Expanding Coordination Class Theory to Capture Conceptual Learning in a Classroom Environment

Lauren A. Barth-Cohen, University of Miami, l.barthcohen@miami.edu
Michael C. Wittmann, University of Maine, mwittmann@maine.edu

Abstract: This article presents an extension to coordination class theory—a theory of conceptual change that was built to capture an individual's learning in an interview setting. Here we extend that theory to capture group and individual learning in classrooms. The proposed extension focuses on different contexts in the sense of groups' and individuals' different interpretations of the same student-generated artifact. A classroom of 9th grade earth science students created embodied models for a specific scientific concept, the steady state energy of the earth. We describes that the students encountered difficulties aligning their embodied models with their conceptual understandings, and yet, they were able to make progress by changing their models to better align their understanding of the scientific concept with their newly modified model—instances of individual and group learning. We conclude with discussing implications for designing classrooms learning environments.

Keywords: conceptual change, group learning, embodied modeling

Introduction

This article extends a theory of learning that was built to capture individual's learning in an interview setting to capture both groups and individuals learning in a classroom. The theory of learning known as coordination class theory (diSessa & Sherin, 1998), describes the organization of knowledge in a well-developed understanding of a concept, the learning difficulties that may arise, and the process of acquiring a well-developed understanding. Our proposed extension describes how a group of students who encountered difficulties were able to make progress at both the individual and the group level. The students generated and modified a series of embodied models for the steady state energy of the earth, they largely modeled energy leaving the sun, entering the earth, and dissipating to space. First we describe the theory and our extensions and then we present several illustrative examples. We conclude with discussing implications for designing classroom-learning environments.

Coordination class theory

Coordination class is a theory of conceptual change that describes the learning of often difficult concepts in science. A coordination class is a specific type of concept that is meant to provide a means for determining information from the world. Knowing that the world is not transparent, learners need to learn how to access relevant information (diSessa, 2002). Different contexts require different means for determining information, and this theory describes how individuals determine information across contexts.

Canonical coordination class theory studies focus on the process of acquiring a well-developed understanding of a concept and the learning difficulties that arise when working to determine the same information in different contexts. For example, diSessa and Sherin (1998) describe how a university student, J, had difficulties determining what is and is not a force in the context of a book sliding across a table and a coin toss. In another empirical study, Parnafes (2007) examined the development of students' understanding of the motion of simple harmonic oscillators through interactions with physical and simulated oscillators. With the physical oscillator, the students' intuitive coordination of "fastness" was different from a scientific coordination of velocity and frequency. Then, with a simulation the students were able to distinguish between velocity and period as they determined the same information and refined their knowledge. Thereby the students' coordination classes were extended to apply to additional relevant contexts of oscillatory motion.

Theoretical machinery

The central function of a coordination class is to determine information from the world, specific classes of information out a variety of contexts in which a specific concept is applicable, for instance determining forces in homework problems, laboratory experiments, and everyday situations. The challenge of "having" the concept is being able to "see" the pertinent information in an appropriate range of contexts, such as "seeing" information about acceleration in physical objects, equations, and with motion detectors in laboratory settings. Learning difficulties may involve having insufficient conceptual knowledge to "see" force or acceleration within a context or having trouble applying the concept across contexts. The organization and structure of a coordination class, learning processes, and difficulties encountered can be broken down according to the following machinery. (See diSessa & Wagner (2005) and Levrini & diSessa (2008) for additional information.)

Architecture: Rather than directly exacting the pertinent information, people *extract* related information (e.g. shape, color, size, or speed), and then generate an *inference* to turn that information into the pertinent information, such as about acceleration or forces. The latter is known as the causal or inferential net, and it is all of the relevant knowledge used to determine how the information extracted relates to the desired information.

Learning: There are two processes for how prior knowledge contributes to learning: 1) Elements from prior conceptualizations can be *incorporated* into new conceptualization. 2) Elements from a prior conceptualization can be dismissed or *displaced* from a new conceptualization. These processes transpire as one applies or "works" a concept across a range of contexts while incorporating and displacing a variety of knowledge elements.

Difficulties: Given that a certain amount of context-specific knowledge is needed to properly work a concept across contexts, there are two difficulties: 1) The *difficulty of span* is not having adequate conceptual knowledge to apply the concept across contexts, for instance, not being able to access sufficient conceptual elements about forces on static objects. 2) The *difficulty of alignment* is having trouble applying the same concept reliability across contexts, for instance, seeing forces on only moving objects and not static objects.

Contextuality is important; different contexts are where work is done to a concept to increase span and improve alignment while also incorporating new knowledge elements and dismissing old ones. When a student applies a concepts to a variety of contexts, that students may encounter difficulties because they do not have sufficient knowledge to apply the concept (lack of span) or they may encounter difficulties because in some contexts they cannot reliability apply the concept (alignment problem). Either way, incorporating new knowledge elements or dismissing old ones can increase span or improve alignment. Through this machinery we can track learning at a moment-by-moment level.

Existing modifications and extensions to coordination class theory

Several empirical studies of learning have used this machinery while also extending it. Initially the machinery was constructed to describe an individual's learning of Newtonian Mechanics concepts in a clinical interview setting (diSessa & Sherin, 1998). More recently, Wagner and diSessa (diSessa & Wagner, 2005; Wagner, 2006) presented an explanation of knowledge transfer based on an incremental refinement of knowledge elements across contexts. Over eight weekly interviews one student came to see various probability problems that she had initially perceived as different as being alike. For her, operating the same concept across different contexts was particularly challenging while determining the same information from different contexts was not challenging. Additional empirical studies have applied this machinery to learning in interview settings that involve other math and science concepts (e.g. Thaden-Kock, et al., 2005; Wittmann, 2002).

Using the same theoretical machinery, Levrini and diSessa (2008) conducted an empirical analysis of a classroom of 18-19 year old students who were learning about the concept of proper time within special relativity. Initially, the students had trouble with proper time, but they were able to make progress and the analysis highlights how students "coordinate" proper time. The students incorporated a more careful definition of proper time in a new context, but they encountered difficulties, prematurely concluding that a new context was the same as a prior context, when it was in fact different, which led to a misalignment. Eventually they were able to make progress when the teacher introduced a new definition of proper time that increased span (through increased conceptual knowledge) with an associated cost of misalignment (reduced ability to apply the concept across contexts). Finally the students achieve alignment through an additional context that harnessed the new knowledge. In the analysis, the entire classroom of students was treated *as if* they all were one individual and the analysis documents classroom-learning difficulties instead of individual learning difficulties. Yet, that work did not distinguish between individual and group learning, which is important because individuals may have different interpretations of the same context, and an analysis of classroom learning would want to take that into account as some individuals might experiencing a lack of span or alignment problem while others do not.

Proposed extension to capture alignment difficulties in a classroom environment

Contextuality is important. In prior coordination class theory analyses, often a student has been presented with a variety of contexts where the mathematical or scientific concept applies, for instance forces on moving and stationary objects or in homework exercises and laboratory activities. Yet, multiple individuals observing the same concept, in a context that is supposedly the same, may not, in fact, view the concept in the same way. Their interpretations of a particular concept in a particular context could be different, and articulating those differences of interpretation can be moments of learning. Building from this rough notion, we outline several kinds of contexts in a classroom-learning environment and then describe the individual and group learning difficulties that may occur.

The data to be presented comes from several team-taught 9th grade earth science classrooms. In the first step of the activity, each classroom of students worked together to collectively build an embodied model for the steady state energy of the earth using a pedagogical activity known as Energy Theater (ET) (Scherr et al., 2012). Next, each classroom presented their model to their peers in the adjacent classroom and there was an opportunity to ask questions. Finally, the two classrooms worked together to build a joint model. Given this classroom-learning environment, we distinguish the following three notions of context. First, there is the *scientific context*, similar to the notion of context used in the aforementioned literature (e.g. Levrini & diSessa, 2008), this notion of content refers to the different scientific phenomena in the external world where the concept is applicable. In our data, the scientific context is the steady state energy of the earth. Second, there is the *classroom context*, which is an entire classes interpretation of an ET model. In our data there were three classroom contexts. The two classrooms each separately built their own models (two classroom contexts), and then, after presenting their model to peers, they build a joint model (the third classroom context). Finally, there is the *student context*. In this activity everyone participates by acting out the motion with their bodies. Each student has his or her own interpretation of what the model is showing. Each person's interpretation acts as the context for that person's thinking and acting, and that becomes pertinent to the group of students and accessible to us as researchers when an individual describes their thinking and it is explicitly considered by others.

Previously the difficulty of alignment has been defined as the difficulty of 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 have delineated the student context and the classroom context we needed to carefully re-define and explain alignment in regards to each of those *contexts*. Thus, we denote three types of alignment difficulties: (1) the difficulty of applying the same concept across sciences contexts (not relevant to the current analysis, but seen elsewhere, for instance diSessa and Sherin, (1998)), (2) the difficulty of applying the same concept across classroom contexts (a classroom of students common interpretation of an ET model), (3) the difficulty of applying the same concept across student contexts (individual student's interpretations of their ET models as seen from a peers perspective).

An example of the second type of alignment can play out in the following manner: there could be a classroom-context/classroom-context disagreement. Imagine one classroom of students that generated and presented an ET model, while the other classroom of students was observing and interpreting their peer's model. For the observing students it may became apparent that their peer's model did not align with their conceptual elements. Perhaps the observing students extracted information that was unexpected, and the resulting inference did not match with their conceptual elements—resulting in a lack of alignment. For instance, perhaps they extracted more energy (people) entering the earth than leaving, leading to an inference that the earth would increase in temperature. Yet, this would be unexpected as the assigned task was to model the steady state energy of the earth and their conceptual elements would have likely supported them to expect equal amounts of energy entering and leaving. The lack of alignment could be resolved by either a modification to the model, which in turn would result in a change to the information extract by cuing different conceptual elements, such as modifying the number of people who enter and leave the earth. Or by directly changing the information extracted, while not changing the ET model, in other words, having the students extract different information from the original model, such as recognizing that individuals are not equal in their amount of energy, leaving open the possibility of despite more people entering than leaving, the earth being in steady state. Either of these modifications could result in learning given the possible incorporation or displacement of knowledge elements.

The third type of alignment can be an instance of a classroom-context/student-context disagreement and play out as follows. Imagine a classroom context in which students are (momentarily) in agreement as they collectively create an ET model. Then, when discussing the model, one student "sees" something new; they might recognize something in the model that is unexpected or perplexing. When that happens, a student might be extracting specific information from that model (the classroom context) that does not align with his or her own conceptual elements. This creates a new interpretation for that student, different from that of the rest of the class. This lack of alignment would likely be apparent in what the student says aloud and heard by peer(s). A result of this lack of alignment might be an attempt to bring that student's interpretation and their concept back into alignment. One option would be to modify the classroom context, change the ET model in such a way as that going forward the future information extracted would align with that students conceptual elements. Thus, after modification the student who previously recognized something being "off" and their peers would all be in agreement. Another potential solutions could involve changing the information extracted from the model thereby having that student cue different conceptual elements.

The problems of alignment and solutions to those problems become complicated because there are three kinds of context (science content, classroom context, and student context) and several ways to fix this kind of problem: modifying the model or modifying the information extracted. Changes to the information extracted can result in changes to the conceptual elements cued through either incorporation or displacement, which are potential instances of learning.

Data collection and analysis

The previously described theoretical extensions are illustrated with empirical examples from classroom data concerning 9th grade earth science students who were using an embodied modeling activity known as Energy Theater (ET) to generate and revise models for the steady state energy of the earth. In ET students create models with their bodies' positions and movements. This 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., 2012). In this article ET forms the backdrop for the analysis, for readers interested in this pedagogical activity we direct them to Scherr et al., (2013; 2012).

Classroom setting

Data were gathered from in-class observations from the classrooms of two 9th grade earth science teachers, Ms. Girard and Mr. London (aliases). Neither Ms. Girard nor Mr. London had done ET in their classroom before, Ms. Girard had attended an evening professional development activity in which Energy Theater was used and she contacted one author signifying that she and Mr. London wanted to repeat the activity with their students. She invited the authors to observe and study her class doing this activity. The teachers assigned their students the task of "Model the energy transfer/flow to show how Earth remains at a fairly constant temperature." Students were expected to use the tools of ET, which were written on the board. As is typical of this activity, each student was to portray a unit of energy. Ropes on the floor were used to delineate objects in the system. Movement from one area on the floor to another indicated movement of energy between objects in the system (e.g. earth and sun). A total of six classrooms (three periods taught by 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 was followed by a joint enactment at the end of each period which included all the students from both classes.

There are some additional points about important aspects of the classroom discussion that will not be discussed further in this paper. ET is purposefully designed to be underspecified as to what one should do. Students had to figure out the model, and this led to a great deal of discussion, often in parallel, with many students talking at once. At times, the discussion was utterly chaotic, and we were unable to adequately discern the conversations. Our data analysis focuses on those moments when only one or a few speakers were talking, which was often facilitated by the teachers asking whole class to listen to one student's ideas.

From our observations, it became clear that the topic was not new to them. Students had studied the different wavelengths of light (ultraviolet, visible, and infrared) and what percentage of each wavelength transfers 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. Overall, students entered into this activity with experience in the topic. Suggesting that the activity was not, for them, an opportunity to discover new ideas, but instead to build on prior ideas.

Knowledge analysis

Data consists of video and audio recordings of the classes participating in ET. 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 in order to analytically track the ET models that were being created and modified. We noticed that many of these moments corresponded with instances in which there were disagreements that often resulted in modifications to the models. We began by examining the conceptual substance of these disagreements and searched for patterns. Eventually, there was a grounded process of coding for conceptual elements, relevant contexts, and moments of misalignment.

The empirical analysis was conducted using Knowledge Analysis. This is a methodological approach to studying knowledge with the purpose of examining learning and it has commonly been used in research that utilizes coordination class theory. We engaged in an iterative cycle of observing, schematizing, and systematizing the theoretical constructs across the data set (Parnafes & diSessa, 2013) while building the proposed extensions. Knowledge Analysis is a developing methodology and details about its history, theoretical foundations, and practical implementation are available in diSessa, Sherin, & Levin (2015).

Analysis

We illustrate our theoretical extensions with three cases of learning in a classroom environment. In the first case the alignment problem was fixed by a modification to the classroom context. In the second case the alignment problem was fixed by a modification to the information extracted. Finally, the third case is more complicated as fixing the alignment problem involved multiple solutions.

Case 1—Modifying the classroom context: Adding a tagging mechanism

The first case presents a lack of alignment between a student context (one student's interpretation of a classroom context) and their relevant conceptual elements, which was determined by the information that the student extracted from the model. This alignment problem was subsequently fixed by way of a modification to the classroom context. Mr. London's classroom of students generated a model of the energy entering and leaving the earth with no sun. Students walked in small circles around the North Pole, South Pole, and Equator, representing energy entering and leaving the earth at those three locations (see Figure 1). During the process of acting out the model, one student stopped the group to point out that the earth was not in a steady state ("It's not in a steady state though.") There was a lack of regulation for when energy entered and left the earth ("That is not steady state because it's not really regulated.")

For this student, at least, a conceptual understanding of steady state included knowledge about a need for a constant number of people inside the circle at a time (to represent a constant amount of energy in the earth) and while acting out this model that student extracted information that violated what the student expected to see as based on available conceptual elements. The number of people inside the circle varied because it was not "well regulated." This was a lack of alignment between the student's interpretation of the classroom context and that student's conceptual elements. Subsequently a solution was proposed, a tagging mechanism to control when individuals enter and leave: "We should have a few people walking around in there, and then at some point switch a person out and, there has to be, an input and an output. So say, 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." This modification to the ET model, having individuals tag each other when entering and leaving the earth so as to insure an equal input and output (Figure 1) had the effect of returning to alignment the student's interpretation of the classroom context and their conceptual elements. It also had the effect of creating agreement between the student context (that single student's interpretation of the classroom context) and the entire classroom context.

A lack of alignment, making a change to the classroom context, and a subsequent return to alignment is a type of learning. Individual learning occurred for the student who pointed out that the earth was not in steady state because of a lack of energy regulation; that individual worked the concept of steady state across contexts—the initial problematic student context and the subsequent classroom context—while incorporating the regulation of energy flow into a new conceptualization. Additionally, group learning occurred through the incorporation of a new element, regulation of energy flow, into the group's conceptualization of steady state; this is evident in the classroom agreement about the lack of regulation as suggested by the proposal and implementation of the tagging mechanism.

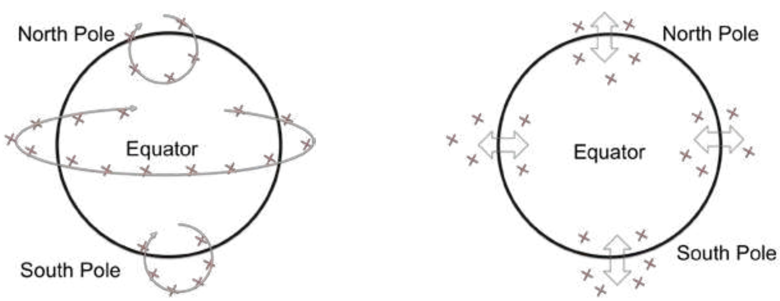

Figure 1. Mr. London's first period class' ET model before (left) and after (right) modification.

Case 2—Modifying the information extracted: The earth would explode

The second case involved one classroom presenting their ET model to the other classroom. There was a lack of alignment between a classroom context (the ET model one class generated) and information that the other class extracted from the former's classroom context. The lack of alignment was eventually fixed through a modification to the information extracted. Mr. London's second period class generated an ET model with three circular ropes on the floor, representing the sun and earth, and a third larger rope surrounding both to represent 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 (see Figure 2). 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, but they represented different types of light.

While observing the model Girard's students questioned why there were three people entering the earth and one person leaving ("How come there is only one thing leaving but three coming in? I think the earth would explode eventually.") Likely the Girard students were accessing conceptual elements that led them to expect equal amounts of energy entering and leaving the earth and they were expecting to extract information aligned with those elements, but that did not occur. In response to the question London students explained that three people entering were meant to be "worth" the same amount of energy as one leaving ("He was worth all three of us. Cause we were just representing all the different kinds of energy that were going through the earth. And he was the one kind of energy coming out of the earth….Oh, so if we were all equal in parts, then the earth would explode. But we're not. There is more of Ian than all of us.") In this episode there was a lack of alignment between the information Girard students extracted, as related to their conceptual elements, and the London student's classroom context. This lack of alignment was fixed by a suggestion that the Girard students extract something different: equal amount of energy in and out of the earth being represented by the one student leaving the earth ("Ian") being worth the same amount of energy as three people entering. This change in the information extracted is an example of working the concept across contexts resulting in a return to alignment.

Modifying the information extracted has the potential to be a good opportunity for learning. It could result in displacement or incorporation of knowledge elements into a new conceptualization. In this case Girard's class' conceptualization of steady state likely contained an element of equal amount of energy (light) entering and leaving the earth. Likely those students' conceptualization contained this element before and after this moment, thus this may not have been an instance of learning for them. But, differently, London's class' conceptualization might have been modified during the discussion. Specifically, this student might have been experiencing a displacement of knowledge about unequal numbers of people entering and leaving with knowledge about equal people entering and leaving. It's not clear from the discussion whether or not the students' knowledge was displaced, but there is additional evidence for the existence of this displacement to be found in the final second period joint ET model in which there were equal numbers of people entering and leaving the earth, suggesting that for London's class there might have been some group learning.

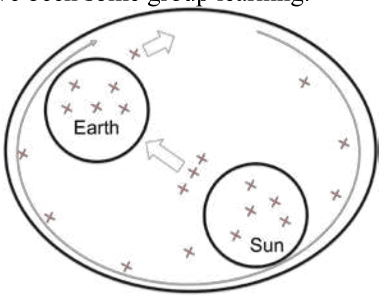

Figure 2. Mr. London's second period classes ET model with three people entering the earth and one leaving.

Case 3—Modifying both the classroom context and the information extracted

The final case presents an example of a lack of alignment in which there was multiple solutions proposed. The first solution involved modification to the ET model; the second solution involved modification to the information extracted. The first solution was eventually taken up in the final joint model. Mr. London's class from Case 1 above presented their model (with the tagging mechanism) to Girard's class. This model did not contain a sun, and during the presentation there arose an alignment problem about the lack of a sun. The problem was a lack of alignment between the London class' classroom context and the Girard class' conceptual understanding. Girard's class' conceptual elements likely involved a sun as a source of energy; their model, not discussed, included a sun as a source. The Girard students observed London's class' model and failed to extract a sun. ("Where is your, if you have energy on the outside, where is it coming from since you don't have a sun?") The London students understood the predicament and they entertained the possibility of changing their classroom context (their ET model) by adding a sun ("You didn't give us anything to be the sun! // Yeah, we didn't have anything for the..! // Mr. London // I am the sun! // Mr. London is the sun.") Modifying their model by adding a sun would have had the effect of solving the alignment problem.

Yet, a second solution was also proposed to the problem of alignment. As the London students recognized that their classroom context did not contain a sun, they recognized the lack of alignment predicament this created for the Girard students. However, rather than accept it as a problem to be fixed by modifying their ET model, they instead asserted that the problem does not exist ("It's pretty much, not, where it's coming from but how it would affect the earth itself. // This is just a model, this is the system boundary.") The London's students' classroom context involved only the inflow and outflow from the earth, not the source. If the Girard students were to change their conceptualization of the phenomena, by changing which conceptual elements were applicable to also only focus on inflow and outflow, that modification would fix the alignment problem. Of the two solutions proposed to address the lack of alignment problem— modifying the model by adding a sun, or modifying the Girard's students' conceptualization of the phenomena—the former was taken up in the final joint model which included a sun (see Figure 3).

In this case, the lack of alignment afforded multiple opportunities 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 knowledge element into a prior conceptualization. Another learning opportunity occurred when the London students suggested that the Girard students change their conception to focus only on inflow and outflow. If the Girard students had 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 earth and the movement of people was from the sun, to the earth, and then outside the bounds of the model where the students prepared to re-enter the model at the sun. The suggestion to focus only on inflow and outflow was not followed up on. As evidenced by the final joint model, the London students incorporated knowledge about a source into their conceptualization, thereby learning, while in this instance, the Girard students did not observably change their conception.

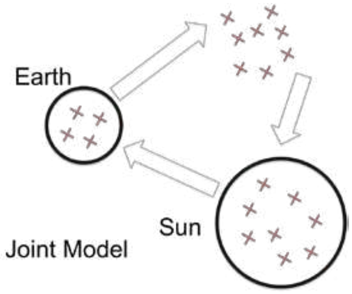

Figure 3. Illustration of the joint model from the first period classes.

Discussion and conclusion

These cases illustrate group and individual conceptual learning in a classroom environment. In the first case, one student's understanding of steady state was not apparent in that student's interpretation of the model that had been generated by their class. This problem was fixed by a modification to the classroom context that resulted in aligning that students' interpretation of the classroom context with the student's conceptual understanding—illustrating individual learning. Furthermore, the modification may have resulted in group learning through incorporating a new element. The second case involved one class presenting its model to the other class. There was a lack of alignment between the presenting class' classroom context and the information that the observing class extracted. The fix involved a modification to the information that the observing class extracted; quite literally, they changed their interpretation of what they saw. Finally, the third case, similar to the second case, involved one classroom presenting its model to the other classroom and a lack of alignment between the presenter's classroom context and the observer's conceptual understanding. Two potential solutions were proposed: modifying the classroom context or modifying the information extracted. Both solutions were learning opportunities and the first solution was taken up in the final joint model. All three cases involved a difficulty, lack of alignment, and a solution; all three were case of learning. The first case incorporated individual and group learning, while in the second and third cases only group learning was observed.

To capture and delineate individual and group learning we needed to distinguish the individual and classroom contexts which necessitated understanding that different individuals can have differing interpretations of the same model that then affect their subsequent reasoning and conceptual learning during key moments of classroom discussion. Practically, we were able to capture these moments through verbal disagreement and negotiation in the classroom, this is important as previously coordination class analyses tended to focus on learning during cognitive-clinical interviews. For this analysis, we expanded the notion of "context" within coordination class theory, thereby expanding our understanding of learning difficulties and successes in classroom environments. A limitation of the current work was only one scientific context, energy of the earth, while elsewhere the focus has been on individual's understanding across multiple scientific contexts (e.g. Parnafes, 2007). Focusing on multiple scientific contexts in a classroom where individual and group learning is present would be a natural direction for future work.

Capturing both individual and group learning in a classroom setting is unusual. Both the individual and collective group levels are critical for analyzing classroom learning (Cobb et al., 2001). One should not focus on collaborative learning to the detriment of individual learning (Conlin & Hammer, 2015). But, all too often, theories of learning and conceptual change have emphasized either group learning or individual learning and not integrated the two. Success in building on a theory of individual learning to expand it into a group-learning environment in a manner that allows integration of the two suggests new utility and areas of relevance for coordination class theory. More generally, this machinery helps us understand how a single student, or a single utterance can rather dramatically change a model, and when that happens, the kind of learning that can ensue, for that individual, and the entire class.

Finally, there are implications for the design of learning environments. Designing for this kind of learning requires facilitating an environment in which students, both collectively and individually, have opportunities to generate and modify the artifact or means by which they present their conceptual ideas. An important feature of this data was that the modifications to the ET 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, there was a low bar to recognize it and that facilitated quick modifications. The classroom lessons were only 45-minutes, and the students had no previous experience with Energy Theater. Possibly these features had a strong influence on facilitating learning; recognizing these key features and building them into other learning environments may be crucial for promoting this type of group learning in the future.

References

Cobb, P., Stephan, M., McClain, K., & Gravemeijer, K. (2001). Participating in classroom mathematical practices. *Journal of the Learning Sciences, 10*(1-2), 113-163.

Conlin, L. D. & Hammer, D. (2015) Commentary: From the Individual to the Ensemble and Back Again. In A. diSessa, M. Levin, & N. J. S. Brown (Eds.), Knowledge and interaction: A synthetic agenda for the learning sciences. New York, NY: Routledge.

diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In *Reconsidering conceptual change: Issues in theory and practice* (pp. 28-60). Springer Netherlands.

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., & 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. (2015). Knowledge Analysis: An introduction. In A. diSessa, M. Levin, & N. J. S. Brown (Eds.), Knowledge and interaction: A synthetic agenda for the learning sciences. New York, NY: Routledge.

diSessa, A. A., & Wagner, J. F. (2005). What coordination has to say about transfer. *Transfer of learning from a modern multi-disciplinary perspective*, 121-154.

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*, 1-18.

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., & diSessa, A. A. (2013). Microgenetic learning analysis: A methodology for studying knowledge in transition. *Human Development*, *56*(1), 5-37.

Scherr, R. E., Close, H. G., Close, E. W., Flood, V. J., McKagan, S. B., Robertson ... and Vokos, S. (2013). Negotiating energy dynamics through embodied action in a materially structured environment. *Physical Review - Special Topics: Physics Education Research 9*(2), 020105 020101-020118.

Scherr, R. E., Close, H. G., McKagan, S. B., and Vokos, S. (2012). Representing energy. I. Representing a substance ontology for energy. *Physical Review - Special Topics: Physics Education Research 8*(2), 020114 1-11.

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 Publishing.

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

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.