“Theory in pieces” – the communal development of a theory

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Abstract: This symposium aims to expose some of the social dynamics of theory development in the learning sciences by examining one particular case. It examines how individual studies contribute to theory development by using and extending an original theory of conceptual development, coordination class theory. We show how the diversity of contexts in which these ideas have been applied has contributed, not so much to validation, but to genuine expansion of meaning and power of the theory. This pattern emphasizes the essentially social nature of theory construction, and also a striking parallel between theory development in professional science and ideas about conceptual development in students that emphasize the role of multiple contexts. We discuss theoretical and methodological issues of communal development of a theory, such as theoretical power, fit, extension and generality.

Symposium Overview

This symposium discusses meta-theoretical questions relevant to the core issue of how theories are developed by a community of researchers. It attempts to expose some of the social dynamics of theory development in the learning sciences through the case of coordination class theory.

What is a coordination class theory? Briefly speaking, coordination classes provide a means for getting a certain class of information (e.g., force, velocity, energy etc.) from the world. The very idea of coordination classes is explicated in diSessa (2002):

> **The fundamental assumption behind the idea of coordination classes is that information is not transparently available in the world. Instead, we have to learn how to access different kinds. Indeed, in different circumstances, we may need to use very different means to determine the same kind of information.**

A well-formed coordination class guarantees that the same type of information would be inferred across different contexts and situations. A coordination class includes two parts: a perceptual part and an inferential part. The perceptual part includes the methods by which information is collected from the world by means of selecting attention to specific aspects. These are called “readout strategies.” The inferential part includes the body of knowledge and reasoning strategies that determine the inferences from the readout information. This body of knowledge is called “causal net”.

While diSessa originally sketched the foundations of the theory, several other researchers joined the enterprise of building a coherent theory that applies to a wide range of contexts. The theory originated in two sophisticated papers that lay the grounds for the theory in much detail and nuance (diSessa, 1991; diSessa, 1994). The widely cited paper by diSessa & Sherin (1998) followed, and attempted to outline the necessary and foundational theoretical constructs of coordination class theory through the examination of a single freshman physics student trying to make sense of the concept of force. The theory was picked by other researchers for its perceived power to generate insights in specific research contexts. The use of the theory in a diversity of contexts led to a genuine expansion of meaning and power.

Wagner’s dissertation (Wagner, 2003) focused on extended case studies of several undergraduate students as they learned statistics and, in particular, “the law of the large numbers.” This work applies coordination class theory in at least three new directions. First, the domain explored is mathematics, which is new for coordination class theory. Second, the larger theoretical framing of the work is the issue of knowledge transfer. Third, this was the first attempt to demonstrate processes of learning as viewed from a coordination class perspective. Prior studies that applied coordination classes only examined students’ knowledge without necessarily observing real conceptual change. These new directions drove the elaboration and modification of some pieces of the theory.

Mestre, et al. (2004), based on Thaden-Koch's dissertation (Thaden-Koch, 2003), analyzed students' judgments of realism of animations of different trajectories among physics-naïve and physics-knowledgeable undergraduates. The study highlighted the important role that readout strategies play in this particular context. While in prior research applying coordination classes the role of the causal net was highlighted in the process of conceptual change, this research presents a specific context where the causal net interacts strongly with readout strategies, resulting in the inability of most of the physics-knowledgeable students to perform accurate readouts (i.e., an inability to detect anomalous motion that was detected by most of the physics-naïve students).

Parnafes' dissertation (Parnafes, 2005) used coordination class theory in the context of studying students' development understanding of harmonic oscillation through the use of computer-based representations. This research expands the theory to the use of representations. In addition, the idea of *coordination clusters*, mentioned briefly in diSessa & Wagner (2005), becomes a central construct in some of the cases explored and is further developed (Parnafes, in review).

Finally, Levrini (Levrini, 2005; Levrini, in preparation) implemented coordination class theory in the context of proper time in special relativity. The particular case highlights *span, alignment and concept projection* as keys for interpreting the process of conceptual change activated by students in transitioning from a Newtonian conception of time to a relativistic one.

Four of these attempts to develop and extend the theory are summarized below. Each presentation, in addition to delineating the context and the theory extension, also refers to the following issues of communal theory development:

Theoretical fit: Why was coordination class theory a good candidate as a theoretical framework for this case, and how is the theory mapped onto this particular case? Were there features in the data corpus that served as particularly strong indicators?

Theoretical power: In what ways was the idea of coordination class insightful for the analysis of this particular case? In other words, were there some important insights that wouldn't have been possible without coordination classes?

Theory extension: How did the particular case suggest modifications or elaborations on the framework?

Specificity and generality: What are the particular properties of the case that led to the particular extension of the theory? In what sense did this case serves as a prototype for general classes of cases or contexts?

Presentations

Coordination Classes: Theoretical and Meta-Theoretical Issues

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This presentation aims to set a general frame for considering multiple lines of research—exemplified by the work of the other contributors to the symposium—inspired by the idea of coordination classes (CC). The presentation gives a sketch of the basic ideas of CC theory and suggests some meta-theoretical issues relevant to the core issue of how theories are developed by a community of people: Why do some theories "catch on" and why don't others? Is it appropriate to consider some theories as more generative than others (without any presumption of "correctness"), and how can generativity be judged or created in advance? Is there a tension between social and epistemic aspects of theory building, and, if so, how do researchers manage the tension?

Coordination Class Theory

Coordination class theory provides a rough model of a particular kind of concept (a coordination class) as a complex system. The model answers three primary questions: (1) What is the primary function of a concept (specifically, a CC)? (2) What are the performance characteristics that allow the concept effectively to perform its function? (3) Structurally, can we decompose the concept (CC system) into parts? Thus:

(1) The primary function of a coordination class is to allow one to *determine a particular class of information in many world circumstances*. (2) The main difficulty that must be overcome is the diversity of situations in which one needs to determine the relevant information. Information is never transparently available, and people need opportunistically to use whatever is easily "read out" of a given situation, and then creatively to infer the particular CC-characteristic information from that. However, all the diverse strategies must be coordinated (hence the name) in order to determine reliably the *same* information in *all* circumstances. (3) A first-cut in terms classifying parts of a CC is to distinguish perceptual-proximal strategies (more directly "seeing") from inferences that may be made on the basis of what is seen. The perceptual-proximal elements, which select and manage attention, are called *readout strategies*. The post-perceptual body of knowledge and reasoning strategies, which takes readouts and infers the required information, is called the *causal* or *inferential net*. In the talk, I will give examples and additional details of the model, including ideas of span, alignment, and concept projections

Meta-theoretical Properties of Coordination Classes

Below I name several more-or-less "designed" characteristics of coordination class theory that might have contributed to its apparent generativity and use by others.

1. The theory is inviting because of its explicitly tentative nature, allowing other researchers both to fill in and to adapt to their particular contexts. CC theory is self-consciously a rough sketch, and limitations have been as highlighted as defining aspects.
2. The theory makes progress by dividing off a subcontext from a complex, but perhaps intractably diverse terrain. CCs are only one type of concept, not all possible concepts. The theory is driven, in part, by the assumption of diversity in kinds of concepts, and it might draw some of its power from this "restricting of domain."
3. The theory went through a self-conscious phase of simplification—although, in its present form, it is still not, and was never intended to be, a "popularly accessible" idea. Simplification can be both sociologically and epistemologically powerful, although there may also be a tension—for example, over-simplifying to promote accessibility.
4. Coordination class theory is one of the few existing technical models of the internal structure of concepts as a complex system, and it allows both theoretical analysis (e.g., of typical difficulties) and empirical tracking of processes of concept use and development. Here, the value of the theory may not be in its details, but primarily in a new grain size of analysis.
5. The theory may be productive mainly for introducing a focus on an, until-now, neglected characteristic of concepts: their perceptual aspects.

Transferring a Theory to a New Context

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In setting out to take a new look at the problem of "knowledge transfer" (Wagner, 2003), I had no expectation that diSessa's research would serve as the primary theoretical underpinning for my own. Early considerations of my data—extended teaching interviews with undergraduate statistics students wrestling with their understandings of the law of large numbers—led me to reconsider the way the problem of transfer has usually been considered. Traditionally, the problem has been framed liked this: *How is it that knowledge learned in one context can be applied to a different context?* I proposed in Wagner (2003) that a different question might be asked that just as readily articulated as the problem of transfer: *How is it that individuals come to see two different situations (contexts) as alike, in that they might be considered examples of the same (mathematical) principle?* This change of focus—from the state of the knowledge to be applied in a new context to the individual's ability to perceive a new situation as an instantiation of some concept—led me to diSessa's work on coordination class theory.

Reframing the question in this way made inseparable "knowledge of a concept" and "the ability to perceive a concept in particular situations." The coordination class components of *readout strategies* and the *causal net* together suggest that learning to recognize some concepts in the world involves learning very particular and context-sensitive means of attending to information relevant to that concept. In other words, the ability to perceive a concept as relevant to a particular situation is not due primarily, if at all, to the "abstract" nature of conceptual knowledge; rather, learning to recognize and see as relevant a concept in a situation depends on an individual having acquired appropriate readout strategies suited to that situation. In this interpretation, it is quite possible for a person to develop a meaningful understanding of some concept that is consistently useful in *some* situations but is not perceived as useful in other situations that may be relevant by normative standards. In our language, we would say that it is common for a learner to construct a *concept projection* for a particular concept that suffices in some situations, but not in others (diSessa & Wagner, 2005; Wagner, 2006). diSessa's theory predicts the very problem that knowledge transfer has always posed: Why is it that some people make good use of knowledge in some situations but not in others?

In Wagner (2003; 2006) I showed how diSessa's coordination ideas, situated within his larger knowledge-in-pieces epistemological framework, could be extended to offer some coherent and powerful insights to the long-standing problem of knowledge transfer. Data were drawn from microgenetic analyses of in-depth interviews carried out over several weeks with undergraduate students learning elementary concepts of probability and statistics. These analyses revealed that knowledge transfer may be rooted in the construction of cognitive structures significantly different from those traditionally assumed in the transfer literature. diSessa's insistence on the context-sensitivity of different forms of knowledge was supported by the data. Analyses suggested that the key to knowledge transfer is not found in the "abstractness" of knowledge that somehow *overlooks* contextual differences, but through the increasing complexity of conceptual structures that include context-sensitive readout and coordination strategies that *account for* contextual differences.

The process of my own research reflected the very theory of transfer that diSessa's and my ideas suggested. Coordination class theory was not simply "applied" to a new set of data in any abstract way. Rather, my ability to perceive it as useful within the specific context of my work emerged only as I learned to attend to particular aspects of my data that served as affordances for "seeing" aspects of diSessa's theory; as the theory itself suggested new ways of looking at my data; and as the occasional lack of fit between the two suggested ways in which the theory itself could be expanded.

Coordination clusters in oscillatory motion

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In the context of investigating how computer-based representations facilitate conceptual change in the domain of harmonic oscillation (Parnafes, 2005), the application of coordination class theory seemed to be an appropriate fit. First, coordination class theory enables one to look at the process of conceptual change at a fine-grained level, which matches the type of analysis that I do, aiming to describe mechanisms of developing understanding. Second, since coordination class theory refers to perceptual processes (in addition to conceptual processes), it was particularly suitable for analyzing processes of learning with external representations, and generated an opportunity to examine possible relations between representations and conceptual change.

More specifically, through observation of eight pairs of students interacting with both physical oscillators and a simulation of oscillatory motion, I examined how students differentiate the concepts of velocity and frequency in oscillatory motion, facilitated by the use of representations. The close examination of this processes led to the refinement of the idea of *coordination cluster*.

The idea of a coordination cluster was motivated and developed through the analysis of students' efforts to make sense of the term "fast" both with physical oscillators, and with a simulation of oscillation. Everyday talk usually refers to both velocity and frequency as "fast", and in many contexts this undifferentiated use is unproblematic. However, in a scientific context, the use of terms to denote certain concepts requires more precision in order to use those concepts properly in a wide range of contexts and relations and with a proper alignment. Moreover, in the context of oscillation, where the term "fast" denotes at least two different scientific concepts (velocity and frequency), precise differentiation becomes even more crucial. A proper differentiation between these two concepts requires that students develop a system that coordinates two coordination classes: velocity and frequency. This system is what we called a coordination cluster, which requires two-level coordination:

1. Coordinating information within one coordination class – students need to learn ways to get information from multiple situations about frequency (or about velocity, in the case of coordination class of velocity).

2. Coordinating information across coordination classes – students need to learn to differentiate the two concepts of velocity and frequency and to know when to use each concept and what the relations between those concepts are. Even if they have a coordination class of frequency, and they know how to get information about frequency, they still need to know that they are dealing with the concept of frequency and not with the concept of velocity.

The construct of coordination cluster seems to be particularly useful for cases of concept differentiation, or in cases where students use different concepts interchangeably. In these cases, the development of one coordination class is constructed with the simultaneous construction of other coordination classes in the cluster.

The application of coordination class theory on Students' Judgments about Animated Motion

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We will discuss an application of coordination class theory to a situation in which students were asked to judge the realism of computer animations showing metal balls rolling on a pair of metal tracks. The animations were based on a variant of a common physics classroom demonstration, sometimes called "High Road/Low Road." Given different sets of animations, students were asked to identify the "most realistic" one from the set. When presented with animations of a single ball, most students focused on the presence or absence of realistic speed changes. Adding a second ball (moving in an adjacent track) to the animations drastically changed the strategies that many students used, to the extent that they identified as realistic a particular (unrealistic) motion with two balls that they had ruled out minutes before with one ball. This motion featured a ball speeding up as it rolled uphill, which the students found unrealistic in the one-ball context. When both balls were present, this same motion (with a ball speeding up while rolling uphill) showed one ball speeding ahead of the other before they reached the ends of their tracks together (a pattern that many students identified as a characteristic of realistic motion on these tracks).

We attempted a concrete (often phrase-by-phrase) mapping of student interview data onto the structures postulated for coordination classes. Students often repeated similar descriptions of similar motions, which allowed us to identify several common expectations of realistic motion, and some of the sources for those expectations; these we mapped onto the causal net. The same repeated descriptions of well-specified stimuli allowed us to make plausible inferences about the readout strategies students used in different circumstances.

Our analysis particularly highlights the effect that students' knowledge can have on the observations they make. The participants in the study were drawn from two different college courses. Students from an introductory physics course were especially prone to the problem of accepting anomalous motion as realistic, as described above. In contrast, students from an educational psychology class were virtually immune to the problem. Mapping interview data onto coordination class structures facilitates an explanation in terms of the knowledge that students brought to the task (causal net elements), and the sorts of observations (readout strategies) that they focused on based on that knowledge. In this explanation, the readout strategies evoked were strongly dependent on the knowledge that students brought to bear on the task, and on details of the context. The emphasis in other applications of coordination class theory attends mostly to the use of readout strategies to gather information, on which the causal net will operate. In our case, different causal net inferences led to very different ways of observing the world—that is, the causal net affected readout strategies.

Another feature of this application of coordination classes is that virtually no attempt was made to identify knowledge structures or concepts that could qualify as coordination classes. To the extent that it is useful, the case provides evidence that coordination, and the language of coordination classes, can be fruitful even in cases where "coordination classes" are of only peripheral interest. These issues are discussed in more detail in a recent article extending our prior work (Thaden-Koch, Dufresne & Mestre, under review).

Summary

Each presentation in the symposium demonstrates the application and extension of coordination class theory. As researchers who attempt to apply this theoretical construct on a corpus of data, one thing that we must do is to refine our ability to recognize that construct in our research context. A number of researchers seem to agree that coordination class is a powerful idea. However, it is not obvious that any two researchers would "see" the same coordination class in the same data, or even that they count the same thing as a coordination class. As part of community theory building, we need to refine the ways in which we "see" things in our data through the lens of the theory. In other words, we need to refine our coordination class of coordination class.

Discussant

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