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Article *in* Science Education · March 2017

DOI: 10.1002/sce.21264

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Science
Education

LEARNING

Aligning Coordination Class Theory With a New Context: Applying a Theory of Individual Learning to Group Learning

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Received 21 March 2016; revised 23 December 2016; accepted 23 December 2016
DOI 10.1002/sce.21264
Published online in Wiley Online Library (wileyonlinelibrary.com).

ABSTRACT: This article presents an empirical analysis of conceptual difficulties encountered and ways students made progress in learning at both individual and group levels in a classroom environment in which the students used an embodied modeling activity to make sense of a specific scientific scenario. The theoretical framework, coordination class theory, has primarily been used to capture individual learning in interview settings, and here it is applied to analytically capture both individual and group learning in a complex classroom environment. Classrooms of ninth-grade earth science students used the position of their bodies to model a specific scientific concept, the steady-state energy of the earth. The students encountered difficulties aligning their understanding of the scientific concept with the models. Subsequently, they changed their models in specific ways that better aligned their understanding of the scientific concept with their newly modified model. The theory is utilized to describe learning by both individuals and the group in this classroom environment and shows how a single student's contribution can dramatically affect the model and subsequent learning. Implications suggest new ways in which the theory may be useful for designing learning environments. © 2017 Wiley Periodicals, Inc. *Sci Ed* 1–31, 2017

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Contract grant sponsor: National Science Foundation, Contract grant numbers: 0962805 and 1222580.

INTRODUCTION

This article applies an existing theory of learning to a new setting. Coordination class theory has often been used to describe individuals learning of difficult science concepts in interview settings (diSessa & Sherin, 1998). Here, this perspective is used to describe learning in a complicated classroom setting in which ninth-grade students generated and modified a series of models. The analysis reveals a series of difficulties they encountered and ways the students made progress.

Two classrooms of students simultaneously generated embodied models for the steady-state energy of the earth. Each classroom presented their model to the adjacent classroom, and after a group discussion, both classrooms collaborated on a joint model that involved a series of modifications and improvements over the prior models. Throughout the process of generating, presenting, and revising their models, students negotiated meaning, which involved moments of agreement and instances of disagreement. The objective of our analysis is to describe the difficulties encountered while modifying the models and the ways they made progress, resulting in learning at both the individual and group levels through modification to their embodied models and modification to their conceptual structures. Our contribution is to show how coordination class theory can be applied to group learning in classrooms through an analytical means that captures conceptual difficulties encountered in a collaborative environment in which individuals are individually and collectively building knowledge. Furthermore, as coordination class theory is one of several theories of conceptual change that have tended to emphasize knowledge of the individual, an additional contribution is to illustrate the individual-collective dynamics of learning in classrooms and to propose ways that it could be orchestrated by teachers.

CONCEPTUAL CHANGE OF INDIVIDUALS AND GROUPS IN CLASSROOMS

Conceptual change research has examined challenges involved with individuals learning important, but often difficult, concepts in science and found that despite years of often high-quality science instruction, students persist in exhibiting difficulties (e.g., Confrey, 1990; diSessa, 2006; Ioannides & Vosniadou 2002). With a goal of uncovering the source of these difficulties, along with instructional techniques to facilitate learning, a substantial body of research has applied various theoretical and methodological approaches to addressing this problem (e.g., Brown & Clement, 1989; Hunt & Minstrell, 1994; Vosniadou, 2008; Wiser & Smith, 2008). The emphasis within this body of work has typically been on an individual's learning, often in interview settings (e.g., Carey, 1999; diSessa, 1993; Slotta, Chi, & Joram, 1995; Vosniadou, 1994) and occasionally classroom setting with general consensus (Levrini & diSessa, 2008).

Yet, pragmatically there is a need for further research examining conceptual change in classrooms. Classrooms comprise many individuals, each of whom has their own conceptual understanding and possible difficulties. We expect that, in these real-world messy classrooms, one individual's verbal utterances may have a noticeable effect on another's conceptual understanding. Individuals may occasionally agree, and sometimes disagree, while working to reach consensus and, through that process, knowledge can spread among individuals while they jointly participate in common intellectual activities. But, when a group of individuals engages in a common intellectual activity, such as building a scientific model, an inherent challenge will be that, at a given point in time, those individuals do not necessarily have a common interpretation of that model or of the scientific concept, despite their joint participation in the activity. These different interpretations within the common intellectual activity can be the locus of learning. That is, despite common instructions and a joint artifact, different individuals within a group are each building their own knowledge and in that process, they influence each other's knowledge-building processes too. Capturing this type of learning requires a means for recognizing when one individual affects other individuals or the entire groups' understanding, along with shifts in understanding, which may be apparent through moments of agreement and disagreement. To do this effectively, we need to toggle between individual's knowledge building and the group understanding. We need to recognize when several individuals have different interpretations of the artifact and when they share a common interpretation.

Analytically, we build from coordination class theory (diSessa & Sherin, 1998), which has generally been applied to individual learning and here is applied to a classroom setting. To do this fruitfully, we need to check the applicability of the theory, and if necessary, refine our understanding of if and how the theory provides an adequate account of group learning. Reexamining this theoretical machinery, refining our understanding of it when applied in a new way, and demonstrating its utility is the purpose of the current article.

COORDINATION CLASS THEORY

Brief History of Coordination Class Theory

The field of conceptual change focuses on the learning of often-difficult concepts. Within this field, coordination class theory is one of many perspectives. A coordination class is a specific type of concept, and the theory describes the organization of knowledge, the learning difficulties that may arise, and the process of how knowledge becomes reorganized over time. The theory was originally built to add a layer of precision in the field of conceptual change, which had previously been vague about the meaning of the term "concept" and had previously focused on conditions for change without specificity about the process (diSessa, 1991; diSessa & Sherin, 1998).

Coordination classes are meant to provide a means for determining certain information from the world. The assumption is that information in the world is not transparent; instead, learners have to learn how to access relevant information (diSessa, 2002). Different situations may require different means of determining the same information. Within this perspective, "having" a concept consists of knowing how to get relevant information from the world, across varied situations.

Canonical studies using coordination class theory focus on the process of acquiring a well-developed conceptual structure and the learning difficulties that may arise as students work to determine the same information across varied situations in the world. In a paper presenting coordination class theory, diSessa and Sherin (1998) offered empirical evidence from an interview setting with a university student, J, who discussed the forces on a book as it slides across a table. J had difficulties determining what is and is not a force in this situation, due to challenges with her knowledge system. She favored her intuitive knowledge in this situation and decided that the equation, $F = ma$, did not apply. Since then, a variety of follow-up papers have applied coordination class theory to numerous content areas and populations, including learning in classroom settings (Levrini & diSessa, 2008), though most of the research has focused on learning in interview settings (e.g., Parnafes, 2007; Thaden-Koch, Dufresne, & Mestre, 2006; Wagner, 2006).

Parnafes (2007) applied coordination class theory to students' learning about the motion of simple harmonic oscillators through their interactions with computational representations. In an interview setting, pairs of high school students interacted first with physical oscillators and then with a simulation of oscillatory motion. In these different contexts, students used different strategies and different knowledge to determine relevant information. In the setting with physical oscillators, the students' intuitive coordination of "fastness" was different from a scientific coordination of velocity and frequency. Then, in the simulation setting, students were able to distinguish between velocity and period as they stabilized their strategies for determining the same information and refined their knowledge. Thereby the students' coordination classes were extended to apply to additional relevant contexts of oscillatory motion.

Wagner and diSessa (diSessa & Wagner, 2005; Wagner, 2006) presented an explanation of knowledge transfer based on an incremental refinement of knowledge resources across contexts, referred to as "transfer in pieces." The analysis focuses on one university student, Maria, who over the course of eight weekly interviews came to see various probability problems that she initially perceived as different to be alike.

Levrini and diSessa (2008) come closest to the work to be described in this paper. They presented an empirical analysis of a classroom of 18–19-year-old students who were learning about special relativity. Initially, the students had trouble with the concept of proper time, but they were able to make progress. The analysis uses coordination class theory to highlight how students "coordinate" proper time. During the instruction, the students incorporated a more careful definition of proper time and a new context, but they also encountered difficulties as they prematurely concluded that a new context was the same when it was in fact different. Also, Levrini and diSessa (2008) proposed extensions to coordination class theory by highlighting the role of definitions and instances in which students are consciously considering new situations as the same or related in some way to other previously considered situations. Though their paper described classroom learning, it focused on many students' difficulties with coordination across contexts and did not emphasize instances in which some students had difficulties while other students did not.

Other studies have used coordination class theory, as well. Thaden-Koch, Mestre, and colleagues (Thaden-Koch, Mestre, Dufresne, Gerace, & Leonard, 2005; Thaden-Kock et al., 2006) in a think-aloud interview setting presented students with a series of simulations for the motion of a ball along a straight-line track, a track with a shallow dip, and a track with a deeper dip. Students were asked to judge how realistic the motions appeared, and the analysis documented various difficulties encountered. Levin (2012) used coordination class theory to examine the codevelopment of conceptual and strategic knowledge in an algebraic problem-solving setting in which a single student developed a sophisticated algebraic algorithm for solving word problems. Lewis (2012) applied coordination class theory to clinical interview cases of students' learning about computational state in computer science. Wittmann (2002) applied coordination class theory to wave mechanics, looking at ways in which different ideas were coordinated to build different concepts of wave propagation and also modeled four different kinds of conceptual change (Wittmann, 2006). Across these studies, coordination class theory has been applied to examine the process of acquiring a well-developed conceptual structure (learning) as well as the difficulties that arise in a variety of content areas within physics, mathematics, and recently, computer science.

Coordination class theory was purposely designed to be specific and incomplete, and it is not intended to cover all instances of learning (diSessa & Cobb, 2004); applying it to various content areas is a natural extension, but, still, questions arise about its applicability. Across multiple studies (diSessa & Wagner, 2005; Levin, 2012; Lewis, 2012; Parnafes, 2007; Thaden-Koch et al., 2005; Wagner, 2006), a common empirical focus has been on student learning in interview settings, with the exception of Levrini and diSessa (2008) who focused on classroom learning. Although there is nothing explicitly within coordination class theory that has previously excluded its application to classroom settings (diSessa, 2016), applying this theory to classroom settings raises analytical questions about how to account for instances when individuals have different interpretations of a joint artifact and how the interaction of those different interpretations contributes to each individual's knowledge building. Hence, the current paper builds on Levrini and diSessa (2008) by applying coordination class theory to classroom learning contexts where disagreements and different interpretations of a common artifact are the locale of potential change. Importantly, this work may help instructional designers and teachers use coordination class theory to support the design of more effective learning environments.

Analytical Tools of Coordination Class Theory

In this section, we present details of coordination class theory in terms of the architecture (organization and structure) of a coordination class, learning processes that result in building of coordination classes, and difficulties students encounter. Similar information, but in greater detail, is also available in diSessa and Wagner (2005) and Levrini and diSessa (2008). We also discuss how the existing architecture can be used to clarify the meaning of context in learning.

Architecture. Rather than directly extracting relevant information of a situation, people extract related information and from that infer the pertinent information. Thus, there are two important pieces of architecture of a coordination class: The *strategies* used to extract information from the world,[1] and inferences that one can use to turn information extracted into the relevant specific information, known as the *causal* or *inferential net*. The *causal net* is all the relevant knowledge that determines that the information observed relates to the desired information. For example, when watching a sliding object, one may extract information about shape, color, size, or speed and then that information may be combined with other existing knowledge to make inferences about force.

Learning. Coordination class theory assumes that individuals have a complex knowledge system consisting of many knowledge elements at various sizes. Within this system, there are two processes for how prior knowledge contributes to learning: (1) elements from prior conceptualizations can be *incorporated* into new conceptualization, and (2) elements from a prior conceptualization can be dismissed or *displaced* from a new conceptualization. These processes become apparent as one "works" a concept across contexts to determine the relevance of that concept. For instance, returning to the prior example, as one works the concept of force across many contexts (e.g., sliding objects, rolling objects, stationary objects, and projectile motion), elements that support recognition of forces in all these situations will come to have higher priority while elements that limit recognition of forces to only situations that involve movement will come to have lower priority. In this process, knowledge elements can be incorporated (or dismissed) as they are deemed applicable (or not) to the concept in a specific context.

Learning Difficulties. In certain contexts, specific knowledge is needed to work the concept, known as a *concept projection*. There are two characteristic difficulties when needing to properly coordinate what knowledge should and should not be applied in a specific context. First, *span* is the difficulty of not having adequate conceptual resources

[1]Elsewhere this has been referred to as a *readout strategy* (e.g., diSessa & Sherin, 1998; diSessa & Wagner, 2005; Levrini & diSessa, 2008), but recently revised terminology has proposed using the term, *extraction* (diSessa, Sherin, & Levin, 2016) and we continue in that tradition.

(knowledge)[2] or not being able to properly apply one's conceptual resources such that one can apply the concept across the many applicable contexts. For instance, one might not be able to adequately apply one's conceptual resources about forces to the myriad of situations in which one might recognize forces. Second, a lack of *alignment* is the difficulty of determining the same information, from different contexts, given that likely different knowledge is being used in those contexts. For instance, a student might have difficulty in determining forces in homework problems and laboratory experiments, given that in those different contexts one might be using different knowledge. In other words, a lack of alignment involves a mismatch between how one's conceptual resources are applied in a specific context, otherwise known as a concept projection, and the context in which they are determining that information. The current paper is about alignment difficulties in a classroom where multiple individuals are applying the so-called "same" concept to the so-called "same" context, encountering difficulties, and then finding ways to overcome those difficulties. This lack of alignment allows for a refinement of the meaning of context in group learning activities.

Addressing the Meaning of Context. There is widespread recognition of the context dependence of learning (e.g., Arcavi, 2003; Enyedy, 2005; Schoenfeld, Smith, & Arcavi, 1993; Stevens & Hall, 1998) to demark how individuals and groups of individuals may interpret a common artifact differently. Yet, there is little agreement about how to define context or use it analytically. For instance, Finkelstein (2005) uses the metaphor of concentric or nested contexts to describe learning in a university physics class. Others compare the classroom and the home or the everyday. Above, for example, we defined context in terms of physical situations (e.g., motion and nonmotion situations involving forces). In another setting, Wagner (2006) pointed out the insufficiencies in the notion of *context* to describe situational features relevant to transfer. Our work in this paper, described in more detail below, takes the idea of *context* beyond a physical situation and includes how one person thinks of another person's ideas. As will be shown, refining the meaning of context to include other's ideas about a situation requires careful attention to the kinds of alignment difficulties that may occur but allows us to describe ways in which resolution of those difficulties provides evidence of learning.

Revisiting an Empirical Analysis of Classroom Learning

Given these analytical tools, now we revisit Levrini and diSessa (2008) to further examine how they applied coordination class theory to an empirical analysis of classroom learning. Their empirical analysis focused on a high school classroom in which students were working to understand the concept of proper time within special relativity. Given that coordination class theory had previously only been applied to individual learning, typically in interview settings, Levrini and diSessa (2008) accomplished an innovation of implicitly treated the entire classroom of students *as if* they were an individual. Using this innovation in the analysis, Levrini and diSessa (2008) documented a series of classroom learning difficulties and successes. First, an intuitive schema took the place of a more refined special-relativity way of thinking about the context. The intuitive schema seeded a misalignment when the students encountered a new context: The students assumed the new context was identical

[2] Although various terms are used within the coordination class literature when referring to knowledge pieces at various grain sizes, we use the general terms *conceptual resources* and knowledge elements knowing the specific size, nature, and content of the pieces is not the central focus of the analysis. A similar approach has been taken by others including Hammer (2000).

to their older context, but in fact this was inappropriate and it led to a misalignment. To make progress, the teacher introduced a new definition of proper time. The new definition increased span, but at the cost of additional misalignment. Eventually the students achieved alignment and an additional context was introduced. That new context played a critical role as it harnessed a new intuitive schema about "riding an object."

From this empirical analysis, Levrini and diSessa (2008) proposed a series of extensions to the theory that they argued are natural extensions without threatening the core theory. The authors proposed a new, stronger, form of alignment known as *articulated alignment.* They observed that, in addition to learning to determine the relevant information from the context, students explicitly and articulately viewed the new contexts as "the same" or "related in some way," meaning students were aware of and articulated the alignment (obviously not in those words) of their ideas. Additionally, Levrini and diSessa (2008) also extended coordination class theory by noting that definitions can seed types of concept projections.

We build on Levrini and diSessa's (2008) empirical paper and continue to examine classroom learning using coordination class theory. However, Levrini and diSessa's (2008) solution for how to model classroom learning, namely to treat the entire classroom of students *as if* they were an individual, does not fully reveal the learning we observed. In our data, there were a series of key moments in which students disagreed with each other and these moments had large effects on subsequent student models. Capturing the conceptual substance of these disagreements and how it influenced subsequent models allows us to not treat the entire classroom as if it were an individual. When applicable, our analysis needs to distinguish among individuals and their differing conceptualizations as it pertains to the substance of the disagreement. The analysis needs to be able to flexibly shift between instances in which all individuals in the classroom are in agreement (as evidenced by the lack of any disagreement) and instances in which one or several individuals in the classroom are in disagreement (as evidenced by their verbal statements).

Specifically, our data consist of group learning in a classroom setting where students engaged in a pedagogical embodied modeling activity known as energy theater (ET) (Close & Scherr, 2015; Daane, Wells, & Scherr, 2014; Scherr et al., 2013). Within this activity, the students built a series of models of the steady-state energy of the earth. Students used different regions of the floor to represent the earth and sun, and they walked between these regions to represent the flow of energy. The collaborative nature of this activity required discussion about what scientific content they were modeling and how they were representing that content. Sometimes the students agreed, sometimes they disagreed, and some of these disagreements resulted in model modification. Over the course of the class period, the students, individually and collaboratively, worked their understanding of the concept across these successive models. By treating each of these models (as expressed through the students' discussions of the models) as new contexts, we were able to analytically capture the conceptual substance of student disagreements and subsequent changes to the ET models across the successive contexts. Below, we highlight elements of coordination class theory that allow us to describe classroom learning successes and difficulties as they unfolded. As will become clear, coordination class theory allowed for capturing moments when individuals have different interpretations of a joint artifact and therefore one individual may affect other individual's or the entire groups' understanding, often through moments of agreement and disagreement. Thus, we are aligning coordination class theory to a new context: group learning in a classroom that was engaged in this embodied modeling activity. This application is important for determining how a well-developed theory of individual learning can be useful in understanding a messy classroom setting, and in turn, also applicable to teachers and instructional designers who are interested in scaffolding conceptual change in classrooms.

Anticipating How Coordination Class Theory Applies to the Empirical Analysis

In coordination class theory, the *concept* is the scientific idea or phenomenon, and the *context* is the particular instance in which that concept or scientific phenomenon is being observed in the external world. For instance, the concept of force can be observed in the context of a coin toss or an object sliding down a ramp. According to diSessa and Sherin (1998), the concept of force can reasonably be described as a coordination class, but not all concepts can be coordination classes. diSessa and Sherin propose that, in general, physical quantities are appropriate candidates for coordination class theory. In this empirical analysis, the concept is relatively straightforward: "steady state." A system is in steady state when the inflow and outflow are equal, similar to a dynamic equilibrium. However, context has a complicated definition and therein lies the crux of our analytical extension.

Several Kinds of Contexts. In the first sense of *context*, in our work, there was one scientific context. The concept of steady state was applied to one relevant scientific phenomenon, the earth's energy. In our data, the concept of steady state was not applied to other science content areas, thus we are unable to analyze the span of steady state. We refer to the scientific phenomenon, the earth's energy, as the *science context*. Our notion of science context is similar to prior coordination class studies where *context* was used to refer to different situations in the external world where the concept is applicable (e.g., the concept of force being applicable to two contexts, a coin toss and a block sliding down a ramp). The accepted model of such a science context can be thought of as the community consensus, an abstract collection of all our knowledge of a situation that is not necessarily known by any one individual (and likely cannot be known by one individual) (Redish, 1999).

However, in another sense of *context*, there were three *classroom contexts* where each one references the entire class's interpretation of an ET model in that setting. There were two classrooms of students that each separately built ET models of the steady-state energy of the earth (two classroom contexts), and then, after presenting their ET model to each other, they jointly built a third ET model (the third classroom context). In some ways our notion of a series of classroom contexts across which students work their concept is analogous to students working their concept across multiple contexts that were offered by a researcher in an interview setting (Parnafes, 2007; 2012; Wagner, 2006). For instance, similar to how a student could work a concept projection of force across various laboratory settings and homework exercises, in our data students worked the concept of steady state across a series of classroom contexts: the original classroom where they built their initial ET model, the classroom situation as they presented it to their peers, and finally, the joint classroom where the two classrooms built a single model together.

In yet another sense of *context*, there were as many contexts as there were students. A model like ET is also an activity and an external representation in which everyone participates. Each person has his or her own interpretation of what that external model is showing. Each person's interpretation acts as the *context* for that person's thinking and acting, but it becomes pertinent to the group of students and accessible to us as researchers when another student explicitly considers it. Thus, when considering an individual's interpretation of an ET model from their own perspective, we refer to their concept projection as their *individual interpretation,* and when referring to their interpretation of the same model from another's perspective, we refer to the *student context*, consistent with a student observing another student's idea "in the external world." This difference creates some asymmetry between two interacting students, but it forefronts the learner and their learning at the center of the *student context.* Our usage of student context is different from how the notion of context was used in prior coordination class studies, but this usage is key for capturing different individual's interpretations of the same model.

Sometimes when an entire classroom (or majority) of students' individual interpretations are in agreement, then that is equivalent to the *classroom context*. That is, when all student contexts are in agreement, then their collective interpretation is equivalent to the *classroom context.* Oppositely, there could be no agreement whatsoever. Even when a group of students creates an ET model, each student could have his or her own individual interpretation in which to view the model. For instance, imagine a classroom of students all examining the same graph and each student coming up with their own interpretation of what that graph means. Admittedly, this situation of no agreement is unlikely.

Disagreements. In our empirical analysis, sometimes there was a disagreement between a student context (one student's interpretation or utterance as considered by another student) and a classroom context (an entire class's common interpretation of an ET model). Other times there were disagreements between two different classroom contexts. Imagine one class of students observing an ET model that had been created and presented by another class. The presenting class has their own classroom context through which to interpret the model that they created and presented. However, the observing class potentially has a different interpretation of their peers' model, a different classroom context of the same ET model. Hence, there would be a disagreement between the two classroom contexts as a result of these two different interpretations of the same model. In sum, with the many levels of context, there are many opportunities for disagreement and several types of alignment difficulties.

As will become more evident in the analysis, delineating the student context from the classroom context and mapping when they are and are not equivalent is key for analytically tracking learning at the individual and group levels and when an individual contributes to the groups' learning. Thus, the utility of our approach is evident in using the theoretical machinery to coordinate the individual and group levels. This is imperative, given that we are applying a theory of primarily individual learning to a situation of group learning.

Difficulty as a Lack of Alignment. Previously, the difficulty of a lack of alignment has been defined as the difficulty of an individual applying the same concept across contexts, where "context" has previously meant what we call the *science context*, different situations in the external world where the concept is applicable. However, since we delineate the student context and the classroom context, we need to carefully redefine and explain alignment in regard to each of those contexts. Thus, we denote three types of alignment difficulties:

(1) the difficulty of applying the same concept across science contexts (not relevant to the current analysis, but this is the typical usage in coordination class theory and has been seen elsewhere, for instance, diSessa and Sherin (1998)),
(2) the difficulty of applying the same concept across student contexts (e.g., an individual student's interpretations of their ET models as seen from a peer's perspective), and
(3) the difficulty of applying the same concept across classroom contexts (e.g., a classroom of students' common interpretation of an ET model).

The previously described classroom-context/student-context disagreement can be an example of the second type of lack of alignment difficulty and play out as follows: Imagine a classroom context in which all student contexts are (momentarily) in agreement as they collectively create an ET model. However, through the process of discussing the model and acting it out, a student might come to "see" something new; they might recognize something in the model that is unexpected or perplexing. That recognition might trigger them to interpret something in the classroom context differently from their peers, a shift in their individual interpretation. The subsequent lack of alignment would likely be apparent in what the student says aloud (e.g., "Hey, wait a second! Something is off!") to be heard by peer(s).

Just as there are multiple kinds of alignment difficulties when thinking of multiple contexts, there are multiple ways to address this lack of alignment to bring that student's interpretation and their concept back into alignment. As one example, the student might propose a modification to the classroom context. Presumably, the proposed modification would change the ET model (and by default the individual student's interpretation of the model and that interpretation as seen from a peer's perspective—the student context) while also changing the classroom context (the remaining group of students' interpretation of the ET model). The result would be a return to alignment of the student's interpretation of the concept in the student context while also bringing the student context and the classroom context back into agreement. In other words, after the modification, the student who previously recognized something being "off" and their peers would all be in agreement and have similar interpretations of the ET model. A second example of resolving a classroom-context/student-context disagreement could come through a modification to the information extracted by the student.

An example of a lack of alignment between classroom contexts can play out in the following manner: Imagine one classroom of students that generated an ET model. While the other classroom of students was observing and interpreting their peers' model, it became apparent that their peers' model did not align with their own (classroom) conceptual resources—resulting in a lack of alignment. In this example, the lack of alignment could be resolved by either a modification to one of the classroom contexts or a change to the information extracted which would thereby cue different conceptual resources.

As will be shown in the empirical analysis, the problem of alignment and solutions to that problem become complicated: There are three types of alignment, each one associated with a kind of context (science context, classroom context, and student context) and several ways to fix the problem. The problem can be solved by changing the ET model, which can result in a change of information extracted from the subsequent model. The problem can also be solved by directly changing the information extracted, while not changing the ET model. In that case, changes to the knowledge resources cued can occur through incorporation or displacement. Incorporation and displacement of knowledge resources are types of learning, and, thus, instances in which the students change the information extracted from the ET model are likely to be instances of learning.

Our empirical analysis will illuminate several different solutions to the problem of alignment. In the first empirical example, changing the classroom context solved a problem of student-context/classroom-context alignment, and the students were able to incorporate new knowledge into their conceptual structures. In the second example, a problem of classroom-context/classroom-context alignment was solved by changing the information extracted and thereby changing the conceptual resources cued. And, in the more complicated third empirical example, there were a series of alignment problems that were solved by combining these two approaches. In the third example, students took conceptual knowledge elements from one classroom context and applied them to a new classroom context. That knowledge was then used to inform the subsequent changes to the classroom context, an example of incorporation.

A Commentary on Span. We have focused our discussion on the issue of alignment across contexts rather than a second learning difficulty, known as span. Span is the difficulty of not having adequate conceptual resources to apply the same concept across contexts. For example, a student might not have adequate conceptual resources about steady state to apply that concept across the various contexts encountered. In our example, they might have limited knowledge about the sources and constraints influencing the equal inflow and outflow of energy. Notably, we did not observe this difficulty in our empirical analysis. Students showed a detailed knowledge of the ideas involved in steady state, radiation from the sun to the earth, and radiation from the earth into space. More importantly, we observed no discussion to clarify these ideas, and instead observed discussion of ideas that went beyond what we analyzed (such as the role of different wavelengths of light at different locations in the system). Perhaps if they had encountered different scientific contexts than what they did encounter, then we might have observed the difficulty of span. By not observing difficulties with span and only observing difficulties with alignment, we are able to focus our analysis on just one element of coordination class theory.

METHODS

Having given an overview of our context, theoretical framework, and results, we return to a more detailed description of our project.

Instructional Activity: Energy Theater

The instructional context for this work is an embodied modeling activity known as Energy Theater (ET), in which students created models with their bodies' positioning and movement. ET is a research-based and -validated learning activity based on a substance metaphor for energy and designed to promote conceptual understanding of energy (Scherr et al., 2012b). In this article, it forms the backdrop for the analysis of model revision and is not the focus of the analysis or contributions. For readers interested in this pedagogical activity, we direct them to Close and Scherr (2015), Scherr et al. (2010, 2012a, 2012b, 2013), and Daane et al. (2014).

When enacting ET, each participant identifies as a unit of energy that has one and only one form at any given time. Groups of learners work together to represent the energy transfers and transformations in a specific physical scenario—for example, a block moving at a constant speed along a floor. Participants choose which objects in the scenario (block, hand, ground, perhaps air) will be represented and which forms of energy are appropriate for each object (kinetic energy, potential energy, or thermal energy). Regions on the floor are used to indicate the objects in the system. As energy moves and changes form in the scenario, participants move to different locations on the floor and change their represented form. This social interaction in a structured environment (of "objects" on the floor, etc.) has been shown to promote the learning goals of modeling of energy as conserved, localized, transferring among objects, and transforming among forms (Scherr et al., 2012a, 2012b). In the data presented in this article, students used ET to represent and model the steady-state energy of the earth. As we will describe in further detail below, the students self-organized their bodies' positions and movements to represent the core ideas about energy flow to and from the earth, with minimal guidance from instructors.

Scientific Content: Steady-State Energy of the Earth

The scientific context for our modeling environment was the steady-state energy of the earth as energy joins and leaves the earth at relatively equal rates, while the earth itself produces thermal energy, as well. The energy of the earth is complicated, given the input of energy from the sun and the complicated role of the earth's atmosphere as certain wavelengths of light are absorbed or reflected. However, all of the models discussed in this study modeled the steady-state energy of the earth without focusing on the earth's atmosphere. Generally these models focused on the role of the earth and sun and the rates of energy leaving the sun, entering the earth, and leaving the earth, although there were exceptions that will be discussed in the data analysis.

Steady state has not been a major content focus in science, technology, engineering, and mathematics (STEM) education, although many scientific phenomena exhibit steady-state and dynamic equilibrium behaviors in which the rates of input and output are equal, resulting in an apparent equilibrium at the macro level while the micro level is in flux. The concept of steady state is widely applicable across chemistry, physics, biology, and earth science fields. For example, the movement of granular matter in sand dunes across a desert involves a dynamic equilibrium in which the relative rates of particles joining and leaving the dune are equal when the size of a dune is constant (Barth-Cohen, 2012). Recent literature on teaching about the greenhouse effect has pointed out the importance of this topic and known difficulties (Besson, De Ambrosis, & Mascheretti, 2010; Tasquier, Levrini, & Dillon, 2016). However, steady state is not commonly addressed in traditional curricula, although static and dynamic equilibrium are highlighted within the stability and change crosscutting concept in the Next Generation Science Standards (Achieve, 2013).

Classroom Setting

Data for this study were gathered from in-class observations of two teachers, Ms. Girard and Mr. London (aliases), teaching ninth-grade earth science. Ms. Girard had attended an evening professional development activity in which ET, described above, had been used to model a variety of situations. We note that she proposed the topic under study in this paper as an example for teachers to enact. Shortly after, she contacted one author to suggest that she repeat the activity with her students and to inquire whether we would like to observe and study her class while doing so. This is consistent with our long history of interacting with these two teachers about issues related to teaching and learning, though past interactions have been informal and not related to research.

Neither Ms. Girard nor Mr. London had done ET in their classroom before. They assigned their students to "Model the energy transfer/flow to show how Earth remains at a fairly constant temperature." Students were expected to use the tools of ET, written on the board. Each student was to be a unit of energy. Ropes were to be used to delineate objects in the system. Movement from one point to the next indicated movement of energy between objects in the system. A total of six classrooms (three periods of Ms. Girard and Mr. London, each, in parallel) were observed. One period was not studied further because class sizes were so small that nearly no discussion happened. In the remaining two periods, we observed a total of six enactments of ET—for each period, one individual class enactment for each class, followed by a joint enactment at the end of each period which included all the students from both classes. Details of the enactments are given below.

We note that several aspects of the classroom discussion are important but will not be discussed further in this paper. First, ET is purposefully designed to be underspecified as to what one should do. Students had to figure out the model on their own. This led to a great deal of discussion, often in parallel, with many students talking at once. This was, at times, utterly chaotic. Given the many voices, we were unable to adequately discern what students were saying during these times.[3] As a result, our data are focused on those moments when only one or a few speakers were talking, even in the large classroom setting. These moments of large-class discussion were facilitated by the two teachers. Both were remarkably adept at hearing comments students were making and asking for the whole class to listen to one student's ideas, in particular. The class would fall silent, listen, and a more-or-less organized discussion would follow. Often, though, the class moved back toward chaotic talk by many different speakers. This cycle of multiple voices, elicited single voice, and discussion was repeated throughout all our observations.

From our observations, it quickly became clear that the topic students were modeling was not new to them. Students had completed a unit on the constant temperature of the earth. As part of this unit, it became clear, they had studied the different wavelengths of light (ultraviolet, visible, and infrared) and to what percentage these wavelengths of light transferred energy from the sun to the earth. They had also talked about the flow of energy away from the earth, but only in one wavelength. We present one episode in which this knowledge is important, but make the more general point here that students entered into this activity with experience in the topic. This suggests to us that the activity was not, to them, an activity in which to discover new ideas, but instead an activity to build on prior ideas. (This may also explain why we did not observe difficulties related to span.)

Data Analysis Methods

The empirical analysis conducted here can be viewed as an example of knowledge analysis, a methodological approach commonly used in coordination class theory research to study knowledge with the purpose of examining learning. Knowledge analysis is a developing methodology, and details about its history, theoretical foundations, and practical implementation are available in diSessa et al. (2016).

Data consist of video and audio of the classes participating in ET. After the data were collected we began by transcribing. Given that the discussions were utterly chaotic at times, we strategically decided to focus on the moments in which only one or a few speakers were talking. Those moments were transcribed in detail and figures were created to analytically track the ET models that were being created and modified. We noticed that many of these moments corresponded to times of model revision. We began by examining the conceptual substance of the model revisions and found that many of these moments of model revision corresponded to instances of intellectual disagreement. Subsequently, we looked across all of these moments for common patterns and recognized that most involved differences in interpretation of an ET model, sometimes between an individual and the entire class and sometimes between two classes. Eventually there was a grounded process of coding the data. We coded the data for various conceptual resources, such as ideas about steady state or different wavelengths of light. We also coded for the information extracted from one's own or others ET models, such as the amount of energy entering or leaving the earth or whether or not the model contained a sun. When identifying the conceptual resources and information extracted, we looked for multiple lines of transcript

[3]Given the nature of the classroom discussions, we were often unable to discern which individual was speaking. Therefore, if the identity of the speaker is unknown, but if it is known which class they are a member of, they are identified as either, LS which stands for London student, or GS which stands for Girard student. If it is unknown which class they are a member of, then they are referred to as Student 1, Student 2, etc.

to triangulate the same code. Consequently, we were able to deduce when there was an implicit expectation violated, and, when possible, we traced those violations backwards to prior ET models or previously used conceptual resources. Looking across many instances of implicit expectations appearing to have been violated led us to common patterns that were cast in light of alignment difficulties. At that point, we more rigorously applied the notion of student context and classroom context when applying the redefinitions of alignment difficulties across all instances of the patterns. On several occasions, we held video viewing sessions (Erickson, 2006) with researchers who were not involved in this analysis to gain additional perspectives.

ANALYSIS

We present three examples of learning in which students work the concept of the earth's steady-state energy across multiple classroom and student contexts.

In the first example, there was a lack of alignment between the student context (the student's interpretation of the ET model from another's perspective) and their conceptual resources. The lack of alignment was fixed by a modification to the ET model and thus, by default also a modification to the classroom context and the student context, resulting in the incorporation of new knowledge.

In the second example, one class was presenting their ET model and the other class was observing. When this happened, there was a lack of alignment between the observing classes' conceptual resources that were used to extract information from the ET model and the presenting classes' classroom context. The lack of alignment was fixed by a modification to the information extracted from the context.

In the third example, each classroom presented their ET model to the other class and there were multiple instances of lacking alignment between classroom contexts and information extracted that were subsequently all fixed in the generation of a new context that was jointly generated by both classrooms.

The first and second examples each illustrate a single lack of alignment and modifications, resulting in learning, whereas the third and more complicated example illustrates several successive lacks of alignment and resulting learning. In all examples, we see how the discussion and negotiation of ideas can dramatically influence changes to the model and subsequent learning.

Example 1: Modifying the Classroom Context to Foster Alignment

In this first example, there was a lack of alignment between the student context (an individual's interpretation of an ET model as viewed from another's perspective) and the information that one student extracted from that classroom context, based on their conceptual resources. The information that the one student extracted did not match their relevant conceptual resources about the concept and the lack of alignment was fixed by a change in the classroom context.

Mr. London's students generated a model in which the earth was represented by a circular rope on the floor. Students walked in small circles entering and leaving the earth around the north pole, south pole, and equator, representing energy entering and leaving the earth at those three locations (see Figure 1). Although they represented energy flow at three locations, it is unknown why they choose these locations.

While acting out their model, one student stopped the class to point out that the earth was not in a steady state because there was no regulation for when people entered and left the earth, thus the amount of energy in the earth was not constant, as it should have been.

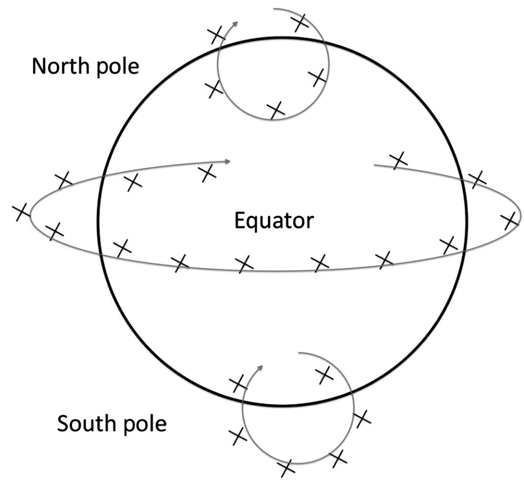

Figure 1. Bird's eye illustration of Mr. London's first period class ET model. The x's represent people, the curved arrows represent their walking path.

1. L S: Does this make sense?
2. L S: No, no, no.
3. L S: It's not in a steady state though!
4. L S: Wow, this isn't steady state!
5. L S: Move slower.
6. L S: I'm trying.
7. L S: Wait, wait, wait, wait, wow, wow.
8. L S: Cut [Students all stop walking and stand still in place]
9. L S: Guys! [Holds hands out as if to say 'stop']
10. L S: That is not steady state because it's not really regulated.
11. L S: Walk steady.
12. L S: Walk steady.
13. L S: I can't tell.
14. L S: Okay, not regulated.
15. [All talking at once, inaudible]
16. L S: Like sometimes there is a lot of people in the circle and then sometimes there is zero people in there.

For (at least) one student, their concept of steady state includes knowledge that requires a constant number of people (a constant amount of energy) inside the circle (earth). When observing this enactment of the model (the classroom context), this student's strategy of counting the number of people inside the circle extracted information that violated their concept projection. More specifically, this violation occurred because the number of people inside the circle was "not really regulated" (line 10). The number of people in the circled varied (line 16). This was a lack of alignment between the student context (the individual's interpretation of an ET model as viewed from another's perspective) and their conceptual resources about regulation, what it means, and that it is important.

Following recognition of the problem, several students generated suggestions that involved ways to regulate the flow of people (energy):

17. L S: We should have a few people walking around in there and then like, and then at some point switch a person out and like, there has to be, an input and an output. So say, like two people on the pole and three on the outside. So one person walks out and one person walks in . . . Give them a tag out and you'll switch . . . just a tap out.

The suggestion of a tagging mechanism to control the input and output of people (energy) into the circle (earth) fixed the previously mentioned problem of there being a lack of regulation (lines 10, 14, and 16). The addition of the tagging mechanism to modify the classroom context had the effect of returning to alignment the one student's extracted information and the student context (their interpretation of the ET model as viewed from another's perspective—the recognized hole of there being a lack of regulation). It also had the effect of creating unification between that individual's interpretation of the ET model and the classroom context (the entire classes interpretation of the ET model). That is, after the change, their individual interpretation was again in agreement with the classroom context. We note that it did *not* change the fact that the number of students in the earth circle was not constant, since people stepping into the circle had yet to tag other students, or students leaving the circle after being tagged were not yet out of the circle. Instead, the tagging mechanism was used by student to indicate *which students counted* to the energy in the earth circle.

This process of there being a lack of alignment, making a change to the classroom context, and a subsequent return to alignment is an example of working the concept across contexts. For the student(s) who extracted information that violated their concept projections, those students worked the concept of steady state across contexts, namely the initial problematic student context and the subsequent classroom context, often resulting in modifications (hence, the introduction of the tagging mechanism). We describe this as learning, as they incorporated the regulation of energy flow into their new conceptualization of steady state. Furthermore, from the entire classroom perspective, given the classroom agreement about the lack of regulation as suggested by the proposal and implementation of the tagging mechanism, this is an example of group learning: A new element, regulation of energy flow, was incorporated into the group's conceptualization of steady state.

We note the contrast between this analysis and that carried out by Levrini and diSessa (2008). Had we assumed that the entire classroom could be treated like an individual, as they did, we could have interpreted this situation as if that individual was developing their idea of the situation. This individual's extraction of counting humans in the circle (and requiring it to be constant) would be reasonable. However, since we are instead attending to the many individuals in a single class, the issue is of alignment between these individuals and how each of them extracts information and makes sense of it. Because of our different analysis framework, we think of this first example as a case of alignment difficulties within a larger group, a theoretical interpretation forced on us by our modeling of the class as a set of individuals, not a single individual. Furthermore, distinguishing between individuals within the class is important if one is to make claims about learning that pertain to some, but not all, of those individuals, as was done our analysis. The next example is of a different case, again illustrating the problems of alignment between many individuals' ideas about a single science context.

Example 2: Modifying the Information Extracted to Foster Alignment

In the second example, there was a lack of alignment between the presenting class's classroom context and the information the observing class extracted from the former's

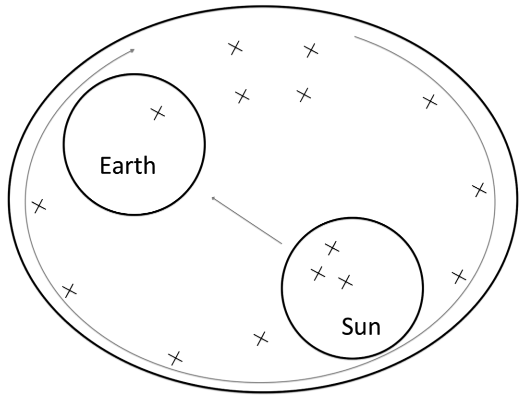

Figure 2. Illustration of Mr. London's second period classes ET model.

classroom context; the lack of alignment was fixed by a modification to the information extracted.

In this example, the classroom context was an ET model generated by Mr. London's second period class. There were three circular ropes on the floor (see Figure 2). One small rope represented the sun, the other small rope represented the earth, and the large rope encasing both smaller ones represented the boundary of the model. Three people at a time left the sun representing three types of light (ultraviolet, infrared, and visible) and entered the earth. Afterwards, one person representing infrared light left the earth and went into space. Mr. London's students had intended that the three people entering the earth were worth the same amount of light as the one person leaving, since the people represented different types of light. Additionally, there were other people wandering outside of the sun and earth representing random energy in space.

A lack of alignment became clear as Mr. London's class presented its ET model to Ms. Girard's class.

18. Ms. Girard: Ronald, what is your question?
19. G S: How come there is only one thing leaving but three coming in? I think the earth would like, explode eventually.
20. [Laughter]
21. G S: Equal input and output
22. Ms. Girard: Why would you think the earth would explode if that happened?
23. G S: Cause, too much energy
24. L S: We have three
25. G S: Not enough [Energy] leaving the earth, I think.
26. . . .
27. G S: I don't know if they already explained it, but how many different rays were hitting the earth, and only 1 coming out. Isn't there supposed to be equal coming in and the same out? But obviously the coming out would be IR [infrared].
28. L S: Yeah, that is basically what we were trying to do, but we were just . . . [inaudible]
29. L S: He [the one person leaving the earth] was worth all three of us. Cause we were just representing the three different kinds of energy that were going through the earth. And he was the one kind of energy come out of the earth.
30. G S: Oh
31. G S: I see.

32. L S: Oh, so if were all equal in parts, then the earth would explode. But we're not. There is more of Ian than there are of us.

When the Girard students were observing the London students' ET model (the London classroom context), the Girard students' strategy of counting the number of people entering and exiting the earth extracted information that violated their concept projection. Specifically, the Girard students questioned why there were three people entering the earth and one person leaving (lines 18 and 26). Based on their questions and statements (lines 18, 20, and 26), the Girard students had access to knowledge elements suggesting to them that there should be an equal amount of energy (light) entering and leaving the earth and they expected to extract information aligning with those resources, but that did not occur. Thus, the information extracted (unequal numbers of people entering and leaving) violated their concept projection. In response to those question, the London students explained that the three people entering were meant to be "worth" the same amount of energy as the one person leaving (lines 28 and 31). This was a lack of alignment between the information Girard students extracted, which was related to their knowledge elements, and the London students' classroom context.

The lack of alignment was fixed by a suggestion from one of the London students that the Girard students should not extract the information they did (signifying increasing amounts of energy in the earth) and should instead extract something different (a constant amount of energy based on "more of Ian than there are of us" (line 31)). Thus, the lack of alignment between the information extracted (by Girard's class) and the classroom context (generated by London's class) would have been fixed by a modification to the information extracted. We note that the offered solution violated the rules of ET, in that they chose to have each person represent a *kind* of energy (infrared, visible, or ultraviolet) and not a *unit* of energy.

Similar to the prior example, this process of there being a lack of alignment, making a change, and a subsequent return to alignment is an example of working the concept across contexts, but differently. In this example, there was a change to the information extracted. A modification to what information is extracted has the potential to be a good opportunity for learning as it could result in displacement or incorporation of elements into a new conceptualization. For Girard's class, their conceptualization of steady state contained an element of equal amount of energy (light) entering and leaving the earth both before and after this episode; therefore, this may not have been an instance of learning for them. However, for London's class there may have been a modification to the knowledge elements in their conceptualization, namely there might have been a displacement of knowledge about unequal numbers of people entering and leaving with knowledge about equal people entering and leaving. The evidence for this displacement comes from the final ET model (not discussed here) in which there were equal numbers of people entering and leaving the earth, suggesting for London's class there might have been group learning.

Example 3: Generating a New Classroom Context to Foster a Solution to Multiple Alignment Difficulties

In the third example, each classroom was presenting their ET models to the other class. During the process of observing the other classroom context and discussing that model, there were multiple moments of a lack of alignment between classroom contexts and conceptual resources that were being cued by the information extracted by the observers. These lack of alignment problems were subsequently all fixed by the generation of a new joint context.

First Lack of Alignment: With No Sun, Where Is the Energy Coming From?. Mr. London's first period class (the same class as discussed in the first example) had created a model in which energy entered and left the earth at the poles and equator, and there was a tagging mechanism controlling the inflow and outflow. Later during that class period, this model was presented to Girard's class, and during the discussion there was a new lack of alignment, namely between the London classroom context, which did not contain a sun, and Girard's class's conceptual resources, which involved a sun.

33. G S: Where is your, if you have energy on the outside, where is it coming from since you don't have a sun?
34. [inaudible]
35. [Laughter]
36. L S: You didn't give us anything to be the sun!
37. L S: Yeah, we didn't have anything for the..!
38. L S: Mr. London
39. L S: I am the sun!
40. L S: The world revolves around . . .
41. L S: It's really just, it's just.
42. L S: Mr. London is the sun.
43. G S: I thought that was the sun, but is that the earth?
44. L S: Yes.
45. L S: Yeah.
46. L S: It's pretty much, not, where it's coming from but how it would effect the earth itself.
47. L S: This is just a model, this is the system boundary.

For the Girard students, their conceptual resources about steady state likely included information about a source of energy. This is apparent from their model (not yet discussed), in which they included the sun as a source. The Girard students were looking at the London students' ET model, and they tried and failed to extract a sun (lines 32 and 42). As a result of their failure to extract a sun, the Girard students' concept of steady state (which likely included conceptual resources about a sun, and thus a source of energy (line 32)) was out of alignment with their classroom context, their interpretation of the ET model that had been created by London's students. The London students understood the predicament, and they entertained the possibility of changing their classroom context (their ET model) by adding a sun (lines 35–41), which would have the effect of solving the lack of alignment problem.

However, there was a second solution proposed to this lack of alignment problem. London students recognized the lack of alignment predicament of the Girard students, but rather than accept it as a problem to be fixed by modifying their ET model, they instead asserted that the problem does not exist (lines 45 and 46). They explained that their science context concerned only the effect on the earth; their classroom context involved only the inflow and outflow from the earth. Implicitly, the London students' concept did not include a source, it only focused on inflow and outflow, and if the Girard students were to change their concept to also only focus on inflow and outflow, that modification would fix the alignment problem. As will be shown later, the first of the two solutions proposed to the lack of alignment problem, adding a sun, was the solution used in the final joint model.

In this lack of alignment, there was an opportunity for group learning. The London students considered adding a sun to their classroom context; adding a sun (a source) to their conceptualization of steady state could have been an example of incorporation of a new element into a prior conceptualization. Another possible instance of learning occurred

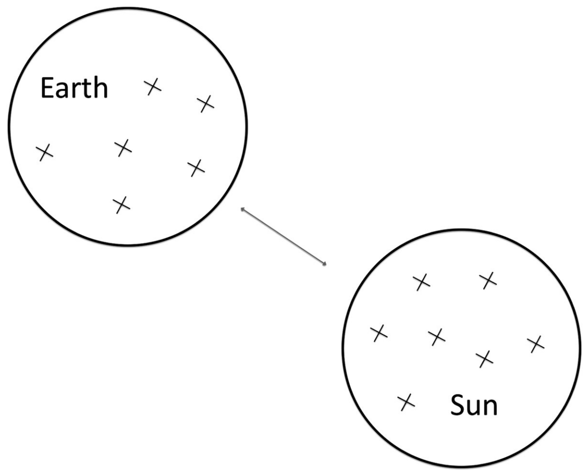

Figure 3. Illustration of Ms. Girard's second first class ET model.

when the London students suggested that the Girard students change their conception to focus on only inflow and outflow. If the Girard students were to have done this, it could have been an instance of group learning by displacing a knowledge element about needing a source of energy with a new element about focusing on only inflow and outflow. In the end, the final joint model included a sun and the suggestion of only focusing on inflow and outflow was dropped. Thus, the London students incorporated knowledge about a source into their conceptualization, thereby learning, while comparably, in this instance, the Girard students did not change their conception.

Second Lack of Alignment: Energy Leaving the Earth and Going Back to the Sun. Following the above discussion, there was a switch of presenters, and Ms. Girard's class presented their model to the students from Mr. London's class. The Girard class had created a classroom context in which there was one circle that represented the earth and another circle representing the sun. Half of the students were inside each circle, and they simultaneously all switched locations (Figure 3).

During the discussion of this model, there arose a lack of alignment between one London student's concept of the sun being the source for the energy and that one student context (their individual interpretation of the ET model created by the Girard class as evidenced by what they said aloud). This lack of alignment was challenged on several fronts, but then it was taken up and applied to a different classroom context.

48. L S: Are you telling us that all of the energy that leaves earth goes back to the sun?
49. L S: Well, it has to be leaving and coming back at the same rate, or, it
50. [Laughter]
51. [Inaudible]
52. L S: But does it all goes back to the sun?
53. L S: Yeah, or does it go elsewhere?
54. [Inaudible]
55. G S: Well, there is a lot of it and not as much of us, so
56. [Laughter]
57. G S: Goes back to the sun.

58. L S: Okay, what did ours do? [Referring to Mr. London's class's model, Example 1]
59. L S: Ahhh? [tone implies uncertainty]
60. L S: Went right outside the system and went right back in.
61. L S: Yeah
62. [Laughter]
63. L S: You have a point there.

Where in lines 47–56, the Girard class was the subject of attention, in lines 57–62 the London class became the subject of attention and reflection. Before line 47, the London students were observing the Girard students' classroom context and (at least) one London student extracted information about the energy leaving the earth and going back to the sun (line 47 and 51). This was a lack of alignment between that student's concept of the sun being the source of energy and their student context (their interpretation of the ET model created by Girard's class). Furthermore, that student's comment indicated a certain amount of incredulousness directed at Girard's class (line 51). Perhaps with that comment the London student was intending to point out a problem, what we refer to as a lack of alignment between what they perceived to be Girard's classroom context and the Girard classes' concept, given a reasonable expectation that Girard's class did not intend to show the apparent nonsensical situation of energy leaving the earth and going to the sun.

In response to that comment, a different London student asserted that the previously raised concern was not a problem if one shifted their conceptual resources. In line 48, a London student pointed out that there would be no lack of alignment if instead one considered the Girard ET model from the point of view of the model that was created by the London classroom, as discussed previously—the amount going out equaled that going in, which was what mattered. In that sense, the relevant conceptual resources focus on the energy leaving the earth and coming back into the earth at the same rate, not on what causes the energy to do so. This perspective is consistent with the London student's comment in line 45 about focusing on how the energy affects the earth, not where it comes from.

Then a student from Girard's class joined in and pointed out that there was no lack of alignment, instead there was a flaw in the available materials, specifically not enough people to illustrate their concept (line 54). In other words, the prior extraction by London students (lines 47 and 51) was incorrect; it was not what was intended to be extracted by Girard students.

Following this conversation, there was a switch as several London students pointed out that the previously identified lack of alignment (lines 47 and 51) applied to the ET model that they had previously created (lines 57–62). Recall, from the previously described analysis, the London students had created an ET model in which energy entered and left the earth at the poles and equator and there was a tagging mechanism controlling when energy entered and left and, importantly, no sun. Here the London students extracted new information, a lack of a sun, from their prior classroom context, the ET model they had previously generated. This new information was not aligned with their conceptual resources, thereby creating a new lack of alignment between their classroom context and their concept, about the lack of a sun in the ET model they had previously generated. This process of taking knowledge extracted from one context, applying it to another context, and using it to inform subsequent changes in that context is a type of learning through incorporation that involves multiple contexts and several individuals.

This episode was relatively complicated as it began when a London student raised a lack of alignment about energy leaving the earth and going to the sun. This lack of alignment was challenged by another London student who suggested shifting conceptual resources. Then it was challenged by a Girard student who suggested a different extraction. Finally, the initial lack of alignment and the embedded extraction was applied by London students to their own, previously presented ET model, a different classroom context. As will be seen in the discussion of the final joint model, this lack of alignment was eventually fixed with a change to the classroom context by having the motion be one directional.

In this instance there is evidence of individual learning and group learning. The London student who suggested a shift of conceptual resources (line 48) may have incorporated a new element into their conceptualization, energy leaving and entering at the same rate, and displaced an element about what causes the energy to do so, both of these processes are considered instances of learning. Additionally, the London students collectively (as evidenced by the lack of any disagreement) recognized that their previously created model did not have a sun. Thus, a knowledge element about needing a sun, or more generally, a source, may have been incorporated into their conceptualization of steady state.

Third Lack of Alignment: "The Earth Would Freeze". Immediately after the prior transcript excerpts, while continuing to discuss the ET model created by Girard's class, another lack of alignment emerged. Again the lack of alignment was between London's students' concept and their classroom context (their interpretation of the ET model that was created by Girard students, Figure 3).

64. L S: When you made the transition there was no energy
65. // Yeah //
66. G S: That wasn't a question.
67. [Laughter]
68. Ms. Girard: Why wasn't there any energy in the earth? Is that your question?
69. G S: That was like crazy.
70. G S: Cause we didn't think about that.
71. [Laughter]
72. Mr. London: You know, it's important to catch little tidbits, someone had an idea about what that, what would happen in a real system if that actually happened. A real system would, somebody said, but I don't.
73. L S: Go to zero //
74. [inaudible]
75. Mr. London: The temperature would, would you say that again? Just so everybody can hear.
76. L S: The earth would freeze.
77. [Laughter]

For the London students, they likely had conceptual resources about steady state that included information about the energy inside the earth being constant, which would be in accordance with how their conceptual resources were used in in their own ET classroom context, as previously discussed. The London students were observing the Girard students' classroom context and they extracted information about the earth being empty with no energy inside (lines 63, 67, 75). Literally, this was a correct extraction; during the moment when Girard students switched locations, there were no people (energy) inside the earth. There was a lack of alignment between London's students' concept of steady state (in resolving the issue named in line 16 of Example 1, London's students had made clear their need to have a constant amount of energy inside the earth) and the London students' classroom context, which was their interpretation of the model that was created by the Girard students.

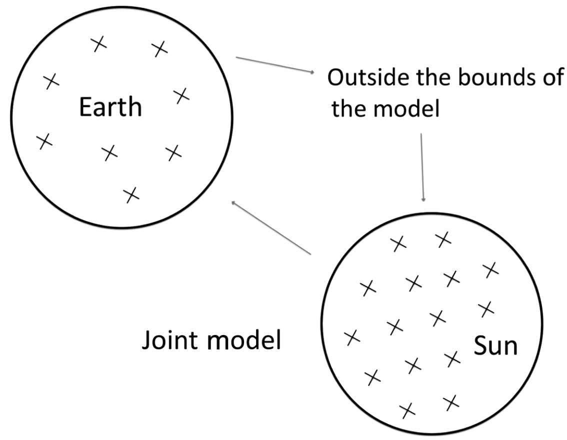

Figure 4. Illustration of the final joint Girard–London classes' model.

Furthermore, there is also some evidence that Girard students experienced a similar lack of alignment. Likely, the Girard students' conceptual resources about the steady-state energy of the earth did not include knowledge elements about the earth freezing due to a lack of energy. Likely, they did not intend to create a classroom context that would show the earth freezing. Perhaps they did not consider what unintended information would be extracted from their classroom context (line 69). This suggests that the Girard students' classroom context was not aligned with their conceptual resources.

The resolution of this lack of alignment is given below. In the final joint model, this lack of alignment was eventually fixed with a change to the classroom context. People walked from the sun to the earth; tagged a peer inside the earth who would then walk from the earth to a location outside the bounds of the model, and then re-enter the model at the sun, thereby ensuring that the earth was never without energy (Figure 4). Furthermore, this resolution may have contributed to Girard's classes group learning. Girard's class may have inadvertently utilized knowledge elements that led them to create a model with no energy inside the earth. During this episode, they may have displaced those knowledge elements as they recognized the inherent problem in their ET model and that resulted in some group learning.

Generating a New Classroom Context. Following each class presenting their ET model to the other class, there was a collaborative discussion in which the two classes worked together to develop a joint model that incorporated attributes of both prior models. Similar to the chaotic nature of the discussions so far, this joint discussion also contained cycles of multiple voices followed by an elicited single voice while the teachers listened and interjected as needed, but throughout this discussion there was relative agreement with no individual explicitly disagreeing, different from earlier in the class.

78. Ms. Girard: So I hear that we need to make sure that what is going into the earth is also going out. But you are saying that instead of going back to the sun, maybe we have some going out to space?

79. Student[4]: Yeah, and then going back.
80. Ms. Girard: Okay, so maybe with more people that will be a little easier.

As a modification to solve the previously discussed problem of alignment in which people left the earth and went back to the sun, there was a suggestion to have people instead leave the earth and go out to space. The conversation again became chaotic, and then later Mr. London facilitated.

81. Mr. London: . . . Bailey [an alias], go ahead. Go ahead, you had an idea.
82. Bailey: Okay, so then, we have more over there [points at the sun on the floor] and some over there [points at the earth on the floor]. We could have them leave from the sun [points at sun] and then once they get to the earth [points at earth], the people in the earth [points at earth], go into space [points at region of the floor that represents space], and then, once the people from the sun are there [points at earth], and then another person [points at sun] from the sun comes, and when they hit the earth [points at earth], the people that were in space [points at space], will then go back to the sun [points at sun], and then the people . . . .

More explicitly than others before her, Bailey suggested that people walk from the sun to the earth, then people leave the earth, go into space, and then go back into the model at the sun.

A few seconds later, the tagging mechanism was again mentioned to control the flow of people.

83. Student 1: So, I think when people come from the sun, they tap someone off the earth, and they just kind of drift into space. And eventually we'll demonstrate it until the sun explodes and becomes a black hole.
84. Student 2: But they will rotate back.
85. Student 1: All right.
86. Student 3: Yeah, go back.

Rather than have the sun become empty of energy, the joint ET model allowed for people to "rotate back" into the model, suggesting that they would for a moment not represent energy (that had "drifted into space," line 82) and instead return to the sun to keep the flow of energy going.

At the conclusion of this discussion, the group acted out the joint model in which there was a sun and earth. The model began with approximately 2/3 of the people in the sun and 1/3 in the earth. The motion was one directional as people walked from the sun to the earth, tapped a peer, who then left the earth and went outside the bounds of the model. People then re-entered the model at the sun (see Figure 4).

This model involved conceptual resources that had been cued in the prior discussions and addressed each of the lacks of alignment, as well. There was a sun, fixing the first alignment issue of no source of energy in London's class. The flow of energy was one directional (even as the movement of people was not!), fixing the second alignment issue in which energy left the earth and had gone back to the sun. Also, the earth constantly had some energy inside of it, fixing the third alignment issue in which the earth would have frozen without energy. In sum, the previously discussed alignment difficulties were fixed with the

[4]In prior conversations, we as outsiders knew which students were a member of the London or Girard class because the observing students sat whereas the presenting students stood. However, in this discussion everyone stood and it was impossible to know who was a London and who was a Girard student.

generation of a new third classroom context. Furthermore, in regard to their knowledge elements, previous models had included knowledge about there being no energy inside the sun, unequal numbers of people entering, and what causes the energy leave and enter the earth. These displaced knowledge elements did not surface in the final joint model, whereas other previously incorporated knowledge elements continued to be cued in this context. Thus, through the incorporation and displacement of these knowledge elements there was learning, both individually and as a group. Furthermore, we saw that in one instance the London students extracted a piece of knowledge from one context and applied it to another while informing subsequent changes. In previous work, Wittmann (2006) has described this as incremental conceptual change, this time at the classroom level, with the newly incorporated conceptual resource having its origin in another context.

DISCUSSION

In this paper we aligned coordination class theory with a new context (pun intended!). That is, we applied coordination class theory to a classroom learning setting. To do this fruitfully we examined the theory and then refined our understanding of *context* and *alignment* in light of our classroom data in which students were individually and collectively building knowledge. This application of the theory was successfully able to capture both individual and group learning as the students' generated and modified a series of ET models.

In doing so, we built on Levrini and diSessa's (2008) extensions of coordination class theory and applied the theory to a learning environment that was created by a group of students who discussed and negotiated their conceptual ideas while collectively generating an embodied model. Although prior work had not explicitly precluded coordination class theory being applicable to group learning (diSessa, 2016), Levrini and diSessa's (2008) extension showed how coordination class theory could be used in classrooms. In their analysis, a group of students were treated *as if* they were an individual and the analysis captured their coordination of a concept across multiple contexts encountering difficulties regarding both span and lack of alignment. In treating the entire class as if they were individuals, the focus of their analysis was not on disagreements or conflicting interpretations of the same artifact. In contrast, students' different interpretations of an ET model were the crux of our analysis. Through the discussion and resolution of multiple individuals' conflicting interpretations, we were able to capture moments when students influenced each other's knowledge building.

We analytically distinguished between an individual's interpretation of an ET model as viewed from their own or another's perspective (student context) and a collection of people's common interpretation of an ET model (classroom context). Once we distinguished between those different contexts we were able to make claims about individual learning and group learning through a redefinition of alignment difficulties. Some of the lacks of alignment involved a student context, others involved a classroom context, and there were some episodes that involved multiple lacks of alignment involving different classroom contexts.

We documented several instances of a return to alignment. Some involved changes to an individual or classroom context, while others involved changes in the information extracted, cuing different knowledge elements. Recognition of these different alignment difficulties and the associated analysis tools to capture them let us illustrate how learning difficulties and successes about concepts in classroom settings can be captured at both the individual and group levels. Across these episodes of discussion and negotiation of ideas, we see how one individual's comments can dramatically change the models and contribute to subsequent learning for themselves and the entire group. In applying this analytical machinery, we have been able to toggle between individual knowledge building and the group understanding in a manner beyond how coordination class theory has been used previously.

Our analysis showed that returns to alignment were accompanied by the incorporation and displacement of knowledge elements at both the individual and the group levels. Incorporation and displacement of knowledge elements are two general types of learning mechanism that have been discussed within coordination class theory (Levrini & diSessa, 2008) and are similar to learning mechanisms described elsewhere (e.g., diSessa, 1993; Izsak, 2005; Kapon & diSessa, 2012; Parnafes, 2007; Wittmann, 2006), but the details of these mechanisms have not been the focus of our analysis. Furthermore, we documented the incorporation of a knowledge element from one context to another, which was important because of how it influenced subsequent changes to the models. By describing the process of incorporating and displacing knowledge elements, our analysis was able to describe moments when there were changes in individuals' conceptual systems, moments when there were changes in the group conceptual systems and moments when the individual influenced the group and vice versa. Thus, the current work took a step beyond prior work that had primarily focused on individual learning in interviews or treated a group of students as if they were an individual, and was successfully able to describe relatively authentic learning in a complicated classroom setting.

Our analysis focused on learning difficulties due to a lack of alignment; we did not observe difficulties due to a lack of span. Hypothetically, if in our data students had shown a lack of conceptual resources about steady state, the earth, or the sun, and therefore had difficulties recognizing the concept in certain models, we would have observed a lack of span. For instance, students might have voiced confusion about the concept of steady state. Or, if students had observed peers' ET models and declared, "what kind of energy leaves the Earth?," we could have interpreted their words as a lack of span. We suspect that not observing a lack of span may have been an idiosyncratic feature of the data and not evident of a larger trend. Instead, it was unique to our situation and allowed us to focus solely on the difficulty of a lack of alignment.

When carrying out the analytical innovation proposed in this article, we clarified the role of context from the perspective of a learner engaging with a physical situation and other learners' ideas. While the broader question of how to define context is not addressed here, we chose a meaning of context that recognized differences in individuals' interpretations and moments in which there were interpretations shared by all or most students. We note that our particular definition was useful in distinguishing individual and group learning and let us successfully capture conceptual change in a realistic classroom setting, but that there are other meaningful and reasonable definitions of context that provide value for different situations.

As expected, both the individual and collective levels are critical for analyzing classroom learning (Cobb, Stephan, McClain, & Gravemeijer, 2001), and furthermore, one should not focus on collaborative group learning to the detriment of individual learning (Conlin & Hammer, 2016). Yet, all too often, theories of learning and conceptual change have emphasized either group learning in classrooms or individual learning in interviews and not integrated the two. Recently, work has been aiming to synthesize knowledge analysis, with its traditional emphasis on the more cognitive side of conceptual change, with interaction analysis, with its sociocultural roots and emphasis on learning through changing interactions between people and artifacts in naturally occurring settings (diSessa, Levin, & Brown, 2016). For instance, Danish, Enyedy, and Parnafes (2016) reanalyzed the data presented in Parnafes (2007) from both perspectives and provided an integrated account of learning with complementary insights from both perspectives. Comparably, here we applied coordination class theory in a way that allowed us to capture the interactions between many people and an artifact in a real-world context. Therefore, we have integrated the individual and collective levels and enlarged the type of learning environment which this theory can capture.

We note that the teachers, though not highlighted in our analysis, played an essential role in this interaction. First, as was clear from our observations, students had learned the essential ideas of energy flow (and the role of different wavelengths of light) from the Sun to the earth and from the earth into space. Thus, our activity was not meant as a learning activity, though learning occurred during instruction. Second, the teachers showed great skill in guiding their students during what seemed to be chaotic interactions. For example, we see examples of them rephrasing student questions (line 67), metacommentary on attending to each other's ideas (the first part of line 71), asking students to complete their thoughts for all to hear (the end of lines 71, 74, and 80), and asking clarifying questions (line 77). We interpret these actions as giving students ownership of the discussion and the ideas being discussed. In sum, these teachers provided us, as researchers, with an environment in which knowledgeable students struggled with ideas and articulated their thinking in a way that allowed us to study the students and their ideas.

Given the high quality of the teaching and the unique situation of the modeling activity of ET in a classroom of students who had already learned the salient material in other ways, the results of our analysis might be brought into question as being limited to a unique situation. We argue that the lack of difficulties with span allowed us to focus on difficulties with alignment, providing us with an opportunity to clarify elements of coordination class theory such as alignment in a large group setting, and the meaning of context when individuals consider both the physical world and each other's ideas. In a typical classroom, difficulties with span and alignment would most likely both exist, complicating the analysis by several magnitudes (as interactions between different difficulties occurred).

Furthermore, the analytical machinery was used to capture a specific type of classroom disagreement that was often straightforward (e.g., the amount of energy in the earth was not constant, as it should have been) and the proposed solutions were typically dichotomous, either modifying the context or the information extracted. One could imagine more complicated classroom discussions where many ideas are proposed, only some are taken-up by the class, and a myriad of solutions are possible. Those types of messy disagreements would present as a challenge for our analytical machinery. Furthermore, disagreements that rely heavily on issues of authority and status would be a step beyond our machinery.

Applications of the Extended Theory

There are several reasonable applications of this extended theory to analyzing learning in classroom settings, particularly ones that do not involve ET, and to designing classroom learning environments with a goal of facilitating this type of conceptual change.

Generally, this analytical approach is relevant to analyzing learning of concepts in classroom settings where there are multiple contexts at play during the discussion and negotiation of those concepts. In this article, the focus was on student and classroom contexts. These analysis tools could reasonably be applied to a classroom setting with many small-group contexts. For instance, imagine a classroom environment with several small groups, perhaps of three to five individuals, who work on a joint activity in which it is expected for all to contribute. Yet, these small groups do not exist independently of the entire classroom or of other small groups in class, nor are they independent from the individual. Capturing learning in this setting may involve three levels: the individual, the small group, and the entire class. Potentially, there could be changes in conceptual understanding at any of these levels through a classroom discussion in which each small group presents, followed by questions and discussion, and then a final collaborative activity that involves everybody.

With some modifications, these three levels of contexts could be built into the theory and one could potentially capture learning across all three levels.

Furthermore, one could imagine using this analytical approach with its focus on different levels of context to explicitly take into account the teachers interpretations of the artifact. In our analysis, given the nature of the data, and the type of involvement of the teachers, teachers were mainly asking questions and prioritizing certain students' ideas; we did not have data on the teachers' interpretations of the ET models. But, if we had access to such data, perhaps in the form of postinstruction debrief interviews, that data could have been analytically incorporated as an additional *teacher context*. Future analyses using this approach may be enriched by explicitly accounting for the teachers' interpretations of the ET model and the students' ideas.

Although the different contexts analyzed were heavily determined by the pedagogical activity, ET, there is no reason to presume that this pedagogical activity is necessary for using these analysis tools. ET was a useful activity as it facilitated quick model revision and a need for group consensus, but these analysis tools could likely be applied to other kinds of modeling activities, for instance, generating, discussing, and revising computational models with a tool, such as Netlogo (Wilensky, 1999). Likely there are many pedagogical activity and learning environments in which groups of students successively generate, discuss, and revise an artifact, and those environments may be good candidates for an analysis of individual and group learning using these analysis tools.

These analysis tools also have utility for the design of learning environments. If one aims to use these analysis tools to capture individual and group learning, it would be crucially important for the students, both as a group and individually, to have opportunities to generate and modify the artifact or means by which they present their conceptual ideas. An important feature of our data was that the modifications to the models were practically instantaneous, relatively easy to execute, and had the potential to be observed by all individuals. When things did not go as intended or expected, it was easy for students to recognize it, and that facilitated quick modifications. The classroom lessons described here were only 45 minutes long, and the students had no previously training or experience with this activity. Yet, importantly the students articulately voiced their views such that we could identify moments of intellectual disagreement. Recognizing these key features of the activity and building them into other learning environments may be crucial for promoting this type of group and individual learning in a classroom environment in the future. For teachers and instructional designers who may wish to scaffold this type of learning, we suggest a learning environment in which students collaborate on an artifact that is easy to generate, modify, and observe. Furthermore, we suggest a classroom discussion where different interpretations of the same artifact are given a high priority, for instance, having a consequential activity where modifications to the artifact are based on the resolution of those different interpretations.

As was apparent in the analysis, one methodological challenge encountered is that we focused on moments where the discussion was relatively easy to follow. We observed cycles of chaotic talk by many speakers that were then followed by the teachers eliciting a single voice, discussion, and then a return to the chaotic talk. By only having focused on those relatively easy to follow moments, we may have overlooked important conceptual ideas that were otherwise masked. However, likely some of these ideas were unseen by the students, too. Going forward, this challenge could be ameliorated by instructional methods to discourage the chaotic discussion, such as the use of a talking stick, or by breaking the class into smaller more manageable groups. Another approach might have been to have the teachers review the video immediately after data collection. Given their familiarity with their students, they may have a keener ear to recognize overlapping voices. Furthermore, having the teachers identify which students were members of which class would have helped the analysis of the mixed-class discussion. In hindsight, the analysis of the mixed-class discussion would have been easier if students were identified by color-coded team shirts or another type of visual marking.

Finally, one more area of applicability is a classroom-learning environment that involves multiple scientific contexts and/or multiple concepts. In the presented data, the students were wrestling with one science context for one concept. What if students are learning about multiple concepts? Using multiple kinds of artifacts? In many ways, those more complicated situations are common in classrooms and potentially important learning environments for testing the utility of these analysis tools. However, those environments would also be analytically quite complicated as the lack of alignment difficulties could involve any number of concepts and any number of contexts. When designing for or analyzing such environments, it would be pertinent to focus on the moments of discussion and negotiation about the concepts, as those are likely instances in which the lack of alignment difficulties would be apparent and potentially be fixed. In our view, however, if one applies these tools to the design and analysis of learning environments, one must carefully chart the relevant concepts, contexts, difficulties due to lack of alignment, and solutions, both those proposed and those implemented, to successfully capture learning across levels.

Integrating a theory of individual learning into a classroom environment is a tricky proposition. Classroom settings are notoriously complicated, and, as seen in this data, one individual's comments can have a large impact on changing understandings. For researchers aiming to capture learning of often difficult concepts, there are a myriad of phenomena that one could pay attention to. Here we presented one means to accomplish this task. Likely there are numerous other approaches, using coordination class theory among other analytical approaches. Expanding theories of individual learning into classroom settings, although difficult, is an important line of work, both for the growth of the particular theory, to find out more about its boundaries and implications, and for the design of classroom learning environments. Furthermore, this provides insights into how one individual can change the group discussion and influence everyone's learning. Theories of learning and conceptual change are important to teachers and instructional designers because they can contribute to the targeted design of learning environments based on precise hypotheses. The more we make learning theories and their implications accessible to teachers and instructional designers the more we can contribute to successful classroom learning.

We thank the teachers and all their students for engaging so deeply in this work. We also thank Daniel Capps and Laura Millay for insightful comments and discussions. We are thankful for the helpful comments from three anonymous reviewers. Earlier versions of this work were presented at the International Conference of the Learning Sciences (ICLS) and the National Association of Research in Science Teaching (NARST) Annual Meeting. This paper is based upon work supported by the National Science Foundation under Grant No. 0962805 and 1222580. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors declare that they have no conflict of interest.

REFERENCES

Achieve (2013). Next Generation of Science Standards. Washington, DC.

Arcavi, A. (2003). The role of visual representations in the learning of mathematics. Educational Studies in Mathematics, 52(3), 215–241.

Barth-Cohen, L. A. (2012). The role of prior knowledge and problem contexts in students' explanations of complex systems (Unpublished doctoral dissertation). University of California, Berkeley, CA.
Besson, U., De Ambrosis, A., & Mascheretti, P. (2010). Studying the physical basis of global warming: Thermal effects of the interaction between radiation and matter and greenhouse effect. European Journal of Physics, 31(2), 375.
Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. Instructional Science, 18, 237–261.
Carey, S. (1999). Sources of conceptual change. In E. Scholnick, K. Nelson, S. Gelman, & P. Miller (Eds.), Conceptual development: Piaget's legacy (pp. 293–326). Mahwah, NJ: Erlbaum.
Close, H. G., & Scherr, R. E. (2015). Enacting conceptual metaphor through blending: Learning activities embodying the substance metaphor for energy. International Journal of Science Education, 37(5–6), 839–866.
Cobb, P., Stephan, M., McClain, K., & Gravemeijer, K. (2001). Participating in classroom mathematical practices. Journal of the Learning Sciences, 10(1-2), 113–163.
Confrey, J. (1990). A review of the research on student conceptions in mathematics, science, and programming. Review of Research in Education, 16, 3–56.
Conlin, L. D., & Hammer, D. (2016). Commentary: From the individual to the ensemble and back again. In A. A. diSessa, M. Levin, & N. J. S. Brown (Eds.), Knowledge and interaction: A synthetic agenda for the learning sciences (pp. 311–325). New York, NY: Routledge.
Daane, A. R., Wells, L., & Scherr, R. E. (2014). Energy theater. The Physics Teacher, 52(5), 291–294.
Danish, J. A. Enyedy, N., & Parnafes, O. (2016). Working towards an integrated analysis of knowledge in interaction. In A. A. diSessa, M. Levin, & N. J. S. Brown (Eds.), Knowledge and interaction: A synthetic agenda for the learning sciences (pp. 160–181). New York, NY: Routledge.
diSessa, A. A. (1991). Epistemological micromodels: The case of coordination and quantities. In J. Montanegro & A. Tryphon (Eds.), Psychologie génétique et sciences cognitives (volume from the 11th advanced course; pp. 169–194). Geneva, Switzerland: Archives, Jean Piaget.
diSessa, A. A. (1993). Toward an epistemology of physics. Cognition and Instruction, 10(2–3), 105–225.
diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limón, & L. Mason (Eds.). Reconsidering conceptual change: Issues in theory and practice (pp. 28–60). Dordrecht, the Netherlands: Springer Netherlands.
diSessa, A. A. (2006). A history of conceptual change research: Threads and fault lines. In K. Sawyer (Ed.), Cambridge handbook of the learning sciences (pp. 265–281). Cambridge, England: Cambridge University Press.
diSessa, A. A. (2016). When will science surpass our intuitive capacities as expert practitioners?: Commentary on Danish et al., "Integrated Analysis of Knowledge in Interaction" In A. A. diSessa, M. Levin, & N. J. S. Brown (Eds.). Knowledge and interaction: A synthetic agenda for the learning sciences. (pp. 182–190). New York, NY: Routledge.
diSessa, A. A., & Cobb, P. (2004). Ontological innovation and the role of theory in design experiments. Journal of the Learning Sciences, 13(1), 77–103.
diSessa, A. A., Levin, M., & Brown, N. J. (Eds.). (2016). Knowledge and interaction: A synthetic agenda for the learning sciences. New York, NY: Routledge.
diSessa, A. A., & Sherin, B. L. (1998). What changes in conceptual change?. International Journal of Science Education, 20(10), 1155–1191.
diSessa, A. A., Sherin, B., & Levin, M. (2016). Knowledge analysis: An introduction. In A. diSessa, M. Levin, & N. J. S. Brown (Eds.), Knowledge and interaction: A synthetic agenda for the learning sciences (pp. 30–71). New York, NY: Routledge.
diSessa, A. A., & Wagner, J. F. (2005). What coordination has to say about transfer. In J. P. Mestre (Ed.), Transfer of learning from a modern multi-disciplinary perspective (pp. 121–154). Greenwich, Connecticut.
Erickson, F. (2006). Definition and analysis of data from videotape: Some research procedures and their rationales. In J. L. Green, G. Camilli, & P. B. Elmore (Eds.). Handbook of complementary methods in education research (pp. 177–192). Washington DC.
Enyedy, N. (2005). Inventing mapping: Creating cultural forms to solve collective problems. Cognition and Instruction, 23(4), 427–466.
Finkelstein, N. (2005). Learning physics in context: A study of student learning about electricity and magnetism. International Journal of Science Education, 27(10), 1187–1209.
Hammer, D. (2000). Student resources for learning introductory physics. American Journal of Physics, 67(January), S45–S50.
Hunt, E., & Minstrell, J. (1994). A cognitive approach to the teaching of physics. In K. McGilly (Ed.), Classroom lessons: Integrating cognitive theory and classroom practice (pp. 51–74). Cambridge, MA: MIT Press.
Ioannides, C., & Vosniadou, S. (2002). The changing meanings of force. Cognitive Science Quarterly, 2(1), 5–62.

Izsak, A. (2005). “You have to count the squares”: Applying knowledge in pieces to learning rectangular area. Journal of the Learning Sciences, 14(3), 361 – 403.

Kapon, S., & diSessa, A. A. (2012). Reasoning through instructional analogies. Cognition and Instruction, 30(3), 261 – 310.

Levin (Campbell), M. E. (2012). Modeling the co-development of strategic and conceptual knowledge during mathematical problem solving (Unpublished doctoral dissertation). University of California, Berkeley, CA.

Levrini, O., & diSessa A. A. (2008). How students learn from multiple contexts and definitions: Proper time as a coordination class. Physical Review Special Topics – Physics Education Research, 4, 010107.

Lewis, C. (2012). Applications of out-of-domain knowledge in students’ reasoning about computer program state (Unpublished doctoral dissertation). University of California, Berkeley, CA.

Parnafes, O. (2007). What does “fast” mean? Understanding the physical world through computational representations. The Journal of the Learning Sciences, 16(3), 415 – 450.

Parnafes, O. (2012). Developing explanations and developing understanding: Students explain the phases of the moon using visual representations. Cognition and Instruction, 30(4), 359 – 403.

Redish, E. F. (1999). Millikan Lecture 1998: Building a science of teaching physics. American Journal of Physics, 67(7), 562 – 573.

Scherr, R. E., Close, H. G., Close, E. W., Flood, V. J., McKagan, S. B., Robertson, A. D., . . . Vokos, S. (2013). Negotiating energy dynamics through embodied action in a materially structured environment. Physical Review – Special Topics: Physics Education Research 9(2), 020105.

Scherr, R. E., Close, H. G., Close, E. W., & Vokos, S. (2012b). Representing energy. II. Energy tracking representations. Physical Review – Special Topics: Physics Education Research 8(2), 020115.

Scherr, R. E., Close, H. G., McKagan, S. B., & Close, E. W. (2010). “Energy Theater”: Using the body symbolically to understand energy. In C. Singh, M. Sabella, & S. Rebello (Eds.), AIP Conference Proceedings 1289 (pp. 293 – 296).

Scherr, R. E., Close, H. G., McKagan, S. B., & Vokos, S. (2012a). Representing energy. I. Representing a substance ontology for energy. Physical Review – Special Topics: Physics Education Research 8(2), 020114.

Schoenfeld, A. H., Smith, J. P., & Arcavi, A. (1993). Learning: The microgenetic analysis of one student’s evolving understanding of a complex subject matter domain. Advances in Instructional Psychology, 4, 55 – 175.

Slotta, J. D., Chi, M. T., & Joram, E. (1995). Assessing students’ misclassifications of physics concepts: An ontological basis for conceptual change. Cognition and Instruction, 13(3), 373 – 400.

Stevens, R., & Hall, R. (1998). Disciplined perception: Learning to see in technoscience. In M. Lampert, & M. L. Blunk (Eds.). Talking mathematics in school: Studies of teaching and learning (pp. 107 – 149). Cambridge, UK: Cambridge University Press.

Tasquier, G., Levrini, O., & Dillon, J. (2016). Exploring students’ epistemological knowledge of models and modelling in science: Results from a teaching/learning experience on climate change. International Journal of Science Education, 38(4), 539 – 563.

Thaden-Koch, T. C., Dufresne, R. J., & Mestre, J. P. (2006). Coordination of knowledge in judging animated motion. Physical Review Special Topics – Physics Education Research, 2(2), 020107.

Thaden-Koch, T., Mestre, J., Dufresne, R., Gerace, W., & Leonard, W. (2005). When transfer fails: Effect of knowledge, expectations and observations on transfer in physics. In J. Mestre (Ed.), Transfer of learning: Research and perspectives. Greenwich, CT: Information Age.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. Learning and Instruction, 4(1), 45 – 69.

Vosniadou, S. (Ed.). (2008). International handbook of research on conceptual change. New York, NY: Routledge.

Wagner, J. F. (2006). Transfer in pieces. Cognition and Instruction, 24(1), 1 – 71.

Wilensky, U. (1999). NetLogo Models Library [Computer Software]. Center for connected learning and computer-based modeling. Evanston, IL: Northwestern University. Retrieved from http://ccl.northwestern.edu/netlogo/models/

Wiser, M., & Smith, C. (2008). Learning and teaching about matter in grades K – 8: When should the atomic-molecular theory be introduced? In S. Vosniadou (Ed.) International handbook of research on conceptual change (pp. 205 – 237). New York, NY: Routledge.

Wittmann, M. C. (2002). The object coordination class applied to wave pulses: Analysing student reasoning in wave physics. International Journal of Science Education, 24(1), 97 – 118.

Wittmann, M. C. (2006). Using resource graphs to represent conceptual change. Physical Review Special Topics – Physics Education Research, 2, 020105