Describing Science Content: Bridging the Gap Between Content and Process

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Abstract: Driven by concern over US students' performance in science, policy makers have tried to ensure change by using standards as a reform implementation strategy. However, we believe descriptions of science content and learning goals as they currently exist are inadequate for two reasons. Firstly, if standards are designed to ensure a common, high level of student achievement, precise descriptions of the desired *understanding*, not simply facts to be learned, are essential. Secondly, in the standards, scientific content is isolated from process skills. These two difficulties–imprecise description and conceptual isolation–combine to frustrate educators in their goal of improving students' scientific thinking. To solve these problems, we must re-conceptualize the very way we talk about science content so that it integrates what we currently call "content" and "process" into a single set of learning objectives. Here we describe that new technical language and analysis framework. Examples of how it can be applied to both curriculum materials and classroom activities demonstrate its effectiveness in the precise and complete description of learning goals, content covered, and the level of students' understanding.

Introduction

Concern over US students' performance in science, in combination with new research in education, has impelled us as a society to change what happens in science classrooms. One approach policy makers have used to ensure change is to use standards as a reform implementation strategy. Standards addressing scientific processes, as well as increased and more rigorous content requirements, have been added to better encompass a new ideal of science literacy (National Research Council, 1995). The goal of these additions is to specify the substance of new requirements and provide descriptions of the kind of scientific understanding desired of students (American Association for the Advancement of Science, 1990 & 1993). However, descriptions of science content and learning goals as they currently exist are inadequate to clearly describe the ways that their authors intend students to understand and apply scientific concepts and methods. Firstly, current descriptions are ambiguous. Many different student performances appear to fill the same standard equally, so the specific requirements for student performance are open to interpretation. If standards are designed to ensure a common, high level of student achievement, precise descriptions of the desired understanding are essential to that aim. Secondly, the isolation of scientific content from process skills leave educators guessing about which processes and scientific themes are appropriately applied to different science concepts. These two difficulties–imprecise description and conceptual isolation–have combined to frustrate both teachers and policy makers in their mutual goal of improving the nature of students' scientific thinking.

To solve these problems, we need to reconceptualize the very way we talk about science content. To date, standards writers and educators have described what is to be learned with a commonsense epistemology–our shared language for talking about scientific knowledge and thought. Here we provide a description of a new, technical language designed to encompass the content of traditional science disciplines as described in standards documents, that also combines science concepts with behavioral indicators of understanding; a division that is firmly entrenched in our current discourse. It attempts to integrate what we have previously called "content" and "process" into a single set of learning objectives, in which "content" encompasses both the science concepts as conventionally defined and the ways that students apply them to solve problems. In this paper, we present the framework as it is currently conceived, then provide examples of how it can be applied to both curriculum materials and classroom activities to provide a more precise and complete description of the learning goals, content covered, and the level of understanding students achieve.

Epistemic Structures

In brief, our goal is to produce an analytic framework that can be applied to curricular materials or observations of science classrooms to produce an analysis of the "content covered." To develop this framework, we drew on current research on understanding and cognition. More specifically, two theoretical components were integrated to create what we call our *Epistemic Structures* framework of analysis. The first is the conception of students' actions as *learning practices*, or the activities and processes students use to demonstrate their understanding of a concept in a learning environment. The second is Collins & Ferguson's conception of *epistemic forms and games* (1993), which contributed significantly to both the new descriptive language and processes of content analysis.

Learning Practices

While there are similarities, learning science in school differs in significant ways from both everyday problem-solving and scientific domain practices. It has both goals and problem-solving methods of its own. As part of our analysis, we seek to understand and describe these goals and methods. Furthermore, in doing so, we adopt a *learning practices* perspective. Rather than address the teaching methods or the learning environment, a learning practices perspective focuses on the things that students do in the learning context to demonstrate understanding (Reif & Larkin, 1991). In a sense, an analysis of learning practices is a task analysis; it describes the steps that students go through to show understanding of a science concept (Bruer, 1993).

A focus on learning practices allows us to understand the practices that occur in classrooms in their own terms, rather than by comparison to either (1) everyday practices (Dewey, 1902; DiSessa, 1996; Lave, 1991; Reif & Larkin, 1991; Rogoff & Lave 1984; Schank, 1994.) or (2) the practices of scientists (Lynch & Wolgar, 1990; Bruer, 1993; Reiser, Tabak, Sandoval, Smith, Steinmuller, & Leone, 2001). In the past, research has emphasized the modification of either real-life or domain practices to the classroom, not on identifying specific sets of practices, aligned with both the domain and classroom context, that might best demonstrate students' understanding. Different approaches focus alternatively on incorporating social (Lave, 1991; Rogoff & Lave 1984), or domain practices (Brown, Collins & DuGuid, 1989; Bruer, 1993) into the classroom context to facilitate learning and demonstrate mastery. These methods of integration have been only partly successful. Describing the learning practices actually used by students in the classroom, and what types of problem-solving those practices support becomes a necessary first step to designing effective curricula.

Epistemic Structures

Through an investigation of experts' reasoning practices in the disciplines of science and history, Collins and Ferguson (1993) developed an analysis of the target structures and sets of general-purpose strategies that guide the process of expert scientific inquiry. They call the target structures *epistemic forms* and the strategies *epistemic games*. An epistemic form is a target for knowledge in the sense that it is an abstract form that can be filled with multiple types of content. For example, a system-dynamics model is one type of epistemic form, made up of variables connected to each other in such a way that a change in one variable impacts other variables. A scientist's account of an ecosystem might take this form; we can imagine constructing a system-dynamics model of an ecosystem to provide an explanation of the food web. Epistemic games go hand-in-hand with epistemic forms. An epistemic game is a set of rules, strategies, and moves that allow a scientist to create a particular epistemic form, such as a systems-dynamics model. Through analyses of the sort we will describe below, we discovered that it was necessary for us to modify Collins & Ferguson's original notion of epistemic forms and games so that it could be used to describe students' practices, rather than those of domain experts. More specifically the three following modifications were made.

Classes of Games

In Collins and Ferguson's original framework, epistemic games are only concerned with the construction of new knowledge. However, much classroom activity is concerned with the use, rather than construction, of knowledge. We were thus led to include three types of epistemic games: *construction*, *manipulation* & *application* games. In *construction* games, students build or "construct" epistemic structures in various ways, including deduction, induction, guessing, and putting together small structures into larger ones, thus ordering and making connections that they were previously unaware of. *Manipulation* games appear when students work with a pre-existing epistemic structure, for example, when students change the value of a variable in a system to determine how that system functions. In *application* games, students apply a structure to achieve a task separate from understanding the structure itself, for instance, to generate new data sets or test instances of a general rule. Students might apply Newton's laws to calculate the force of a car crash. Recognizing these classes of games allows the analytic framework to distinguish among qualitatively different learning practices. For example, by describing learning practices in terms of their relationship to epistemic structures–how students construct, manipulate or apply those structures–this analytic framework not only registers that the "raw data" is employed in a curriculum, it also characterizes how students employ the data and to what end.

Embedded Epistemic Structures

In our framework, epistemic structures can be embedded within each other. This is important, because science instruction often begins with modest knowledge goals, only later (if ever) progressing to more ambitious and encompassing goals. Students connect simple forms, such as *sets* and *functional relationships*, to create increasingly complex forms such as *dynamic systems*. For example, students might begin by examining the relationship between incoming solar energy and temperature, then integrate that relationship into a more complex model of the earth's energy balance. As students progress through the curriculum, they build epistemic structures through the sequences of games they play in one activity, across activities as connections are made, and ideally at the unit's end, they reach the curriculum level learning goal.

A Schema Approach

Within the classrooms and curricula we studies, we have found recurring patterns in the sequencing of epistemic games around particular epistemic forms, prompting a schema approach to analysis. For example, students tend to play multiple iterations of *brainstorming*, *compare/contrast*, and *decomposition* games when constructing *sets*. As applied in this framework, this means that each epistemic structure has a series of slots that are filled with epistemic games. It is the ordering, specific patterns, and combinations of games that lead to the construction of an identifiable epistemic structure. This allows an analysis to extend beyond one instance of knowledge use to encompass multiple actions within an activity, as well as progress across a series of activities or an entire curriculum. Because epistemic structures are constructed over time and through interaction, the schema approach provides a means of identifying both individual games and their trajectory towards an end form.

Activity & Curriculum Analysis

One of the goals of this research is to provide an analysis tool that is of broad applicability across curricular and classroom contexts. For this reason, we have been testing our analytic framework on a variety of curricula and design approaches. These include: project (problem)-based (LeTUS, Northwestern University), laboratory-based (FOSS, Full Option Science System), and traditional (Science New Edition, Prentice Hall) design approaches, as well as both full year and modular style curricula. Multiple scientific domains were considered, including Earth Science (solar energy, global warming, and plate tectonics), Biology (human physiology) and Physics (energy transformation).

In this paper, we draw on our empirical study of four 8th grade science classrooms. Data sources include the curriculum materials, videotaped classroom observations, along with pre- and post-interviews with four to six students per class and pre- and post-test data for most students in all four classrooms. These sources provide information about the desired learning goals, how students manipulate and represent content to meet those goals, and the final understandings students show. Collecting multiple types of data ensures that the data provide a broad and representative sample of the types of activities that are found in these science classrooms.

Two main criteria were used to evaluate of the success of the framework when it was applied in an analysis of these data. First, we wanted the framework to yield different descriptions of curricula that we judged to have distinctly different styles. Second, the framework needed to be inclusive in the extent to which it would be applied to all of the observed curricula activities, and the extent to which it captured the features of these activities that we judged to be important.

With modifications throughout the development process, the framework has proven effective in describing differences between curricula as well as students' classroom activities. In the remainder of this section, we briefly illustrate the use of the framework. First, we present an analysis of one learning episode. We then use the framework to compare three class periods that take place at the beginning, middle and end of one curriculum enactment. The sample here is taken from the I,Bio curriculum, which was created by a development team led by David Kanter, as part of the Center for Learning Technologies in Urban Schools (LeTUS) at Northwestern University. In I,Bio, middle school students design and redesign their school lunch choices as a way of understanding their bodies energy needs. Students' modify their choices until a measurement of the energy their school lunch choices add to their bodies' energy stores is equivalent to the energy their bodies use up doing work. Completing this design project, students acquire and employ knowledge of how their bodies' organs and organ systems interact first to transform energy in food into energy used up doing work, then provide all cells' energy needs. The curriculum is divided into "spirals" which correspond to threads of related content. For example, Spiral 1 focuses on food and energy, while Spiral 2 covers the processes by which food is transformed into energy in the body.

Sample Detailed Analysis

There are multiple stages to the detailed analysis. First the videotape is transcribed, then a rough coding of games is done. Once this preliminary coding is complete, it is moved into a chart that allows the researcher to more easily identify patterns of games. It is these patterns of games that are then used to identify the forms and whether students are constructing, manipulating, or applying those forms. For the sake of clarity, the transcript in Table 1 was divided into coding instances based on the appearance of different games.

Table 1. Sample I,Bio Videotape Transcript and Analysis

Transcript	Games	Forms
00:21:00 T: Why do you think its 130? E: First I went with 4 slices of white bread right, so for one corn on the cob I did t 35 and two it would be 70, just double it. And 2 hamburgers plain, what did a lot of they say for hamburgers? T: Hamburgers, lets see, we've got a range from 40, something around 40, we've got 20 all the way to 140. E: 8 slices of bread. If you do 40, so 8 slices of bread is equal to 2 hamburgers.	*Compare/contrast* • The energy difference between bread, corn and hamburgers	*Functional Relationship* • Type of food and the amount of energy it has
00:22:06 S: Its only 4 slices of bread E: No if they do 40 then its 8 slices of bread S: Its 20 E: Pause…what? So, that's what they're saying. T: If they agree with everything else for you, then you're saying that they're making those equal in their mind or that they're not supposed to be equal and people are making them be.	*Compare/contrast* • The certain amount (number of slices) of bread that equals one hamburger.	*Functional Relationship* • Comparison of weight to substance, ratio
00:23:56 T: OK, why don't we try to justify why you made yours 130 which seems to be the only one that's way out there. So why did you make the brownie, lets focus on the brownie, why did you make the brownie 130? E: Cause see, brownies have a lot sugar, a lot of sugar in them. And then they have a lot of sugary stuff in them. S: And protein E: yeah S1: Eggs, S2: butter, Oil	*Decomposition* • Brownies are made of sugar, protein, eggs, butter and oil. These things give brownies lots of energy.	*Sets* • Things in bread • Things in brownies

S3: A brownie would be more than 4 ounces, 2 large would be more than four ounces S2: And eggs in there T: the protein in eggs S3: with all that stuff in them…it would be way more than 4 ounces. Its not the same cause… T: Wait, wait, 4 ounces of meat you're saying is not equal to 4 ounces of bread. E: Meat has much more protein that S: Much more things in it E: …in it than bread, yeah.	*Decomposition* • Brownies are made of protein and eggs. These things make it weigh more. *Compare/Contrast* • The energy in equal amounts of bread and meat.	*Functional Relationship* • Composition determines energy *Ordered Sets* • Foods ordered by amount of energy • Ingredients ordered by amount of energy

In the excerpt in Table 1 students discuss the relative amounts of energy found in different types of food. The following transcript analysis provides an example for discussion. Students begin to construct a functional relationship that describes how the amount of energy in food depends on what components are in the food. They move from a general comparison between different foods to an examination of what specifically those foods are made of, and finally towards a more complex comparison that considers both the amount of food and its components. (Here, we use the phrase "functional relationship" to apply to any quantitative relationship between two features of a physical phenomenon. This use is more general than is typical in mathematics and science.)

Because they are discovering this relationship by themselves, constructing relationships between different types of food, their ingredients, and the amount of energy each has, these can be identified as *construction* rather than application or manipulation games. In other words, students are building a new form rather than using a form that currently exists in their knowledge structures. Below is a more concise summery of the games that coders identified and the forms that they correspond to as students work towards understanding.

Games

Compare/Contrast: Students compare the energy in different types of food to begin to construct an ordered set or hierarchy of foods with less and more energy.

- Brownies have more energy than bread

Decomposition: Teacher requires students to explain the reasons behind energy differences in different kinds of food. They identify ingredients, amounts, and composition (i.e. fat, sugar, protein)

- Brownies have lots of sugar, eggs, butter & oil
- Meat has more protein and fat than bread

Forms

Sets

- Ingredients in particular types of food
- Basic components of all types of food

Functional Relationships

- Amount of energy in food is related to the composition of food.
- Amount of energy in food is related to the amount (quantity) of food.
- Equating different kinds of food (taking into account composition and amount)

As you can see, students work with current and formative knowledge to, with the teacher's help, construct an increasingly complex and abstract understanding of the relationships between food and energy as exemplified in the forms that they construct. They build content in the form of *sets*, which are comparatively simple, through *hierarchical sets*, and finally towards *functional relationships.*

Within-Curriculum Comparison

Where the framework is most powerful, is in comparisons of learning activities, both within and across curricula and classrooms. Here, for illustration, we describe some conclusions that were reached by applying the framework to activities across one enactment of the complete I,Bio curriculum.

In the early I,Bio activities, students are primarily engaged in the construction of a variety of sets, overlapping sets, and subsets. These include: human activities that constitute *work* (e.g., thinking, running), sources of energy for the human body (i.e. food), its ingredients (e.g., flour, sugar, eggs) and basic components (e.g., vitamins, fat, carbohydrates, etc). For example, in one curriculum activity (Spiral 1.1.6-7) called "What do we do all day?" students read passages from the book Hatchet, written by Gary Paulson, and make a list of the things the protagonist's (Brian's) body does as work. This includes, both obvious work like chopping wood, and less obvious forms of work such as living and growing. Students then consider what *they* do all day and compare that list to Brian's list. So in this introductory activity, students generate a *set* of *things that are work*. In fact, the curriculum explicitly supports this interpretation through the use of Venn diagrams and T-tables to help students represent the sets of things that are work and further refine those sets into what students learn to call "internal" and "external" work (Spiral 1.1.10-13).

As the curriculum progresses, students are asked to think in more detail about the ways in which the ingredients in food are related to the amount of energy in different types of food, as discussed in the classroom example above (Spiral 1.4.16-24, Table 1). In this activity, students first individually estimate the energy values of common foods. They then reconvene as a class to debate those values. In this debate, students must defend their choices, which leads to a discussion of each item's specific ingredients and what components of food provide various levels of energy. While there is still some discussion in terms of sets during the enactment of this activity, the curriculum and the majority of the classroom conversation is focused more on constructing multiple functional relationships that describe, more specifically, the relationships between food, work and the maintenance of energy balance. In this middle section, each of the functional relationships that make up the systemic understanding of the curriculum-level learning goal (energy inputs and outputs required by the human body) is discussed in isolation.

Students then further refine the functional relationships in the system and describe them in specific mathematical terms, rather than in terms of tendencies or qualitative relationships. For example, in the Energy Detection Lab (Spiral 2A.1.16-25), students measure the energy in some food samples. To do this, they first individually identify the data an experimental apparatus must capture in order to measure energy. Then, for homework, they design a calorimeter that they think will collect the correct data. Next, they explain their design to the class. After evaluating each other's designs, they work in groups to build a calorimeter based on a model provided in the curriculum. They then burn a corn chip and use their calorimeter to measure the energy released. Lastly, using class data, they calculate the average energy (calories) per gram of corn chip.

Finally, in the most advanced stage of the curriculum, students discuss multiple functional relationships that include some of the same variables, thus allowing students to see connections between functional relationships. Ultimately, they are guided toward the assembly of those relationships into a complete systems model. In Spiral 2A, students focus on how to measure the energy added to our stores from the food they eat. Using the foundation in Spiral 2A, Spiral 2B builds on that knowledge and focuses on how to measure the energy used up from their energy stores doing the work they do. For example, as part of Spiral 2B, students learn a technique in which oxygen consumption during an activity can be multiplied by a constant to calculate the amount of energy the body uses up when doing that activity. Finally students must integrate their knowledge of these two sides of an *input-reservoir-output system* as they complete the curriculum-level objective of redesigning their school lunch so that it meets their body's energy needs.

Our hope is that the analysis in this section illustrates how the framework can be used to capture the development of content within a curriculum. The central point is that this account does more than describe the content in terms of the topics that are addressed, such as "work" and "calorimetry." Instead, it is specific about the form of the content that is addressed (its epistemic form) and the way that this content is addressed (the epistemic game).

Further Within-Curriculum Comparison: Patterns observed

Some preliminary patterns of learning practices have emerged through this longitudinal analysis of the I,Bio curriculum materials and classroom activities. One such pattern is that there are regularly occurring cycles of games. When a new topic is introduced, the games students play are simple, and focus on the construction of different types of sets. As they build understanding, the games move towards the construction of functional relationships. When a new functional relationship is introduced, the games again become simpler.

For example, Spiral 1 addresses both the energy in food and the energy the body uses doing work. At the beginning of the group of activities addressing work, students are asked to brainstorm the set of things they consider work, making simple lists, then progressing to Venn diagrams, and finally, by the end of this group of activities, to functional relationship between the type of work and the amount of energy burned. As students begin the next section, the energy in food, students again generate simple sets as they brainstorm possible things that give a body energy. (Initially this list often includes incorrect answers such as vitamins, water, caffeine etc. as well as food). Again they build towards more complex functional relationships between the substances that food is made of (fat, carbohydrates, protein) and their caloric values.

These examples also illustrate how the forms addressed can be “embedded,” one within the other, and learning can be understood as building up this embedded structure. By decomposing this system into its simplest forms (sets), refining those forms, and using them to build more complex forms, students move from their naive conceptions of the relationship between the body, food and energy, to understanding the intricate workings of human physiology.

The second pattern that we observed is relatively simple to state: We saw substantial instances of *construction* games in the I,Bio curriculum. This is in contrast to more traditional materials that we have analyzed. Since our goal is to distinguish among styles of curriculum, we take this as a simple validation of our scheme. It appears to be significantly more difficult both for students to construct forms and for teachers to support that construction, than it is for students to either manipulate or apply forms that are already provided. The comparison of this curriculum to Exploring Earth’s Weather, Prentice Hall Science Series, in which students do not derive formulas as they do in I,Bio, but rather are given mathematical equations and asked only to apply them supports this hypothesis. It was much more difficult to support students development of an understanding of *how* to calculate the amount of energy in food, than to have them perform the computation using the mathematical formula they were given directly.

A third notable pattern is that the games grew in complexity as the curriculum progressed. As students advanced in the curriculum, the forms they were constructing become more complicated, as did the games they played. In the earlier activities, more of students’ time is spent defining and differentiating between sets, rather than on building functional relationships. The preceding paragraphs in this section describe a particular cycle of games. As their understanding of a topic increases, they move towards more complex forms, building functional relationships from overlapping sets and systems from overlapping functional relationships. A systemic understanding of the human energy balance requires defining and understanding each variable and how it is related to the other. By understanding the iterations of we are able to shed some light on the development of student understanding and how it grows over time. Because of the iterative nature highlighted by this analysis, with further analysis we hope to understand how increased understanding can be supported at different stages of learning a complex topic.

Conclusion

In this initial analysis of curricula and classroom enactments, we hope to have illustrated the benefits of our reframing of "content." With this new kind of account of content, we believe it will be possible to better support complex learning. Asking difficult questions about how we describe scientific content takes an initial step towards identifying solutions to students’ disappointing performance in science. By examining the difficulties and intricacies of such descriptions, this research hopes to provide strategies for writing more effective standards, new insight for curriculum design and evaluation, and a practical means of identifying whether students have met the learning goals described in these documents.

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