how she navigated tensions between representing mathematics content, respecting children as thinkers, and developing a sense of community in the classroom. Similarly, Hammer (1997) describes how he negotiated the sometimes competing goals of fostering students' inquiry and supporting their learning of traditional content knowledge in a high school physics course. And a clear breach of traditional school science boundaries, Calabrese-Barton et al. (2003) articulate how their instructional plans for an after-school science program had to be modified in order to allow students to construct a practice of science that is meaningful and transformative to them. For example, one student takes the supplies to build a bird house and makes a desk instead. Another group of students, upon being told they cannot build a clubhouse, decide to build clubhouse furniture. In each of these moments, Calabrese-Barton and her colleagues had to make difficult decisions about what ideas, reasoning, connections, and projects to foster, and which to re-route, all with an eye toward their educational goals.

So, returning to the opening question, what kinds of coherence seeking should educators foster (or not) in science class? Surely, if an all-encompassing list—complete with every potentially productive form of coherence seeking in science class—could even be generated, it would certainly be too long to be useful. Furthermore, any such list would mischaracterize the "inherent uncertainty" of "intellectually honest" teaching (Hammer, 1997, p. 490; Ball, 1993, p. 394). Thus, I suggest rather simply that educators approach students' coherence seeking as a rich terrain to explore, whereby their instructional decision-making includes a careful consideration of the kinds of information students connect, the ways that they connect it, and the possible places to which these connections might lead. Finally, if we want students' inquiries ultimately to lead to the sorts of coherence seeking that seem to be productive in science, then we also need to reconceptualize what coherence means in science curricula.

8.3 Re-thinking What Coherence Means in Science Curriculum

Curriculum lies at the core of educative tools to support student progress. Recently, educators have sought to incorporate the idea (or perhaps ideal) of coherence into science curricula. According to Beane (1995):

> A 'coherent' curriculum is one that holds together, that makes sense as a whole; and its parts, whatever they are, are unified and connected by that sense of the whole. (p. 3)

The push for coherent curricula stems largely from the problem identified at the outset of this dissertation—that students seem to see science as a collection of disconnected facts. The NRC (2007) Report *Taking Science to School* blames poorly organized curricula that marches students through a series of topics, facts, and equations without any apparent connection between them for students' perceptions of science. Thus, a variety of projects have worked to develop so-called "coherent curricula" which consist of carefully sequences activities and lessons designed to help students see relationships between ideas, and also see big ideas and underlying principles that cut across different disciplines of science. According to the recent Science Frameworks (2012):

> An important aspect of coherence is continuity across different subjects within a grade or grade band. By this we mean "sensible connections and coordination [among] the topics that students study in each subject within a grade and as they advance through the grades" [3, p. 298]. The underlying argument is that coherence across subject areas contributes to increased student learning because it provides opportunities for reinforcement and additional uses of practices in each area. (p. 306)

However, the perspective on coherence seeking that I have outlined in this work is fundamentally at odds with coherence as conceptualized in current science curriculum and the frameworks, for three key reasons:

1. A universally coherent curriculum cannot exist because coherence is perspective-dependent.

2. Coherent curricula are built on the assumption that scaffolding is required for students to seek coherence, rather than on the assumption that students are always seeking coherence with respect to something.

3. In asking students to build particular connections, often toward canonically correct understandings, curriculum designers fail to attend to the epistemic purposes of students' coherence seeking.

8.3.1 A Universally Coherent Curriculum Cannot Exist

Researchers spend years, and significant financial resources, painstakingly constructing new, sensible sequences of instruction for students. Each curriculum includes its own organizing structure: benchmarks and curriculum blocks (Ahlgren & Kesidou, 1995), key/big ideas (Shwartz et al., 2008), projects (Nordine, Krajcik, & Fortus, 2010), etc. From the designers' perspectives, these sequences hang together, illuminate underlying connections between phenomena, and are thus coherent. However, we have good reason to question whether these connections, even when made explicit, are actually coherent to students.

In their work on evaluating the coherence of students' mental models, Vosniadou and Brewer (1992) note that "what may appear as contradictory and inconsistent from the adult or expert point of view may not be contradictory from the point of view of the child" (p. 580). That is, assessments of coherence depend on the knowledge and experiences we bring to bear in that moment, as well as the "frame of reference against which we judge whether an appropriate range and selection of phenomena are covered" (Sherin, Krakowski, & Lee, 2012, p. 27).

When educators construct curricula, they draw on their vast experiences in science, their philosophies of science and learning, and importantly, their carefully reflection and search for underlying connections and themes within the content area(s) of interest. Indeed, "the connectedness of things is what the educator contemplates to the limit of his capacity" (Van Doren, 1959). Often, these connections were not even apparent to the educators while learning the subject, but were constructed as part of their teaching practice. Marion Brady (1995) describes her own search for coherence in designing a novel curriculum framework:

> How do I begin to understand—make coherent—such varied experience? We make sense of experience by breaking it into intellectually manageable pieces, pieces we call occurrences, events, incidents, accidents, happenings, movements, situations, things, actions, eras, ages, this moment. When we want to be more specific, we give these parts of reality more precise conceptual labels—call them wars, volcanic activity, elections, chemical reactions, marriages, writing articles. When we want to be even more specific, we name the parts: The Battle of Bull Run, Mount Saint Helens' eruption, Woodrow Wilson's margin of victory, the World Trade Center bombing, "that Charles and Di thing," a piece for the 1995 ASCD Yearbook called "A Supradisciplinary Curriculum" (p. 27)

In curricula with pre-determined sequences of topics, students are often asked to set their own questions and coherence seeking aside to preserve the "coherent" sequence learning goals. Even if students try to build connections between these activities, or teachers make some connections explicit, it is unlikely that the sequence holds together for students in the same way that it holds together for the designers of the curriculum.

8.3.2 Coherent Curricula are Built on the Assumption that Scaffolding is Required for Students to Seek Coherence

Designers of coherent curricula speak as though students need support in order to start building connections between information, or even more problematically, that the curriculum itself must make these connections:

> To build integrated understandings, instruction must be built from coherent curriculum. To be coherent, curriculum must align with learning goals based on a set of core scientific ideas while avoiding nonessential information, making connections between new ideas and prior knowledge explicit, connect evidence to scientific ideas, and connect the ideas of science to the natural world. (Nordine, Krajcik, & Fortus, 2010, p. 675)

According to Nordine et al., integrated understandings are only achieved through carefully constructed curriculum. The curriculum should lay out the pieces and relationships between those pieces in order to help students see science as more than disconnected facts. Their view characterizes many existing approaches to coherent curriculum.

In prior chapters, I argued using studies from perceptual processing, psychology, and studies of language and reading comprehension that people are always seeking coherence with respect to something, and so I will not recap all of those points here. But briefly, we know that students constantly build understandings that are integrated to them, even if not evident to the outside observer (Gomez, Benarroch, & Marin, 2006). Students coordinate many kinds of information in science class, and information about the physical world as conveyed by the teacher, the text, or the curriculum are but small pieces of that information set. Ironically, the fact that students see science as a set of disconnected facts is precisely evidence of this coherence seeking among their years of experience in the typical science classroom.

8.3.3 Coherent Curricula May Reinforce the Message That Science is a Collection of Disconnected Facts

In asking students to build particular connections, often toward canonically correct understandings, curriculum designers fail to attend to the epistemic purposes of students' coherence seeking. Standards documents and curriculum work cited in this chapter explicitly aim to help students build connections between information and experiences in their science classes. Importantly, many of these projects also hope that students will come to value and to actively seek coherence (including consistency, connections, and a sense of wholeness) in science class. But when curriculum designers ask students to build *particular* connections, to seek *particular* kinds of coherence, these conceptual and epistemological goals are in tension, and this tension can manifest in a number of ways in the classroom.

Shwartz et al. (2008) explain that pre-determined sequences of activities generally favor particular connections chosen by curriculum designers over students' own coherence seeking. For example, in one of their Investigating and Questioning our World through Science and Technology (IQWST) curriculum modules, Shwartz et al. ask students to generate and categorize questions about light. During the activity, we can imagine the class focusing in on one question, generating plausible answers to that question, and then finding ways to test and refine those answers. Or, the class might begin to sort and categorize their questions, and in the process consider which types of categories are meaningful and useful. Both of these possible next moves are characteristic of productive disciplinary engagement in science (Engle & Conant, 2002).

However, the IQWST curriculum requires that as a next activity, students sort their questions into pre-defined categories, which relate to important conceptual learning goals, for example: "How does light let me see? How does light interact with matter? (Shwartz et al, 2008, p. 16). While these questions might lead to particular concepts about light, as well as open up opportunities to engage in scientific practices, they also are also limiting in an epistemic sense. More specifically, in constraining how students work with their own questions about light, the IQWST curriculum limits students' opportunities to negotiate what ideas and experiences about light should be connected, and how they should be connected.

Constructivist accounts of learning hold that students build new knowledge from existing knowledge, but the question I have raised repeatedly throughout this dissertation is—what information are students trying to connect? Coherent curricula like IQWST focus on students' attempt to connect conceptual information, with little attention to for example, the epistemological information that students try to process, or how the two might interact. And in the most extreme examples of curricula that carefully sequence or "fabricate" coherence, students may eventually come to see connections as facts to be memorized, thus ironically positioning "coherent curricula" as part of the problem they are meant to solve (Buchmann & Floden, 1992, p. 8).

Unlike existing approaches to coherence curriculum, a curriculum that aligns with the perspective on coherence seeking outlined in this work must: i) recognize that students are always seeking coherence, ii) consider coherence from the students' perspective, and thus iii) consider how students' seeking of connections between conceptual information intertwines with their seeking connections between epistemological, social, material, affective, etc. information. The Learning Progression modules were an attempt to create such a curriculum.[29]

8.4 Summary of Implications for Teaching and Research

The implications discussed here—characterizing progress in science and curriculum design—lie at the intersection of education research and practice. I have argued that coherence seeking might be a fruitful constructing for re-uniting disciplinary practices, an achievement which is both highly sought after and elusive.

[29] I first presented these arguments in *A case for reconceptualizing coherence in science curricula. Paper presented at the National Association for Research in Science Teaching Annual Conference, March 2012, Indianapolis, IN.*

Further, coherence seeking may also be useful for developing a context-sensitive notion of sophistication, a notion which will affect not only how researchers code students' reasoning, but perhaps more importantly how teachers evaluate and respond to it. Finally, the perspective on coherence seeking outlined in this work implies that attempts to develop so-called "coherent curricula" are misguided, and quite possibly counterproductive.

8.5 Concluding Remarks

The goal of this study was to create, refine, and illustrate a perspective on coherence seeking in order to better understanding how students make sense of physical phenomenon. That perspective consists of i) assuming students are always seeking coherence, and ii) recognizing coherence seeking as a dynamic activity. As a result of applying and refining that perspective in response to classroom data, I found:

- Much of the coherence seeking we proclaim to care about in science education (such as distinguishing between competing ideas) are not captured by existing frameworks, but are captured by the perspective offered in this dissertation.
- Some of the coherence seeking we generally ignore or discourage in science education (such as reaching consensus for social reasons, or building non-canonical ideas) may actually play important roles in students' coming to engage in the work of science.
- The sophistication of students' coherence seeking cannot be meaningfully determined without taking into account the context in which that coherence seeking occurred, and possibly also what followed it.

- Our perceptions of students' intent likely influence our interpretations of what information they are trying to connect; more generally, additional work to understand what meaning and purpose *students* attribute to the relationships they try to build is warranted.

And finally, the recognition that students are always seeking coherence may serve as some relief to educators concerned that students see science as a set of disconnected facts. Indeed, no longer needing to 'fabricate' coherence for students in the form of carefully constructed curricula, educators may instead focus on carefully understanding and supporting the connections that students already seek.

Appendix A: Example Analysis Describing "Evidence of Coherence Seeking" As a Dichotomous Category

The following analysis comes directly from a course paper I wrote during the Fall of 2009 (EDCI 771, Instructor David Hammer), titled *Stance as an "Upper Anchor" for a Learning Progression in Scientific Inquiry*. I have marked in bold the language indicative of a dichotomous view of evidence of coherence seeking, and underlined language indicative of a degree-of-membership view.

Episode Title: Water vapor or steam?
Data Source: Ms. H's 5th grade class, Year 1, Water Cycle Module

During the puddle experiments, many students reported seeing some sort of "stuff" rising off of the puddles. On the third day of the module, Ms. H leads a discussion of what this "stuff" might be. Most of the students decide the stuff is "water vapor." Ms. H asks the students to work in small groups to explain how they know it is water vapor:

> [1] Leah: (inaudible) in the puddle, and then there a vapor that comes out so it's water vapor.
> [2] John: Well, how do you know it wasn't like a breeze of sand or something?
> [3] Ari: Because um, it, it- have you ever seen a pan or water boil how coming off? It looked like that,
> [4] Leah: Mhm…
> [5] John: It looked very much like it was steam.

Leah begins with a sort of tautological argument—the stuff is vapor that comes from water so it must be water vapor [1]. <u>The contribution might be evidence of coherence seeking in a textual or linguistic sense, but provides no evidence of coherence between *ideas*</u> (Trabasso, Secco, & Van Den Broek, 1982). Her comment might also indicate a sort of disdain for the task, as though it is pointless or already resolved. John challenges Leah to explain away the idea that the stuff is sand, and **this is evidence of seeking coherence**. **The coherence seeking continues** as Ari jumps in to point out that the stuff coming from the puddle looked like the stuff coming from boiling water. The group begins to dismantle the idea that the stuff is steam:

> [6] Ari: But, I knew that it wasn't steam because um
> [7] John: Steam- it wasn't boiling.
> [8] Leah: No.
> [9] Ari: Because I- if it was boiling we would be…
> [10] Leah: It would be bubbling. Bubbling. (Ari: We would be a little bit)
> [11] Ari: warmer.
> [12] John: It would be bubbling.
> [13] Ari: It'd be a tad warmer out there.
> [14] Leah: A tad.
> [15] Molly: And the water was colder than the actual ground.
> [16] Ari: Yea, and also, um, we didn't see any bubbling
> [17] Molly: Yea.

The pace of the exchange, though not captured here, is remarkable. The students build off of one another, and in rapid succession. In Ford's (2005) terms, all four students seem to quickly recognize the "game" they are playing. The game is as follows: considering the evidence that might support the idea that the stuff is "steam", and then show that the evidence is absent: the water is not bubbling, it was not hot enough outside, and the water was cool. This game—systematically showing how the evidence does not fit with the theory—is <u>**essentially a game of coherence seeking**</u>. And despite research suggesting that students are unable to distinguish theory and evidence (Kuhn, 1989), in this instance, the focus group is clearly playing that game well. The group also takes on the idea that the stuff is sand:

> [18] Ari: so it- we didn't think it was sand because it was coming actually like off of the puddle.
> [19] Molly: Yea up not like…
> [20] Ari: And we, and we…

[21] John: Well it came up for a little and then the wind pushed it in a certain direction.
[22] Molly: Ya then it came up and out.
[23] Ari: And we, and we definitely, um, and if it was sand, we didn't see any sand zooming up off the soccer field.
[24] Molly: Yea.

The stuff cannot be sand, the students reason, because the stuff came *from* the puddle, and not from anywhere else. Even so, Leah suggests that they should have swept the ground before starting the experiment:

[25] Leah: Maybe we should have swept it- the areas that we poured it in before.
[26] Molly: Maybe.
[27] Ari: But, um…
[28] John: Well how would we do that without a broom?
[29] Ari: But from previous experiments of when we would, when we uh, made the water evaporate in the Petri dishes with the salt and stuff, the salt did not, salt, and like, I don't think salt or dirt would evaporate with the water. Just the water would. It even separates solutions. So…
[30] Molly: Okay, who's gonna say that?
[31] John: Ari, because he came up with it.

Leah's suggestion to sweep the testing area is surprising. She previously argued that the stuff must be water vapor because it is vapor coming from the water. However, she seems unwilling to accept a natural extension of that argument—if the stuff came from the water, then it cannot be sand. Her reasoning might be that they should sweep the area "just in case." But, John points out the pragmatic problem of not having a broom. Ari's next statement discounts the need for a broom, and **is very clear evidence of coherence seeking**. He recalls that they previously conducted an evaporation experiment with salt water—the water evaporated and the salt did not. He expects this result to be consistent in similar situations, that is, even if the sand were in the testing area, it should not evaporate. The students seem impressed by Ari's idea, and nominate him to share with the whole class [30, 31].

Appendix B: Annotated Transcript of a Focus Group Presentation

As described in Chapter 3, my attempts to distinguish between evidence of coherence seeking and evidence of sophisticated or productive coherence seeking were hindered by a sort of bias in my episode selection. I tended to overlook clips that did not contain what I intuitively felt were rich examples of coherence seeking.

For example, the following episode comes from Ms. H's 5th grade class on the last day of her Year 1 implementation of the water cycle module. On that day, Ms. H asked students to look into their minds, books, on the computer, etc. for more information about weather and the water cycle. The students then presented the information they found to the rest of the class. I initially ignored the presentations because students just seemed to be reciting information that they copied out of the textbooks. Though I could articulate how what the students were doing was still a form of coherence seeking, it just did not seem that interesting in terms of their trying to build a coherent, mechanistic account of weather. Instead, it felt like the students were just "doing school."

The presentation format, with the focus group (Leah, John, Molly, and Ari) standing at the front of the class, also seemed to close off, rather than opening up, collaborative inquiry. In fact, that formal presentation mode rarely occurred during Ms. H's implementation of the module; usually, the groups shared ideas from their seats. But during these more formal presentations, the audience was very (and unusually) quiet, and the focus group looked uncomfortable. Again, there were many episodes like this in the Learning Progressions data, which I generally overlooked. However, as indicated in the annotations below (in italics), these clips could be useful in continuing to refining the framework for coherence seeking, especially in terms of thinking about how I support normative claims about students' work and reasoning.

1 Leah: Okay, so uh we found some stuff in a book.
2 John: It's called, "The Weather Engine."
3 Leah: And it said that [*reading from chart*] "If the temperature of the air below a cloud is higher than the freezing point, the water droplets begin to fall as rain. If, if it is below the freezing point, ice crystals stay frozen and fall as snow or freezing rain. Hail only occurs in large clouds with powerful air currents. As the air currents swirl, layers of ice build up and hail stones grow."

I wondered whether Leah and her group mates came up with this explanation themselves, or whether they copied it directly out of the book. To me, copying seemed like a less useful sort of coherence seeking than creating an explanation based on readings from different sources. The video from the group work before the presentations revealed that John was the only student in the group who read *The Weather Engine* (Morrison, 2003). While he was reading, he put sticky notes on the pages to indicate which ones Leah should copy onto the group's chart paper. However, because the sticky notes did not indicate specifically which sections to copy, John later read the passages to her directly as she copied them onto the group's chart paper.

4 Ms. H: So how many of you understood what they just said? *[one student shakes his hand as in "so-so"]*
5 Molly: And I created a picture. *[pointing to parts of the picture as she speaks]* This is a small cloud and it's below the freezing point and it creates the snow and this is the large cloud with the powerful air currents right here and it creates hail.

Unlike the explanation, which was copied directly from the book, Molly created her picture on her own while Leah was writing the explanation. She would periodically look up at the words, then draw something, then look back at the words, and continue drawing, etc. In line 4, Ms. H asks if the class understands what was said. That move reinforces the presentation-mode of the class. Molly, perhaps sensing that the explanation has not been understood, refers to her picture possibly in the hopes of clarifying the group's ideas and saving the presentation. The students' attention to social dynamics seems to occlude their sense-making with respect to ideas about weather.

6 Ms. H: So it's powerful air current withIN the cloud?
7 Molly: Ummm
8 Ari: Yeah. It the--
9 John: [opens book]
10 Ms. H: You're having to go back and look.
11 Ari: Um, it's inside the cloud. [John directs Ari to a paragraph in the book. Ari reads quietly.]

The students apparently have not considered Ms. H's question about the placement of the air currents. Interestingly, rather than try to generate an explanation from their drawing or together using their own senses, John immediately refers to the book as the authoritative source of knowledge. Ms. H appears to sanction his turning to the book for an answer. Again, in a moment where the students could draw on their own ideas to make sense of the air currents in the cloud, instead they turn to an authoritative source of knowledge. That alone does not make what they are doing unsophisticated, but it was the type of observation that initially led me to overlook this clip.

12 Ms. H: So now do you think // Ari. Do you think ONE book's going to be enough or do you think you need to look on a lot of things to double check.
13 Molly(?): A lot.
14 Ari: Um, I looked al // I also was reading a book and I was reading, or seeing what hail is, hail and it said stuff along that lines but worded differently. [John holds up the book Ari was reading, and passes it to Ari. Ari opens the book.]

Ms. H suggests a particular kind of coherence seeking—to check for consistency between multiple sources. But Ari jumps in to clarify that he did read another book, and in fact, it said something similar to the Weather Engine. He seems to be trying to provide evidence that he did his due diligence as a student, rather than providing additional evidence about the dynamics of clouds.

15 Ms. H: So did hail definitely need wind?

In what becomes obvious later in the clip, Ms. H begins a leading line of questioning in 15. Earlier in the conversation, students claimed that the formation or presence of snow fall requires wind. Ms. H has recognized that the focus group's explanation and drawing contradicts the idea that snow requires wind; she uses a line of questioning to draw students' attention to that inconsistency.

16 Ari: Yeah.
17 Molly: Yes.
18 Ms. H: Did snow need wind?
19 Molly: No. [Leah shakes her head no]
20 Ms. H: So maybe write "wind" on that big cloud and no wind on the small one. Would that clear it up a little bit? So did that fit with what people were thinking or not? [Molly adds "no wind" to the small cloud in the picture] Megan, what do you think?
21 [Ari shows something in the book to Molly, then makes a gesture on the picture in a swirl pattern. Molly adds some sort of writing next to the big cloud.]
22 Mia: Kind of, yeah.
23 Ms. H: Kind of, but wasn't Colin over here // and Chuck was going, "Have you ever seen it snow and it only goes at a diagonal." What did the diagonal mean?

In [23], Ms. H signals that Mia's response is not sufficient, because in fact the idea that hail requires wind and snow does not contradicts Chuck's observation that snow only goes at a diagonal.

24 Alan?: The wind was pushing it.
25 Ms. H: The wind had to have been pushing it. Did Molly say we

needed wind to have snow?
26 Student B: No.

Like Mia in [22], Student B in [26] provides short answers to Ms. H's questions. The dynamic seems to follow the initiate-respond-evaluate style of questioning.

27 Colin: Also there needs to be that freezing point. I went on the internet and looked at freezing point. It was [ruffling through papers] uh 32 degrees for hail and 30 degrees for snow.

Colin breaks the IRE pattern established in previous lines. He points out that like the wind/no wind requirement, there is also a freezing point requirement for hail and snow to form.

28 Ms. H: 32 for sno // hai // okay so Molly, in that cloud, hail, write // hail was what? 32?

The focus group's chart paper has become established as a tool for keeping track of ideas, as Molly continues to modify it in response to Ms. H's suggestions, but it also shapes the class's thinking, as most of the utterances relate directly to some aspect of the artifact. In other words, the artifact bounds what information students draw on in the moment.

29 Colin: Hail was 32.
30 Ms. H: Hail was 32 and snow he said was
31 Colin: 30.
32 Ms. H: 30.
33 John: And we also found some stuff about temperature. And it says, "Sinking air prevents clouds formation, but rising air increases it. So high pressure therefore means clear sunny weather and low pressure usually means cloudier weather."

John demonstrates a coordination of both conversational and social norms in utterance 33. First, he introduces his statement with a preliminary "and we found out some stuff about temperature." However, in the information that follows, he does not refer to temperature. John appears to use the term temperature to connect back to

Colin's point about freezing point not in substance, but to adhere to the conversational norm that what comes next ought to follow what was said before. Possibly, John sees a substantive link as well—that sunny and cloudy weather correspond to different temperatures. John's utterance in [33] also marks the completion of a presentation norm—to share all information that is recorded on the chart paper.

34 Ms. H: So, then what kind of air pressure do you think we have this morning?

Again, Ms. H opens an initiate-respond-evaluate (IRE) line of questioning. Her questions may serve the dual purpose of 1) asking students to connect the information they have read to their everyday lives, and 2) check that students were actually paying attention to John's utterance in [33].

35 John: Probably...
36 Ari: Um, high pressure.
37 Ms. H: Was it really cloudy this morning?
38 Molly: Yeah.
39 Ms. H: So what kind of air pressure?
40 John and others: Low pressure.
41 Ms. H: Low. What do you think we have now?
42 Students: High.
43 Ms. H: Or at least
44 John: High-er.
45 Ms. H: In the middle, maybe higher. K. Alan?

This little segment [lines 34-45] seems separate from the rest of the conversation in terms of conceptual substance. The high/low pressure questions are self-contained, and do not connect back to the larger picture that students are building about weather. However, in terms of social norms, the questions reinforce the presentation mode and also the IRE discourse pattern.

46 Alan: So, my hypothesis was right about the // you know the little ice

thing, oh hail. Well, it can't be 32 degrees in um San Diego.

Again, like Colin, Alan jumps in with a point that seems important to him. Previously, Colin said that hail comes from somewhere else and lands in San Diego. Alan apparently has taken Colin's data as evidence for his idea, because if hail requires a temperature of 32 degrees, and San Diego is not 32 degrees this time of year (hail had occurred the week before in San Diego), then the hail must come from somewhere else. His sense-making seems to center around the phenomena of hail and its source, rather than around the information in the focus group's presentation.

47 Ms. H: So both of em can't be
48 Alan: so it must have been some from somewhere else (*** ***)
49 Ms. H: So where would it have had to have been 32 degrees?

Again, Ms. H asks a closed question, and as indicated in [51], she has a pre-determined answer in mind.

50 Student: Cold places!

The students point out that the hail must have come from a cold place. The comment is important because students might have posited that the hail blows in from a cold place like Alaska. Instead, Ms. H directs them to the idea that the air is colder higher up in the atmosphere, and idea that appears in the state science standards.

51 Ms. H: But the cloud's above me...Okay, wake up it's Friday afternoon, we're almost done. Where must it be 32 degrees? The cloud's above me and I'm getting hailed on.
52 Student: In the cloud.
53 Ms. H: Dunn.
54 Dunn: Well, I was just wondering cuz of do you know what the temperature it was when it was hailing on the freeway? Cuz I--
55 Ms. H: The other day, it was 50s/60s at ground.
56 Dunn: And that said thirrrrtyyyy twooo for it to be hail.

Dunn has stumbled upon the same inconsistency that Alan and Ms. H are talking about, but apparently without recognizing that to be the case. Perhaps he is adding to the conversation a specific case of when hail occurs on a warm day.

57 Chuck: It could be up in the air like by // like how it said the pressure in the clouds. The wind could be up in the air.

Chuck's idea seems to fit Ms. H's appeal for students to notice that the cold air could be up higher in the sky. However, the details of Chuck's idea are unclear. He mentions pressure, but does not elaborate on that term. He also comments that wind could be up in the air, which happens to align with the picture Molly drew on the chart paper.

58 Ms. H: So, ok so Chuck, do you guys want to use that? Go.
59 Chuck: Well, cuz it said the um
60 Ms. H: Chuck. You guys can move up and explain it then, to feed in. [Chuck's group comes up. The focus group sits down.]

Clearly, even a preliminary analysis reveals some interesting aspects of the students' coherence seeking in the episode. In particular, the episode brings to light considerations about how students bound what information is in play in the moment. The focus group's written work dominates the earlier part of the conversation, but Colin and Alan both bring in information from earlier in the conversation. There are local moments of coherence seeking around conceptual information (for example pressure) that seem disconnected from the larger conversation. And, the focus group does a lot of work to coordinate social and affective and material information, possibly at the expense of their coordinating conceptual information.

My initial failure to even notice or transcribe this episode even late into my dissertation study demonstrates how my perception of *quality of coherence seeking* intersects with my perceptions of *evidence of coherence seeking*. Because I saw the clip as an example of completing school-ish tasks like presenting and copying information out of a textbook, I failed to recognize it as a possibly useful source of data for evidence of coherence seeking more generally. As a result, I nearly missed the opportunity to carefully consider why copying information out of a textbook seems unproductive, and if and when that normative judgment is actually justified. What is it about copying that seems limiting in terms of students' sense-making? Could copying information prove to be a useful aspect of students' sense-making? Or scientists' work? Future work might explore these kinds of clips in more detail, to consider not only what they can say about evidence of coherence seeking, but also to inform the conversation around how we judge the sophistication of students' engagement in science.

Appendix C: Summary of Episodes Presented in the Dissertation

Chapter 2

Title: Raphael's Cloud Story
Description: Raphael spontaneously connects together conceptual ideas about the water cycle into a cyclical narrative
Source: Ms. M's 5th grade class, Water Cycle Module, Year 1, Learning Progressions project

Title: Darcy's Ideas about the Shape of the Earth
Description: During a clinical interview, Darcy modifies her answer in response to interviewer's demands.
Source: Vosniadou and Brewer (1992, p. 570)

Chapter 3

Title: Raphael's Cloud Story (see previous)

Title: Jason and the Magnets
Description: Jason identifies an inconsistency in and requests reconciliation of a classmate's idea that magnets contain electricity.
Source: Ms. B's 4th grade class, Batteries and Bulbs Module, Year 1, Learning Progressions project

Chapter 4:

Title: Evaporation in Winter
Description: Nate constructs a question about how evaporation can happen in winter as he speaks.
Source: Ms. H's 5th grade class, Water Cycle Module, Year 1, Learning Progressions project

Title: Jacuzzi Analogy
Description: Leah spontaneously constructs an analogy to explain the strange experimental finding that cold water evaporates faster than hot water.
Source: Ms. H's 5th grade class, Water Cycle Module, Year 1, Learning Progressions project

Title: "You skipped a line!"
Description: An example of seeking linguistic coherence while reading an explanation for how a bulb lights.
Source: Ms. F's 4th grade class, Batteries and Bulbs Module, Year 2, Learning Progressions project

Title: Cork/Corkscrew
Description: A student recognizes he has misspoken while presenting his group's ideas about weather and evaporation.

Source: Ms. H's 5th grade class, Water Cycle Module, Year 1, Learning Progressions project

Title: Clouds cold
Description: Raphael uses a preliminary to introduce his question about how clouds can be cold when they are close to the sun.
Source: Ms. H's 5th grade class, Water Cycle Module, Year 1, Learning Progressions project

Title: Questions!
Description: Leah tries to get her group to come up with questions about evaporation.
Source: Ms. H's 5th grade class, Water Cycle Module, Year 1, Learning Progressions project

Title: "Dear World Science News"
Description: Student work coded as "incoherent" in the Davis (2003) coding scheme.
Source: Davis (n.d.), Available online at:
http://www-personal.umich.edu/~betsyd/CoherenceCoding.pdf

Chapter 5

Title: Which evaporates faster—a "3 ounce" puddle or a "6 ounce" puddle?
Description: Episode from an experiment during which students predict that the asphalt from which water evaporates will be warmer than the surrounding asphalt; their results suggest the opposite.
Source: Ms. H's 5th grade class, Water Cycle Module, Year 1, Learning Progressions project

Title: Daylight Savings Time
Description: A student explains the cause of the seasons during a clinical interview.
Source: Sherin et al. (2012)

Title: Write down your theories
Description: A student tries to explain a strange experimental result while his peers mates focus on "writing theories."
Source: Ms. H's 5th grade class, Water Cycle Module, Year 1, Learning Progressions project

Title: Which evaporates faster, hot or cold water?
Description: Students disagree over the validity of the experimental finding that cold water evaporates faster than hot water.
Source: Ms. H's 5th grade class, Water Cycle Module, Year 1, Learning Progressions project

Title: Jacuzzi Analogy (see episodes for Chapter 4)

Chapter 6

Title: Newton's Third Law Tutorial
Description: Students try to make sense of curriculum designers' intentions while completing an introductory physics laboratory tutorial.
Source: Conlin, Gupta, & Hammer (2010)

Title: Train Analogy
Description: A group of teachers tries to incorporate instructor's directions into their analogy for how a simple circuit works.
Source: Professional Development Summer Workshop, Year 1, Learning Progressions project

Title: Killing Analogy
Description: A complex interaction between two students over whether "positive and negative energy" can "kill each other" to make a bulb light.
Source: Ms. F's 4th grade class, Batteries and Bulbs Module, Year 2, Learning Progressions project

Chapter 7

Title: Chemical Reactions
Description: A string of Baxter's utterances about how a bulb lights.
Source: Ms. F's 4th grade class, Batteries and Bulbs Module, Year 2, Learning Progressions project

Title: Anne tries to light a bulb.
Description: A series of screen shots demonstrating non-verbal evidence of coherence seeking.
Source: Ms. C's 4th grade class, Batteries and Bulbs Module, Year 1, Learning Progressions project

Chapter 8

Title: What we agree on
Description: The group of teachers and staff tries to establish a set of ideas we all agree on related to the question of why it rarely rains in San Diego.
Source: Teacher Professional Development Summer Workshop, Year 3, Learning Progressions project

Title: Clouds weren't made that way
Description: A teacher suggests that clouds do not dump water all at once because 'they weren't made that way.'
Source: Teacher Professional Development Summer Workshop, Year 3, Learning Progressions project

Appendix A

Title: Water vapor or steam?
Description: The focus group discusses possibilities for the identity of the "stuff" they observed rising up off a puddle on a hot day.
Source: Ms. H's 5th grade class, Water Cycle Module, Learning Progressions project

Appendix B

Title: Focus group shares ideas about weather
Description: On the last day of the water cycle module, the focus group presents information they have read about weather to the rest of the class.
Source: Ms. H's 5th grade class, Water Cycle Module, Learning Progressions project

Appendix D: Table of Evidence of Coherence Seeking

Operational Definition	Relevance	Example from Classroom Data
Notice an (in)consistency between • two or more pieces of information • a claim, prediction, or explanation and one or more pieces of information	Seeking coherence involves checking that ideas and information are mutually consistent. Noticing an inconsistency, whether intentionally or spontaneously, can be first step towards resolving the inconsistency. In addition, noticing the inconsistency is evidence that students are aware of something that just "doesn't make sense." Often, this form of evidence is concurrent with "Draw attention to an inconsistency."	a. A student identifies an inconsistency between two pieces of information (electricity goes through metals, magnets are metal) and another student's claim that magnets have electricity in them. He brings this inconsistency to the attention of the teacher and the class: *"…how could a magnet have electricity in it because, isn't a magnet metal too? sort of? If it had electricity in it, it would go out. Because once electricity hits metal it goes, it keeps going in the metal until it goes—until there's no other metal on to for it to travel through and then it goes out."*
Draw attention to an (in)consistency	Bringing the (in)consistency to the attention of others indicates that an (in)consistency is a worthy object of discussion, and also allows for possible reconciliations; often, this form of evidence is concurrent with "Notice an (in)consistency"	b. A group of students are copying experimental data from a "group paper" to their individual papers. A student interrupts this process to point out an inconsistency between

		his expectation (a puddle with twice as much water takes twice as long to evaporate) and experimental results (the puddles evaporate in about the same time): *“You know what's probably really interesting…you would think that, let's say that three inches evaporated in five minutes…then wouldn't you think that the six inches would evaporate in ten minutes?”*
Request reconciliation of an inconsistency	This move explicitly indicates that the inconsistency is something that must be resolved, or reconciled. Requesting reconciliation can also take the form of a challenge to another person’s explanation or argument.	*“…since the the clouds are so high, high up and it's cold, and the sun, and they're closer to the sun than we are, why is it cold?”* The student requests reconciliation for the inconsistency that clouds are cold even though they are “closer to the sun than we are.”
Offer reconciliation of an inconsistency	These are bids to increase the mutual consistency between ideas and information. These offers may be explicit or implicit, and can involve, among other things, identifying relationships between the potentially conflicting	A student finds that, contrary to his prediction, the asphalt from which a puddle evaporated is cooler than the surrounding asphalt. He offers a reconciliation: *“I think the water kind of acted like a cover for the asphalt for a few*

	information. This is one of the broadest categories of evidence—attempts for reconciliation occur during the development of explanations, models, criteria for the evaluation of evidence, experimental designs, etc.	*moments. So it, so that it, so this [asphalt] started to heat up, so it was like putting a cover over this so this doesn't heat up as fast...”*
Indicate that a result or observation is unexpected	Surprise may indicate a violation of expectations, or the lack of an anticipated outcome. The anticipated outcome may be grounded in expectations of consistency between ideas, experience, and information.	A group of students are investigating whether temperature affects the evaporation time of water. They find that puddles of cold water evaporates faster than puddles of warm water, and are surprised by the result: *“Student 1: Coldest evaporates first. The warmer it is, the slower than the cold.* *Student 2: That's weird.* *Student 1: Yeah that is weird.”*
Attend to the fairness of experimental condition	Concern for fairness of experimental conditions may involve both attention to consistency and the formation of relations between information. Inconsistencies in results may be due to experimental inequalities. Information that is not acquired in a “fair” manner may not be subject to integration into explanations,	a. Upon finding that a puddle of cold water evaporates faster than a puddle of warm water, a student expresses concern about the experimental conditions: *“I don't like the test area. I thought the test area [for the two puddles] was way too different.”*

	theories, models, etc. Likewise, information that is acquired "fairly" must be related to other information.	The students repeat their experiment on a different test area and confirm the result that cold water evaporates first.
Suggest or actually attempt to confirm an observation or experiment; "multiple trials"	If students choose to repeat an observation or experiment, this could suggest that they are seeking consistency with respect to experimental results.	A group of students conducts an experiment involving the evaporation of a puddle. They expect the asphalt under the puddle to be warm after the water evaporates. However, they find instead that the asphalt from which a puddle evaporated is *cooler* than the surrounding asphalt. To confirm this result, they check if this is true for another puddle: *Student 1: …if you put one hand one here [evaporated spot on asphalt], one hand on here [regular asphalt], this part [the regular asphalt] is hotter*. *[00:02:01.06] Student 2: Just by a little. (…) Let's try that with the other one [puddle]*.
Devise a hypothetical situation involving a contradiction	This is a way of drawing attention to and/or requesting reconciliation of an inconsistency.	*"…what happens if lightning struck the top of a tire with the rim in it? Like what would happen because that ha—the rim is metal and if it struck*

		the top of it, would it reflect off because you have metal under the rubber so?" The student sets up a hypothetical situation with the implicit contradiction that electricity behaves differently in rubber and metal.
Identify or construct a relationship (implicitly or explicitly) between ideas and/or information, for example: a. cause and effect b. part-to-whole c. category and example d. temporal/chain of events e. analogy, etc.	Coherence seeking is not just collecting mutually consistent sets of information, but also linking that information. The meaningful relations that might be formed vary and depend in part on the discipline and phenomenon under investigation. Like "Offer reconciliation of an inconsistency" this is a very broad category of evidence for coherence seeking. It may include students' explanations, models, predictions, etc.	*"...She said that it was heat coming up. Me and Robert were thinking maybe it's like um cause and effect. Heat is the cause and the water vapor is the effect."* Students are debating what the "stuff" is that they see rising from an evaporating puddle—steam, water vapor, or heat. As part of her argument for why the "stuff" is not heat, the student explicitly identifies a cause and effect relationship between heat and water vapor.
Notice (and/or draw attention to) a phenomenon or	"Disconnected" bits of information may be troublesome to those who are trying to fit information and ideas together.	*"...if they [clouds] need to get rid of their energy and it turns into electricity, why does that only happen in certain areas?...Some areas they have like storms and rain and uh*

observation that is unaccounted for		*everyday. Um, why does that not happen here?"* The student recognizes that another student's idea that clouds have to get rid of energy does not explain why some places are stormier than others.
Question the relevance of a claim, observation, or piece of evidence	Questioning relevance can be a means of reconciling an inconsistency (i.e., that observation is not related to the phenomena we are studying). It might also take place during the process of trying to fit ideas together.	While talking about how condensation forms in a bottle, a student brings up condensation in on a car window. Another student questions the relevance of mentioning condensation on the car window: *I'm just wondering, I'm kind of getting confused now cause we kinda have gone off subject like we've gone from a glass or a bottle to a car and…It's-I started with the glass, not the car…I just want to know how it comes from the the bottle or the cup or something.*

Request a relationship between ideas or pieces of information	Falling directly from the definition of coherence seeking, this is an attempt to uncover connections between ideas/information.	A class is discussing clouds and lightning. One student asks about the relationship between lightning, electricity, and clouds: *"If, if lightning is, like, electricity, then does that mean there's electricity in a cloud?"* The student appears to use a chain of deductive reasoning to infer that clouds *contain* electricity.
Comment on if/how one's comments fit into the larger conversation	From research on narrative coherence and also conversational topic analysis, this is an attempt to demark an idea as being part of, or distinct from, other ideas that have been discussed. Often, these take the form of preliminaries (Schlegoff, 1980). More generally, evidence of linguistic coherence seeking.	a. During a discussion about lightning, a student brings up a question about temperature of the atmosphere: *Raphael: And also, <u>I know this is kind of off our main question</u> but, I just thought like since the the clouds are so high, high up and it's cold, and the sun, and they're closer to the sun than we are, why is it cold?* b. A teacher asks the class why a toy car apparently made of plastic moves with magnets. Rather than answer this question, a student responds:

		Rick: Well, <u>I just wanted to say</u> 'cause our group found out something <u>else</u> about the toy car.
False starts, pauses, or re-phrasing midway through speech	These moments can an indicator of one's knowledge construction in the moment, and they can reveal how participants are linking together ideas, in a conceptual sense. . More generally, evidence of linguistic coherence seeking.	In a discussion about what causes the marine layer over ocean-front towns, one teacher re-structures her idea midway through: *Maggie: So we were saying that we notice in our classrooms, about 1 or 1:30 in the afternoon, all the sudden, this wind hits. We get a breeze. And, you know, generally, and especially when you see that marine layer. That marine layer is coming in because things are cooling down. <u>It takes a while, but it comes in okay, and um // no that's when it goes out</u>. Right, it's cooling down, it goes out.*

Appendix E: Transcript Conventions

==	"a speaker's pause at the end of uncompleted utterance, seemingly to encourage another speaker to talk" (Varelas et al., 2007, p. 93)
//	"false starts or abandoned language replaced by new language structures" (Varelas et al., 2007, p. 93)
…	Short pause within an utterance
… …	Long pause within an utterance
…..	Pause (other)
-- or —	"breaking off of a speaker's turn due to the next speaker's turn" (Varelas et al., 2007, p. 93)
(***)	"One word that is inaudible or impossible to transcribe" (Varelas et al., 2007, p. 93)
(*** ***)	"longer stretches of language that are inaudible and impossible to transcribe" (Varelas et al., 2007, p. 93)
## ##	Overlapping language
Italics	Emphasis/drawn out word
< >	"Uncertain words" (Varelas et al., 2007, p. 93)
[ ] or ()	"identifies what is being referred to or gestured and other nonverbal contextual information" (Varelas et al., 2007, p. 93)
Bold	Emphasis added for analytical purposes

Appendix F: Fieldnotes from an Interview with Ms. F

The impromptu interview took place on August 11, 2010. I did not videotape the interview, however, I wrote up field notes after the interview, and Ms. F read over them as a member check. I include those notes, verbatim, below:

Watched the Anthony solids don't flow clip, and bits of a different day where Baxter and Anthony are talking about whether a light bulb saves energy. I couldn't find my killing clip!!! GRRR.

Ms. F mentioned that these students all have "strong personalities" and know each other very well, grew up together, and many have kind of a brother/sister relationship.

Larry and Ari are self-perceived experts, and so students will attack their ideas just because of who they are, rather than because of their ideas. (Especially Ari.)

Ari is a student who will stick to what he thinks regardless of contradictory evidence, whereas Shaye will modify his ideas in response to other ideas that he hears.

There are a handful of talkative boys. Phoebe is a "lawyer in training" and will hold her own. Alia started out very involved and talkative but became quieter over the course of the module, perhaps because she felt she had already said everything she needed to say. Erin has a tendency to be worried about being wrong. She will share ideas but also becomes annoyed or frustrated or cry in class, and puts pressure on herself to be correct.

Phoebe and Larry have a brother/sister kind of relationship.

Ms. F says that at the beginning of the year, she did regular FOSS, and the students went along with it. But then when the cameras came she said all the rules that students had before about school went out the window (this is how they felt). They started arguing with each other and coming up with ideas, but then when the module was over, she said the students didn't go back to before. They were still arguing about things. There was in particular a lot of continued debate about the direction of current in a circuit, and students continued to support their two ingredient model despite what the book said. Erin would often refer to what was in the book as the correct answer, and try to convince students to attend to the book.

Ms. F worried that one issue was that she couldn't get the students to agree upon anything. She compared her students to her own experience in the water cycle workshop science time…how we run off in many different directions with many different ideas, and when Sharon tried to ask us what we agree on, we didn't agree on anything! But next year, she would like to try to get that agreement. I asked if she maybe saw clusters of students agreeing about things, and she said that often when she would try to get students to pick a camp, they would avoid it.

She thinks that there is both a strong component of arguing about ideas, and a strong component that is about whose idea it is. Baxter's ideas are often a target. The relationship between Baxter and Phoebe might be contentious.

However, all students were friends with each other at some point in the year; in 5th grade, relationships are dynamic and constantly changing.

Appendix G: Transcript for Baxter's Reaction Ideas

[00:08:16.14] Baxter: ##I'm starting to think## now that --

Student: ##I think##

Ms. F: Let's hear Baxter.

[00:08:19.09] Baxter: Well, they're, they're probably can't be a chemical reaction because, like if there's a chemical reaction, in chemical reactions, doesn't like something explode inside or --

Student: No.

[00:08:31.17] Baxter: You gotta get a sign of the chemical reaction // Well, um now I'm starting to think Ari's way because when you were holding the wires, if you were holding the metal, then it would get really hot, and then it would burn your fingers for a second. Well I think that would be the positive and negative energy mixing. --

[00:08:48.17] Phoebe: That could kind of be the reaction (***).

Baxter: Yeah.

Phoebe: (***)

[00:08:54.04] Ms. F: [points to Tony]

[00:08:55.01] Tony: Now I...I agree with both of them.

[00:08:59.14] Ari: ##He's just adding on to what I said.##

Erin: ## I think that## um // I think that is a good idea...because // but um, I think it's // I think like they're both good ideas so um... // K, and // but I dunno which one is right and // I think the chemical is, it sounds right but I just think that um it um that it would get hot um with a chemical reaction but if there was a chemical reaction then you wouldn't have to have a positive side [touches the + on the chart] and a negative side [touches the - on the chart].

[00:09:44.24] Shaye: Well, well I think it's just they, they like // negative and positive are just naturally opposites and so like, they like spread to one side, each ==

[00:09:57.12] Baxter: Wait. Wait, now I sorta think they go together because I'm sorta thinking about math now, and how // let's just say you add 20 plus 20. Well a way to um check that is uh // you could get your answers by 20 minus twe-uh 40 and what would that ##equal##? It'd be // yeah.

Shaye: ##No, 40 minus 20.##

[00:10:19.12] Baxter: Yeah, it'd be 20. So you'd have two 20's and one 40. ##They go together as a fraction.##

Shaye: ##Well, I'm just gonna## I'm gonna draw it. [draws a battery next to the chart] See. See this is the battery. It's like // I think maybe the negative side and the positive side but they could change if like they moved [gesture] and but even if the negative went on this side [the side labelled +], the positive would still have to go on that side [the side labelled -] because their opposite. But --

[00:10:42.28] Baxter: Or, or maybe ##the positive side## // Maybe the positive side has more like um, more like power and the negative side takes away power. So ##Like adding builds## it up and minusing takes it down. So maybe uh the plus // well the positive side um has a lot more energy, like a lot of energy so the negative has to take some away or like it will be ##dangerous##.

Shaye: ##But, two different energies always came out.##

[00:10:55.06] Phoebe: So they (***) ##(*** ***)##

Phoebe: [turning around to face Baxter] ##What do you say? One side's empty, empty?##

[00:11:19.27] Shaye: Well, it'd still be in the battery, right?

Baxter: Yeah, but like maybe one liquid is a negative liquid and like it takes away power. And the positive uh adds power so when they combined it's just neutral. And it stays the same so it, it doesn't become dangerous and it won't, and it // like it will make it so it won't light up. So it's right in the middle. Like if you use one battery and two lights, the lights will only light up a little bit. [Andrew looks at the chart] Maybe the minus, well the negative takes away a lot of the power because if you took all the positive it would like make, make it really uh light up. And like, it would be like, dangerous like, it could burn your hands if you touched it or something.

References

Abrahamson, D. (2009). Orchestrating semiotic leaps from tacit to cultural quantitative reasoning—The case of anticipating experimental outcomes of a quasi-binomial random generator. *Cognition & Instruction, 27*(3), 175-224.

Ahlgren, A., & Kesidou, S. (1995). Attempting curriculum coherence in Project 2061. In J. Beane (Ed.), *Toward a Coherent Curriculum* (pp. 44-54). Alexandria, VA: ASCD.

Ball, D. (1993). With an eye on the mathematical horizon: Dilemmas of teaching elementary school mathematics. *The Elementary School Journal, 9*(4), 373-397.

Bang, M., & Medin, D. (2010). Cultural processes in science education: Supporting the navigation of multiple epistemologies. *Science Education, 94*(6), 1008-1026.

Barber, J. (2009). *Insights about the role of reading and writing in science*. Paper presented at the 2009 STANYS Conference, Rochester, NY.

Bartlett, F. C. (1932/1995). *Remembering: A study in experimental and social psychology*. Cambridge: The University Press.

Beane, J. (1995). Introduction: What is a coherent curriculum? In J. Beane (Ed.), *Toward a Coherent Curriculum* (pp. 1-14). Alexandria, VA: ASCD.

Berland, L., & Lee, V. (2010). Anomalous graph data and claim revision during argumentation. In Gomez, K., Lyons, L., & Radinsky, J. (Eds.) *Learning in the Disciplines: Proceedings of the 9th International Conference of the*

Learning Sciences (ICLS 2010) - Volume 1, Full Papers (pp. 314-315). International Society of the Learning Sciences: Chicago IL.

Berland, L., & Reiser, B. (2008). Making sense of argumentation and explanation. *Science Education*, 1-30.

Blake, D. (1933). Storm types and resultant precipitation in the San Diego area. *Monthly Weather Review, 61*(8 August), 223-225.

Bloome, D., Puro, P., & Theodorou, E. (1989). Procedural display and classroom lessons. *Curriculum Inquiry, 19*(3), 265-291.

Brady, M. (1995). A supradisciplinary curriculum. In J. Beane (Ed.), *Toward a Coherent Curriculum* (pp. 26-33). Alexandria, VA: ASCD.

Bransford, J., Brown, A. L., & Cocking, R. R. (Eds.). (1999). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academies Press.

Bricker, L. A., & Bell, P. (2008). Conceptualizations of argumentation from science studies and the learning sciences and their implications for the practices of science education. *Science Education, 92*(3), 473-498.

Bruck, M., & Ceci, S. J. (1999). The suggestibility of children's memory. *Annual Review of Psychology, 50*, 419-439.

Buchmann, M., & Floden, R. (1992). Coherence, the Rebel Angel. *Educational Researcher, 21*(9), 4-9.

Cajete, G. (1999). *Native science: Natural laws of interdependence*. Santa Fe, NM: Clear Light Books.

Calabrese-Barton, A., Ermer, J. L., Burkett, T. A., & Osborne, M. D. (2003).

Teaching science for social justice. New York: Teachers College Press.

Canpolat, N. (2006, December). Turkish undergraduates' misconceptions of evaporation rate, and vapour pressure. *International Journal of Science Education, 28*(15), 1757-1770.

Carpenter, F. A. (1913). *The Climate and Weather of San Diego, California*. Retrieved from http://www.archive.org/details/climateweatherof00carprich

Cavicchi, E. (1997). Experimenting with magnetism: Ways of learning of Joann and Faraday. *American Journal of Physics, 65*(9), 867-882.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63*(1), 1-49.

Coffey, J., Hammer, D., Levin, D., & Grant, T. (2011). The missing disciplinary substance of formative assessment. *Journal of Research in Science Teaching, 48*(10), 1109-1136.

Conlin, L. (2012). *Building shared understanding in introductory physics tutorials through risk, repair, conflict, and comedy*. (Unpublished doctoral dissertation). University of Maryland, College Park.

Conlin, L., Gupta, A., & Hammer, D. (2010). Where to find the mind: Identifying the scale of cognitive dynamics In K. Gomez, L. Lyons, & J. Radinsky (Eds.) *Learning in the Disciplines: Proceedings of the 2010 International Conference of the Learning Sciences* (pp. 277-284). Chicago, IL: ISLS.

Covitt, B., Gunckel, K., & Anderson, C. W. (2009). Students' developing understandings of water in environmental systems. *The Journal of Environmental Education, 40*(3), 37-51.

Dahl, R. (1961). *James and the Giant Peach*. New York, NY: Penguin.

Davis, E. (2003). Prompting middle school science students for productive reflection: Generic and directed prompts. *Journal of the Learning Sciences, 12*(1), 91-142.

Davis, E. (n.d.). *Examples of levels of coherence*. Retrieved from www-personal.umich.edu/~betsyd/CoherenceCoding.pdf.

Dilworth, C. (2008). *Scientific progress: A study concerning the nature of the relation between successive scientific theories*. Springer.

DiSessa, A., Gillespie, N., & Esterly, J. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science, 28,* 843-900.

Donaldson, M. (1979). *Children's Minds.* New York: W.W. Norton & Company.

Driver, R., Guesne, E, & Tiberghien, A. (1985). Children's ideas and the learning of science. In R. Driver (Ed.), *Children's ideas in science* (pp. 1-9). Philadelphia, PA: Open University Press.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. *Science Education, 84*(3), 287-312.

Duckworth, E. (1996). *"The having of wonderful ideas" and other essays on teaching and learning*. New York: Teacher's College Press.

Dunbar, K. (1999). How scientists build models: *In vivo* science as a window on the scientific mind. In L. Magnani, N. Nersessian, & P. Thagard. (Eds.), *Model-based reasoning in scientific discovery* (pp. 89-98). New York: Plenum Press.

Ellis, J. (1986). The superstring: Theory of everything, or of nothing? *Nature, 323*(6089), 595-598.

Emerson, R., Fretz, R., & Shaw, L. (1995). *Writing ethnographic fieldnotes*. Chicago: University of Chicago Press.

Engle, R., & Conant, F. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and Instruction, 20*(4), 399-483.

Everett, L. J., & Pennathur, A. (2007, June). *A design process for conceptual based, counter-intuitive problems*. Paper presented at the American Society for Engineering Education Annual Conference, Honolulu, HI.

Festinger, L. (1957). *A theory of cognitive dissonance*. Stanford, CA: Stanford University Press.

Ford, M. (2005). The game, the pieces, and the players: Generative resources from two instructional portrayals of experimentation. *The Journal of the Learning Sciences, 14*(4), 449-487.

Ford, M. (2006). “Grasp of Practice” as a reasoning resource for inquiry and nature of science understanding. *Science & Education, 17*(2-3), 147-177.

Frisch, M. (forthcoming). Models and scientific representations or: Who is afraid of inconsistency? *Synthese*.

Gonzales-Espada, W., Birriel, J., & Birriel, I. (2010. Discrepant events: A challenge to students’ intuition. *The Physics Teacher, 48,* 508-511.

Gotwals, A. W., & Songer, N. B. (2008). *Scenario-based assessment: Gathering* *evidence of student reasoning in biodiversity*. Paper presented at the Annual Meeting of the American Educational Research Association, New York, NY.

Gieryn, T. (1983, December). Boundary-work and the demarcation of science from non-science: Strains and interests in professional ideologies of scientists. *American Sociological Review, 48*(6), 781-795.

Girod, M., & Wong, D. (2002). An aesthetic (Deweyan) perspective on science learning: Case studies of three fourth graders. *The Elementary School Journal, 102*(3), 199-224.

Graesser, A. C., Mills, K. K., & Zwan, R. A. (1997). Discourse comprehension. *Annual Review Psychology, 48*, 163-189.

Halloun, I., & Hestenes, D. (1985). Common sense conceptions about motion. *American Journal of Physics, 53*(11), 1056-1065.

Hammer, D. (1995). Student inquiry in a physics class discussion. *Cognition and Instruction, 13*(3), 401-430.

Hammer, D. (1996). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions? *The Journal of the Learning Sciences, 5*(2), 97-127.

Hammer, D. (1997). Discovery teaching, discovery learning. *Cognition and Instruction, 15*(4), 485-529.

Hammer, D., Elby, A., Scherr, R., & Redish, E.F. (2005). Resources, framing, and transfer. In J. Mestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective* (pp. 89-120). Greenwich, CT: Information Age Publishing.

Hammer, D., Goldberg, F., & Fargason, S. (in press). Responsive teaching and the beginnings of *energy* in a third grade classroom. *Review of Science, Mathematics and ICT Education.*

Hammer, D., Russ, R., Scherr, R. E., & Mikeska, J. (2008). Identifying inquiry and conceptualizing students‟ abilities. In R. A. Duschl & R. E. Grandy (Eds.), *Teaching Scientific Inquiry: Recommendations for Research and Application* (pp. 138-156). Rotterdam, NL: Sense Publishers.

Hammer, D., & van Zee, E. H. (2006). *Seeing the science in children's thinking: Case studies of student inquiry in physical science.* (Book and DVD) Portsmouth, NH: Heinemann.

Hatano, G., & Inagaki, K. (1986). Two courses of expertise. In H. Stevenson, H. Azuma, and K. Hakuta (Eds.), *Child Development in Japan* (pp. 262-272). W.H. Freeman & Co.

Hatano, G., & Inagaki, K. (1991). Sharing cognition through collective comprehension activity. In L. B. Resnick, J.M. Levine, & S.D. Teasley (Eds.), *Perspectives on socially shared cognition* (pp. 331-348). Washington, DC: American Psychological Association.

Holyoak, K. J., & Thagard, P. (1995). *Mental leaps*. Cambridge, MA: MIT Press.

Hume, D. (1910/1999). *An enquiry concerning human understanding*. USA: Oxford University Press.

Hutchins, E. (1995). How a cockpit remembers its speeds. *Cognitive Science, 19,* 265-288.

Hutchinson, P. (2008). *Epistemological authenticity in science classrooms*.

(Unpublished Doctoral Dissertation). University of Maryland, College Park.

Jimenez-Aleixandre, M., & Rodgriguez, A. (2000). “Doing the lesson” or “Doing science”: Argument in high school genetics. *Science Education, 84*, 757-792.

Jimenez Gomez, E. J., Benarroch, A., & Marin, N. (2006). Evolution of the degree of coherence found in students’ conceptions concerning the particulate nature of matter. *Journal of Research in Science Teaching*, *43*(6), 577-598.

Kalnay, E. (2003). *Atmospheric Modeling, Data Assimilation and Predictability*. New York, NY: Cambridge University Press.

Kelly, G. & Crawford, T. (1997). An ethnographic investigation of the discourse processes of school science. *Science Education*, *81*(5), 533-559.

Koch, C. (2009, July). A “complex” theory of consciousness. *Scientific American Mind*. Retrieved from http://www.scientificamerican.com/article.cfm?id=a-theory-of-consciousness.

Kramer, J. (1999, Spring). The nature and origins of musical postmodernism. *Current Musicology, 66*, 7-20.

Kuhn, D. (1989). Children and adults as intuitive scientists. *Psychological Review, 96*(4), 674-689.

Kuhn, T. (1962). *The Structure of Scientific Revolutions*. Chicago, IL: University of Chicago Press.

Kuhn, D., & Pease, M. (2008). What needs to develop in the development of inquiry skills? *Cognition & Instruction, 26*(4), 512-559.

Kuhn, D., & Udell, W. (2003). The development of argument skills. *Child Development, 74(*5), 1245-1260.

Labaree, D. F. (1997). Public goods, private goods: The American struggle over educational goals. *American Educational Research Journal, 34*(1), 39-81.

Lakoff, G. (1999). Cognitive models and prototype theory. In E. Margolis & S. Laurence (Eds.), *Concepts: Core Readings* (pp. 391-424). Cambridge, MA: MIT Press.

Latour, B., & Woolgar, S. (1979). *Laboratory life: The social construction of scientific facts*. Princeton, NJ: Princeton University Press.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. New York: Cambridge University Press.

Lehrer, R., & Schauble, L. (2009). Invited comment: Images of learning, images of progress. *Journal of Research in Science Teaching, 46*(6), 731-735.

Lemke, J. (1982). Talking physics. *Physics Education, 17*, 263-267.

Levrini, O., Parnafes, O., Bamberger, J., diSessa, A.A., & Hammer, D. (submitted). The essential nature of complexity in learning.

Li, Z., Niu, F., Fan, J., Liu, Y., Rosenfeld, D., & Ding, Y. (2011). Long-term impacts of aerosols on the vertical development of clouds and precipitation. *Nature Geoscience*. Advance online publication.

Lindfors, J. W. (1999). *Children's inquiry: Using language to make sense of the world*. New York, NY: Teachers College Press.

Lineback, J. (2012). *Mrs. Miller's evolution in teaching science as inquiry: A case study of a teacher's change in responsiveness*. (Unpublished doctoral dissertation). University of California, San Diego/San Diego State University.

May, D., Hammer, D., & Roy, P. (2006). Children's analogical reasoning in a third-grade science discussion. *Science Education, 90*(2), 316-330.

Meheus, J. (Ed.) (2002). *Inconsistency in Science*. Norwell, MA: Kluwer Academic Publishers.

McNeill, K. L., Lizotte, D. J., Krajcik, J., & Marx, R. W. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. *Journal of the Learning Sciences*, *15*(2), 153-191.

Morrison, Y. (2003). *The weather engine*. Australia: Pearson Education.

Mott, N. (1974). *Metal-Insulator Transitions*. Bristol, PA: Taylor & Francis Ltd.

Nathan, M., Eilam, B., & Kim, S. (2008). To disagree, we must also agree: How intersubjectivity structures and perpetuates discourse in a mathematics classroom. *Journal of the Learning Sciences*, *16*(4), 523-563.

National Academy of Sciences and Institute of Medicine (2008). *Science, evolution, and creationism*. Washington, DC: National Academies Press.

Nespor, J. (1994). *Knowledge in motion: Space, time and curriculum in undergraduate physics and management*. Oxon: RoutledgeFalmer.

Ng, H., & Mooney, R. (1990, July). On the role of coherence in abductive explanation. *Proceedings of the Eighth National Conference on Artificial Intelligence (AAAI-90)*, Boston, MA, 337-342.

Nisbett, R. E., & Wilson, T. D. (1977). Telling more than we can know: Verbal reports on mental processes. *Psychological Review*, *84*(3), 231-259.

Nordine, J., Krajcik, J., & Fortus, D. (2010). Transforming energy instruction in middle school to support integrated understanding and future learning. *Science Education, 95*(4), 670-699.

(NRC) National Research Council (2007). Learning Progressions. In Duschl, R. A., Schweingruber, H. A., Shouse, A. W. (Eds.) *Taking Science to School: Learning and Teaching Science in Grades K-8* (pp. 213-250). Washington, DC: The National Academies Press.

(NRC) National Research Council (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: The National Academies Press.

(NSTA) National Science Teachers Association (2012). Q & A on the teaching of evolution. *Evolution Resources*. Retrieved from http://www.nsta.org/publications/evolution.aspx.

O'Brien, T. (2010). *Brain-powered science: Teaching and learning with discrepant events*. USA: NSTA Press.

Oliver, D., Serovich, J., & Mason, T. (2005). Constraints and opportunities with interview transcription: Towards reflection in qualitative research. *Social Forces, 84*(2), 1273-1289.

Ostriker, J. P., & Steinhardt, P. J. (1995). The observational case for a low-density Universe with a constant non-zero cosmological constant. *Nature, 377*(19), 600-602.

Paladino, S. (Producer) (2008). Throw down your heart [Motion picture]. United States: Argot Pictures.

Pennington, N., & Hastie, R. (1992). Explaining the evidence: Tests of the story model for juror decision making. *Journal of Personality and Social Psychology, 62*(2), 189-206.

Peshkin, A. (1988, October). In search of subjectivity—One's own. *Educational Researcher*, *17*, 17-21.

Popper, K. (1968). *The logic of scientific discovery*. New York, NY: Harper & Row.

Ranney, M., & Schank, P. (1998). Toward an integration of the social and the scientific: Observing, modeling, and promoting the explanatory coherence of reasoning. In S. Read & L. Miller (Eds.), *Connectionist models of social reasoning and social behavior* (pp. 245- 274). Mahwah, NJ: Lawrence Erlbaum.

Ranney, M., & Thagard, P. (1988). Explanatory coherence and belief revision in naïve physics. *Proceedings of the Tenth Annual Conference of the Cognitive Science Society* (pp. 426-432). Hillsdale, NJ: Erlbaum.

Reed, T. (1932). Weather types of the northeast Pacific Ocean as related to the weather of the north Pacific coast. *Monthly Weather Review, 60*(December), 246-252.

Rosch, E. (1973). Natural categories. *Cognitive Psychology, 4*, 328-350.

Rosch, E. (1975). Cognitive representations of semantic categories. *Journal of Experimental Psychology: General, 104*(3), 192-233.

Rosebery, A. S., & Warren, B. (Eds.) (1998). *Boats, balloons and classroom video: Science teaching as inquiry*. Portsmouth: Heinemann.

Russ, R. (2006). *A framework for recognizing mechanistic reasoning in student scientific inquiry*. (Unpublished doctoral dissertation). University of Maryland, College Park.

Sacks, O. (1985). *The man who mistook his wife for a hat and other clinical tales*.

New York, NY: Simon & Schuster.

Sampson, V., & Clark, D. (2008). Assessment of the ways students generate arguments in science education: Current perspectives and recommendations for future directions. *Science Education, 92*(3), 447-472.

Sandoval, W. A. (2003). Conceptual and epistemic aspects of students' scientific explanations. *The Journal of the Learning Sciences, 12*(1), 5-51.

Samarapungavan, A., & Wiers, R. (1997). Children"s thoughts on the origin of species: A study of explanatory coherence. *Cognitive Science, 21*(2), 147-177.

Schank, P., & Ranney, M. (1992). *Assessing explanatory coherence: A new method for integrating verbal data with models of on-line belief revision.* In Proceedings of the Fourteenth Annual Conference of the Cognitive Science Society (pp. 599-604). Hillsdale, NJ: Erlbaum.

Schegloff, E. A. (1980). Preliminaries to preliminaries: "Can I ask you a question?" *Sociological Inquiry, 50*(3-4), 104-152.

Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Acher, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632-654.

Sherin, B., Krakowski, M., & Lee, V. (2012). Some assembly required: How scientific explanations are constructed during clinical interviews. *Journal of Research in Science Teaching, 49*(2), 166-198.

Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *Perception, 28*, 1059-1074.

Smith, C., Maclin, D., Houghton, C., & Hennessey, M. (2000). Sixth-grade students' epistemologies of science: The impact of school science experiences on epistemological development. *Cognition and Instruction, 18*(3), 349-422.

Smith, L. B. (2005). Cognition as a dynamic system: Principles from embodiment. *Developmental Review, 25*, 278-298.

Solomon, M. (1992). Scientific rationality and human reasoning. *Philosophy of Science, 59*(3), 439-455.

Solomon, M. (1994). Social empiricism. *Nous, 28*(3), 325-343.

Songer, N. B. (2006). BioKids: An animated conversation on the development of complex reasoning in science. In R. Keith Saqyer, (Ed.) *Cambridge Handbook of the Learning Sciences* (pp. 355-369). New York: Cambridge University Press.

Songer, N. B., Kelcey, B., & Gotwals, A. W. (2009). *How and when does complex reasoning occur? Empirically driven development of a learning progression focused on complex reasoning about biodiversity*. Paper presented at the Annual Meeting of the American Education Research Association (AERA), San Diego, CA.

Stevenson, R., Knott. A., Oberlander, J. & McDonald, S. (2000). Interpreting pronouns and connectives: Interactions among focusing, thematic roles and coherence relations. *Language and Cognitive Processes*, *15*(3), 225-262.

Strauss, A., & Corbin, J. (1994). Grounded theory methodology: An overview. In N. Denzin & Y. Lincoln (Eds.), *Handbook of qualitative research* (pp. 273-285). Thousand Oaks, CA: Sage.

Su, H., Cheng, Y., Oswald, R., Behrendt, T., Trebs, I., Meixner, F., Andreae, M., Cheng, P., Zhang, Y., & Poschl, U. (2011). Soil nitrate as a source of atmospheric HONO and OH radicals. *Science, 333*(16 September), 1616-1618.

Tang, X. (2010). *From interaction to interaction: Exploring shared resources constructed through and mediating classroom science learning*. (Unpublished doctoral dissertation). University of Maryland, College Park.

Thagard, P., & Nowak, G. (1988). The explanatory coherence of continental drift. In *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association*, Vol. 1: Contributed Papers (pp. 118-126).

Thagard, P. (1989). Explanatory coherence. *Behavioral and Brain Sciences, 12*, 435-502.

Thagard, P. (2000). *Coherence in Thought and Action*. Cambridge, MA: MIT Press.

Trabasso, T., Secco, T., & Van Den Broek, P. (1982). *Causal cohesion and story coherence*. Paper presented at the Annual Meeting of the American Educational Research Association, New York, NY. (ERIC Document Reproduction Service No. ED214147). Retrieved August 29, 2008, from EBSCOHost ERIC database.

Van Dijk, T. A., & Kintsch, W. (1983). *Strategies of discourse comprehension*. San Diego, CA: Academic.

Van Doren, M. (1959). *Liberal Education*. Boston, MA: Beacon Press.

Van Veen, V., Krug, M., Schooler, J., & Carter, S. (2009). Neural activity predicts attitude change in cognitive dissonance. *Nature Neuroscience, 12*(11), 1469-1475.

van Zee, E. H., Hammer, D., Bell, M., Roy, P. & Peter, J. (2005). Learning and teaching science as inquiry: A study of elementary school teachers' investigations of light. *Science Education, 89*(6), 1007-1042.

Varelas, M., Pappas, C., Kane, J., & Arsenault, A. (2007). Urban primary-grade children think and talk science: Curricular and instructional practices that nurture participation and argumentation. *Science Education, 92*(1), 65-95.

Varelas, M., Pappas, C., & Rife, A. (2006). Exploring the role of intertextuality in concept construction: Urban second graders make sense of evaporation, boiling, and condensation. *Journal of Research in Science Teaching, 43*(7), 637-666.

Vosniadou, S., & Brewer, W. (1992). Mental models of the Earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*, 535-585.

Warren, B., Ballenger, C., Ogonowski, M., Rosebery, A., & Hudicourt-Barnes, J. (2001). Rethinking diversity in learning science: The logic of everyday sense-making. *Journal of Research in Science Teaching, 38*(5), 529-552.

Watts, D. M. (1983). Some alternative views of energy. *Physics Education*, *18*, 213-216.

Weber, E., & De Clercq, K. (2002). Why the logic of explanation is inconsistency-adaptive. In J. Meheus (Ed.), *Inconsistencies in Science* (pp. 165-184). Norwell, MA: Kluwer.

Wilson, T. (2002). *Strangers to ourselves: Discovering adaptive unconscious*. USA:

Belknap.

Wolman, D. (2012, March). A tale of two halves. *Nature*, *483*, 260-263.