Conceptual Dynamics in Project-Based Science

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Abstract: The purpose of the Conceptual Dynamics Project (CDP) is to understand what is learned by students in project-based science curricula. As we have argued elsewhere, the content "covered" in a project-based curriculum tends to cut across the lines that are traditionally drawn in carving up disciplines. For this reason, it is typically hard to localize learning around familiar disciplinary constructs. The goal of CDP is the development of frameworks and techniques that are specifically adapted for dealing with these complexities. In this regard, two aspects of our framework are of particular importance, and are emphasized in this article: (1) We adopt a two-tiered framework that unites a cognitive analysis with what we call a *disciplinary* analysis; (2) In our cognitive analysis, we attempt to build an account at the level of cognitive *systems* defined by their *function*. The aims of this short paper are modest. Our primarily goal is to give a broad sketch of our current analytic framework, with an emphasis on the two features mentioned above. In addition, we will illustrate the types of implications that the framework has had for our empirical work.

Introduction

This article reports on the first year of work of the Conceptual Dynamics Project, an NSF-funded research project that operates within the Center for Learning Technologies in Urban Schools (LeTUS). LeTUS is a collaboration among two research institutions, Northwestern University and the University of Michigan, and the public school districts in Chicago and Detroit. Much of LeTUS's work is centered around the development of middle-school science curricula, which are then enacted by teachers in the collaborating school districts. These curricula are primarily project-based (Krajcik, Czerniak, & Berger, 1999).

The purpose of the Conceptual Dynamics Project (CDP) is to understand what is learned by students in these project-based science curricula. Our focus, roughly speaking, is on the learning of science *content*, as it is traditionally conceived. For example, for a project-based science curriculum relating to human biology, we would want to know the specifics of what students learn about particular bodily systems, rather than what they learn more generally about the nature of scientific inquiry or even inquiry in biology.

This task has proven to be particularly challenging, both theoretically and methodologically. One way to understand the source of the difficulty is to note that, in a project-based curriculum, the particular content addressed is driven by the needs of the task, rather than some type of analysis of the structure of a discipline. For this reason, as argued in Sherin, Edelson, and Brown (2000), the content "covered" in a project-based science curriculum tends to cut across the lines that are traditionally drawn in carving up disciplines. This can pose problems for building simple accounts of what students learn in a project-based curriculum. Because the content tends to cut across traditional disciplinary structures, it is typically hard to localize learning around familiar disciplinary constructs, such as *temperature* or *density*.

This feature is not unique to project-based curricula. The project-based approach is one variant of a family of prescriptions that share the belief that science learning should be embedded in a rich, meaningful task, and that the need to complete this task should drive learning. In addition to project-based science, this family of approaches includes Learning by Design (Harel, 1991; Hmelo, Holton, & Kolodner, 2000) and "anchored" or "problem-based" instruction (Barron et al., 1998; Williams, 1992). Elsewhere, we have referred to this family of curricular approaches as *task-structured*, in contrast to more traditional *content-structured* curricula (Sherin et al., 2000).

Thus, the goal of CDP is the development of frameworks and techniques for capturing the learning that occurs in these task-structured interventions, and that is adapted to the particular features and complexities of the task-structured approach. In this regard, two aspects of our framework are of particular importance, and will be emphasized in what follows.

1. *Two intertwined analyses*. We adopt a two-tiered framework that unites a cognitive analysis with an analysis that we refer to as a *disciplinary analysis*.

2. *Focus on functionally-defined cognitive systems*. In our cognitive analysis, we attempt to build an account at the level of cognitive *systems* — larger aggregates of knowledge. In particular, we argue for the analytic importance of cognitive systems that are defined by their *function*.

The aims of this short paper are modest. Our primary goal is to give a broad sketch of our current analytic framework, with an emphasis on the two features mentioned above. Moreover, we will not present any systematic attempts to apply our framework to observations or discuss how students' cognition changes throughout the curriculum enactment. Instead, we will briefly illustrate the types of implications that the framework has for our work empirical work.

Our framework: Two types of analyses

Central to our framework is the notion that it is helpful to intertwine analyses of two distinct types. The first type of analysis is what we refer to as a *disciplinary analysis*. A disciplinary analysis is an analysis of the shared knowledge and knowledge-building activities in a discipline, generally using the language and structure of the discipline itself. If we are using language of this sort we might say, for example, that a student had "learned about forces" or "learned about Newton's Second Law." The table of contents of a science textbook can be read as an analysis of this sort; it divides the subject matter into parts employing the language and perceived structure of the discipline itself.

The second type of analysis is what we refer to as a *structural modeling* analysis. In this type of analysis, one attempts to model the behavior of individuals and groups by positing structures in the person-environment system and processes that act on those structures to generate behavior. A cognitive analysis, in the traditional sense, is one variant of this type of analysis. In a cognitive analysis, one explains the intelligent behavior of individuals by positing mental representations and processes that act on those representations. For example, we might hypothesize that student understanding in a domain consists of certain specific schemas or rules that function together to generate explanations, by individuals, of particular scientific phenomena.

For illustration, consider the learning that might occur in an introductory course on Newtonian Mechanics. A disciplinary analysis might say, for example, that a student had "learned Newton's three laws." However, such an analysis does not say anything about the cognitive particulars — it does not tell us what mental representations individuals have acquired that constitute their understanding of these laws.

Given that a structural modeling (cognitive) analysis is, in a sense, more powerful and complete, one might ask why the disciplinary analysis is necessary. There are several reasons. First, the disciplinary analysis can provide a bridge between our (comparatively messy) analyses of cognitive systems and familiar reference points in a discipline. Second, there are a number of questions that are most usefully framed in terms of a disciplinary analysis. Such questions concern, for example, how content is sequenced in various types of curricula and how "prerequisites" are covered.

In what follows, we discuss the two main components of our framework in more detail.

A framework for disciplinary analysis: Epistemic forms and games

In a separate submission to this conference, Schwarz and Sherin discuss the disciplinary component of our framework in more detail. Here, we present a brief overview of this component in order to outline the role that it plays within our larger program.

Our particular disciplinary analysis builds upon the work of Collins and Ferguson (1993). Like all disciplinary analyses, Collins and Ferguson's framework provides an analysis of the shared knowledge products and knowledge-producing activities of a discipline. However, in analyzing this shared knowledge, Collins and Ferguson steal a page from the book of cognitive scientists: they propose to describe shared disciplinary knowledge in part by its *form*. Just as a cognitive scientist describes a mental structure by its form — as a schema or rule, for example — Collins and Ferguson describe disciplinary knowledge in terms of what they call *epistemic forms*. These epistemic forms include relatively simple structures, such as *lists*, as well as more complex structures, such as *constraint systems* and *system dynamics models*.

A second part of Collins and Ferguson's framework centers around what they call *epistemic games*. For Collins and Ferguson, epistemic games are the "rules and strategies" that guide the *construction* of instances of particular epistemic forms. In our own work, we extend the notion of epistemic games to include activity associated with the *application* of instances of epistemic forms, as well as with their construction.

As a simple example, suppose that some students are concerned with making a list of the things found in food. Their list might, at some point, consist of these items: *Vitamins, minerals, sugar, water*. In this case, the students have constructed knowledge that can be characterized as having a particular epistemic form — the *list* form. Furthermore, as they are making their list, the students are engaged in a particular epistemic game of the *construction* variety. Moreover, once they have made a list, they can engage in a variety of *application* games that employ the list. For example, given some new item, the students can answer the question of whether that item appears on their list.

Structural modeling analysis: Functionally-oriented cognitive systems

Our structural modeling analysis is, in many respects, a cognitive analysis in the traditional sense. We see ourselves as attempting to describe knowledge in the form of mental representations possessed by individual students. Our stance is very general; we assume that there is knowledge of a variety of types and at all levels of abstraction. We include, for example, highly general explanatory primitives of the sort described by diSessa (1993) (e.g., *blocking*) as well as specific "episodic" memories of events (e.g., the time my eyeglasses fell in the toilet) and knowledge stored as strings of words (e.g., "all things fall at the same rate").

Analysis at the grain-size of individual knowledge elements is an important component of our analysis. However, given the extent and complexity of learning in task-structured curricula, we believe that it is also extremely helpful to capture changes in large-scale aggregates (systems) of knowledge. To facilitate our discussion of this large-scale structure, we will begin with a simple image of the larger knowledge system. As shown in Figure 1, we will think of this system as consisting of a large number of undifferentiated elements that we will refer to simply as *nodes*.

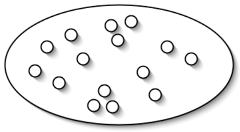

Figure 1. A large knowledge system consisting of nodes.

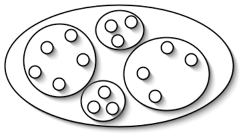

Figure 2. Nodes grouped into sub-systems.

Given this simple image, what are some candidates for large-scale organization of the knowledge system? One way to rephrase this question (which we will soon reject) is to ask how we might draw circles around the nodes in Figure 1 in order to group nodes into sub-systems. (An example is shown in Figure 2). In the cognitive literature, there are many candidates for sub-structure of this sort. For example, the circles in Figure 2 could correspond to intuitive theories, such as intuitive biology or intuitive psychology. (See, for example, Carey, 1988.)

Other candidates for the sub-systems in Figure 2 are mental models. In this case, the circles around nodes would correspond to models of particular physical systems or of classes of systems. Yet another candidate for sub-structure is organization of knowledge *by kind.* For example, we could imagine that one of the circles around nodes in Figure 2 contains only episodic memories and that another contains only p-prims (diSessa, 1993). Furthermore, there need not be only one type of sub-structure. Some circles in Figure 2 could correspond to theories and some to mental models.

Even allowing for such hybrid models, there is an important sense in which all of the above possibilities are overly simplistic. One problem is that it might not be the case that any one node is associated with only one sub-substructure. For this reason, we believe that a more flexible and dynamic image is required. More specifically, we propose the following:

1. To the extent that there is large-scale structure in the knowledge of individuals, we see it as the product of emergent, recurrent patterns in the activation of nodes. We refer to these recurrent patterns as *modes*.

2. Roughly speaking, we believe it is profitable to think of many modes as *functionally* defined. Each mode corresponds to a class of reasoning tasks that present themselves to individuals. The proposal to take functional systems as a unit of analysis is not new. Most prominently, a similar notion has appeared in the writings of the activity theorists (e.g., Vygotsky, 1986).

Furthermore, when we look at the level of these modal systems, we believe that it is possible to make useful correspondences between our cognitive and disciplinary analyses. In particular, we hypothesize that as students are initiated into a domain, they begin to develop some modes that correspond to particular epistemic games. Because of this correspondence, the analysis in terms of epistemic forms and games can guide us in constructing the system-level cognitive analysis.

The framework in use

The cognitive modeling framework we have defined here is still somewhat spare; the notion of functionally-oriented modal structure is relatively simple and leaves much work to be done. Nonetheless, we believe that even this small step is powerful enough to give our research substantial direction and allow us to make preliminary progress on tough issues. For example, we believe it is profitable to understand some learning in terms of the evolution of modes and the development of new modes.

In this final section, we attempt to illustrate how the framework has driven our empirical work. Here, our emphasis will be on our structural modeling analysis. (See the submission by Jennifer Schwarz for more detailed examples of the application of our disciplinary framework.) Furthermore, we will only present data from interviews conducted with students before and after instruction. This omits much that is important, including the details of how students are actually learning in interaction with teachers, materials, and each other. These classroom learning processes are part of what our project seeks to understand. However, for the purposes of making our points clear and stark, we restrict ourselves in this paper to a simple comparison of pre- and post-interviews.

Introduction to I,Bio

For this illustration, we draw on the work that we have done around one curriculum called *I,Bio*. I,Bio is a 6-8 week middle-school science curriculum on human biology, developed within LeTUS. Like all LeTUS curricula, I,Bio is project-based. As the project in I,Bio, students are given the task of redesigning their school lunch choices with an emphasis on meeting the body's energy needs. In order to work through this project, a great span of content is touched upon. This content includes, for example, topics relating to nutrition, the functions of bodily systems, cellular respiration, and basic notions of energy transformation.

Although it is not our focus here, we will say just a little about our own epistemic forms/games disciplinary analysis of I,Bio. At the high level, I,Bio attempts to teach a simple *system dynamics* model of the movement of energy into and out of the body (refer to Figure 3). The students are guided in the construction of the model, and they then play a variety of games with this model. For example, one common game involves narrating the movement of energy into and out of body stores.

There are also many ancillary epistemic forms. For example, students learn a number of simple *functional relationships* such as the relationship *more food➔more energy*, and they construct a number of simple lists, such as a list of *foods that have high energy content*. More complex epistemic structures are also layered on top of the energy system dynamics model. For example, students learn *spatial decompositions* of body systems and this is linked with the energy system dynamics model.

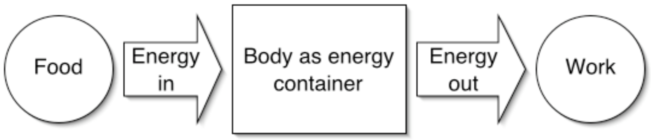

Figure 3. The system dynamics model taught in I,Bio.

Design of an interview

We have engaged in a variety of kinds of data collection around I,Bio. We have collected student work and observed classrooms. In addition, we have conducted 39 interviews with students, spread over enactments by several teachers. In order to see how the framework has driven our empirical work, it is illustrative to begin with a discussion of the design of our interview protocol.

In some respects, designing a post-instruction interview was relatively straightforward. Given the discussion of I,Bio in the preceding section, we can hypothesize that, after instruction, students possess a cognitive mode that is associated with a particular epistemic game: the narration of changes to the body's energy stores. This means that, during the post-interview, it should be sensible to ask students questions of the form: What would happen to your body's energy stores if you ate these foods and engaged in this particular sequence of activities?

However, prior to instruction, it is unlikely that any question that refers to changes to "your body's energy stores" will be sensible to students. This means that during pre-interviews we need to ask different sorts of questions. This requires that we make some guesses about the relevant modes that exist, and design questions to explore those modes.

In designing our pre-interviews, we made guesses of just this sort. We thought that it would be sensible to pose questions about which foods and activities were "healthy" or "good for you." Specifically, we guessed that there might be three modes here:

- *Is this meal healthy?* A mode for reasoning about the healthiness of food, based on general nutrition factors. We speculated, for example, that students would think that vegetables and fruits are healthy, but candy is not.

- *What if you are "on a diet?"* A mode for reasoning about the appropriateness of various meals and activities if someone were trying to lose weight.

- *What makes you "fit?"* A mode for reasoning about what activities make the body "fit." Here we had in mind concerns about increased stamina and flexibility, as well as concerns about muscle building.

In designing our interview, we chose to start with quite minimal prompts. We simply wanted to activate the hypothesized modes and explore the shape of these modes. For this reason, we started our pre-interview with a very open question. We asked students to imagine that there was a student just like themselves (same age, gender, etc.) who wanted to stay healthy over the next two or three days. We then asked: What choices should this student make in order stay healthy?

After this initial part of the interview, we asked more structured questions to further probe the shape of the already activated modes and activate additional modes. Much of this structured questioning was conducted around some sheets of paper that showed a particular food or activity along with some relevant data. For example, some of these information sheets resembled the nutrition labels that are found on commercial food items (refer to Figure 4).

Facts
Serving Size 1/2 Cup 2% milk (4 ounces)
Amount per Serving
Calories 60
Total Fat 2.5 g
Cholesterol 10 mg
Sodium 60 mg
Total Carbohydrate 5.5 g
Sugars 5.5 g
Protein 4 g
Vitamins
Vitamin A 5%
Vitamin C 2%
Vitamin D 12.5%
Minerals
Calcium 15%
Iron 0%

2% Milk

Facts
Time 1 hour (60 minutes)
Amount per Time
Calories/minute 6.5
Total Calories 390

Playing Soccer

Figure 4. Sheets showing food and activity items along with relevant data.

Calvin Before I,bio

The transcript in Figure 5 shows how the first open-ended question was posed to one student who we call "Calvin." The interviewer asks: "So what kinds of things should that student do over the next two or three days to stay healthy?" In his brief response, Calvin mentions two broad categories of choices, food and exercise. In addition, he mentions specific foods, including salad and "nonfattening stuff — like not a lot of meat."

1 Interviewer: The first thing that I want you to do is imagine that there is some student, just like you, same grade, and we want to make sure that they stay healthy over the next several days and we get to say what choices they get to make about how to stay healthy. So what kinds of things should that student do over the next two or three days to stay healthy?
2 Calvin: Eat good food. The right food like salad and nonfattening stuff—like not a lot of meat. Exercise. That's about it.

Figure 5. The first question posed to Calvin, along with his response.

Calvin has not said much yet, but there are already some important points we can make. Note that the interviewer has not yet mentioned food at all. Nonetheless, Calvin has not only starting talking about food, he has mentioned specific food items. To us, this suggests that our question has at least succeeded in targeting territory in which Calvin possesses knowledge that we can explore.

Second, it is worth emphasizing that we are paying attention to relatively mundane features of Calvin's knowledge here, such as his knowledge about salad. This sort of supporting detail is often ignored in studies of science learning. Instead, research tends to search for core, underlying explanatory models. In our attempts to understand large-scale knowledge aggregates, we believe it is important to attend to these details. It is part-and-parcel of the modal structure.

3 B: So you said salad. Why is salad good to eat?
4 C: Because vegetables are good for you. Salad usually has vegetables in it, which is good for you. Salad is the main thing that people usually eat when they are on a diet or when they are trying to stay healthy.
5 B: And being on a diet is that different than trying to stay healthy?
6 C: Yeah because you can get too big and that's not healthy for you so you go on a diet that's more healthy for you because you are trying to lose your weight and stay average. I think it's about the same thing.

Figure 6. Interviewer presses to further explore and differentiate modes.

As the interview proceeded, the interviewer attempted to more fully explore the modes that had been activated, and to see if it was possible to separate empirically our three hypothesized modes (refer to the transcript in Figure 6). In line 3, the interviewer simply asked for an explanation of Calvin's statements in line 2: "Why is salad good to eat?" Calvin's response was nearly tautological; he asserted that vegetables are "good for you" and that salad is the "main thing that people usually eat when they are on a diet or when they are trying to stay healthy." Calvin's response prompted the interviewer to ask straight out whether "being on a diet" and "trying to stay healthy" are the same (Line 5). In response, Calvin waffled a bit, but ultimately said that they are "about the same thing" (Line 6).

These brief passages suggest a conclusion that, based on other observations, we believe we will be able to make quite strongly. There is a stable mode of reasoning that is activated by this line of questioning. However, across many students, this mode appears to be large and relatively flat; we found it hard to distinguish between the three modes hypothesized above, and asking for explanations did not yield much beyond simple assertions of which foods and activities are healthy.

1. I: I'm going to tell you a little story. A student in your classroom leaves class and goes to the cafeteria with her friends. And she sits in the cafeteria, and at the end of the period, she gets up and goes back to the classroom. So, what happens to her level of energy stores from the time she leaves the classroom to the times she returns?
2. M: … Well it might stay the same because in the class she wasn't eating. Then she goes to the cafeteria and burns some on the walk. She eats, comes back and burns more, but she has stored energy, which makes her back to basically the same spot that she was before she went to the cafeteria.

….

3. I: Would it matter what she ate when she got there?
4. M: Yeah, she could have ate two pieces of celery stick or she could have eaten a whole meal with Salisbury steak and mashed potato.
5. I: So what if she ate Salisbury?
6. M: She would get more energy and more fat and all that because they have more vitamins...

Figure 7. Start of an interview with Michael, following I,Bio.

Michael after I,Bio

For contrast, we look now at an interview that was conducted with another student, Michael, after he had completed I,Bio. Near the start of the interview, the interviewer asked Michael how a student's energy stores would change in a brief hypothetical scenario (refer to Figure 7). Understandably, the differences between Michael's and Calvin's interviews are dramatic. Note that in the first line, the interviewer asks directly about energy stores in the body and how these stores change. Not only were these questions sensible to Michael — he answered them quickly and with confidence — he seems to have well-worn reasoning patterns available for answering. We take these observations as preliminary evidence that there is a mode here, adapted for this type of reasoning. Furthermore, it is a mode that is aligned with one of the central epistemic games in I,Bio, the narration of changes to the body's energy stores.

Other features that are typical of modal structure are evident in the transcript in Figure 7. It is not the case that the activated mode consists only of a simple, streamlined model. In addition, there is significant ancillary knowledge. For example, In Line 4, Michael mentions celery and Salisbury steak as prototypical instances of food with certain properties.

Finally, we note that the approach that we are adopting seems to make it straightforward to describe the pre/post differences that exist between Michael and Calvin; there are clear differences in the modes that each student has available. One might argue that this is simply an artifact of the particular questions we asked each student. This is part of our point; one of the main ways we should understand learning is as changes in the modes of reasoning that are available to students. Prior to instruction, certain types of questioning simply do not make sense. This may be a simple observation, but we believe that it is just the right observation for making a start on understanding the complex learning that occurs in a task-structured curriculum.

Conclusion

In this paper, we reported on the first year of work by the Conceptual Dynamics Project, whose goals are to develop a set of frameworks and techniques for understanding the learning that occurs in task-structured curricula. Our aims in this paper were modest. In the first part of the paper, we set out to give a broad overview of our analytic framework. In that discussion, we emphasized two features of our framework: (1) We combine both *disciplinary* and *structural modeling* frameworks, and (2) in our structural modeling analysis, we focus on functionally-defined cognitive systems we called modes.

In the second part of the paper, we attempted to illustrate how this emerging analytic framework has driven our empirical work. We discussed how the design of our interview protocol was driven by the search for modes. In addition, we tried to illustrate how the analytic framework influenced what we attended to when looking at students' answers to our questions, and how the framework helped us to straightforwardly capture some pre/post differences.

Acknowledgments

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