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Science Education as Conceptual Change

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The respective literature on science and math learning provide many detailed analyses of the alternative conceptual frameworks that students bring to the classroom and of the conceptual changes necessary for students to learn the concepts that are the targets of instruction. Examples range from young students' understanding of number, astronomy, biology, and matter to the high school and college students' understanding of mechanics, chemistry, thermal phenomena, or evolution. This paper shows that, for the average student, the conceptual changes sketched here are not completed until well into the second decade of life.

The last concerted national initiative to improve math and science education was in the 1960s, in response to Sputnik. Prominent mathematicians and scientists joined forces with educators to analyze core concepts in mathematics and the sciences, to work out a coherent timetable for developing these concepts, and to work out many innovative curricular approaches for meeting this timetable. Despite this massive effort, math and science instruction in this country is now in a crisis. Many of the reasons for this have nothing to do with shortcomings of the materials developed under the 1960s initiative, but there *was* one crucial shortcoming, with vast implications for the art and practice of educating our youngsters. Simply put, in the 1960s, educators and psychologists misanalyzed the very problem math and science education must solve.

All good teachers have always realized that one must start "where the student is." Since the 1960s, we have come to a completely new understanding of what this means. Back then, it was defined in terms of what the student lacked, and this was seen as a lack of science content knowledge, combined with age-related limitations in general cognitive capacities (e.g., the elementary school child is a concrete thinker not capable of abstract reasoning). Now we understand that the main barrier to

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learning the curricular materials we so painstakingly developed is not what the student lacks, but what the student *has*, namely, alternative conceptual frameworks for understanding the phenomena covered by the theories we are trying to teach. Often these conceptual frameworks work well for children, so we face a problem of trying to change theories and concepts.

Cognitive science heralds both good and bad news about the nature of human concepts and the process of conceptual change. The bad news is that conceptual change is extremely difficult to achieve, for reasons that have been understood at least since the early writings of Kuhn (1962) and Feyerabend (1962). The good news is that all normally developing children have the capacity for conceptual change, and science educators and cognitive scientists, working collaboratively, are making very good progress at understanding how to foster conceptual change in the classroom. This paper focuses on the conceptual challenges that science educators face, leaving others to comment on what we have learned about how to meet this challenge.

The Structure of Concepts

Concepts are units of mental representation roughly equivalent to a single word, such as *object*, *animal*, *alive*, *heat*, *weight*, and *matter.* Theories of how people represent knowledge require concepts to fulfill many distinct functions, and there are currently no theories that successfully provide a picture of mental representations in which concepts discharge all the burdens placed on them.

Individual concepts can be connected to build complex representational structures, such as propositions (e.g., *all animals die*) and theories (e.g., the theory of natural selection). Within a particular representational structure, concepts help us to make inferences and explain complex ideas. For example, from the proposition *aardvarks are mammals*, one may infer that aardvarks bear live young. One may also explain a particular aardvark's coloring by considering the color of its mother and father and appealing to the concept of *inheritance.* Outside of a particular conceptual system, concepts have a referential role: they pick out entities in the world that fall under them.

Most cognitive scientists agree that concepts are themselves complex representational structures. Many properties of the entities picked out by a concept are represented as part of it and serve roles in explaining, inferring, and referring. Many cognitive scientists also agree that there is a distinction between core properties and more peripheral properties. One way to think about this distinction is in terms of explanatory depth. Explanation is asymmetrical (e.g., one explains family resemblance through appeal to biologic inheritance, not vice versa), and the core features of a concept are the deepest properties of the entities picked out by that concept.

This picture of concepts raises several problems long discussed in the respective literature of the history and philosophy of science, such as the problems of distinguishing between belief revision and conceptual change and of analyzing the relationships between concepts and theories. Science educators must also face these analytic problems as they examine the goals of science education and consider why those goals are so hard to fulfill.

Distinguishing Belief Revision from Conceptual Change

The respective literature of science education, cognitive development, and the history of science are filled with examples of tenaciously held beliefs that seem bizarre from the standpoint of modern scientific literacy. Examples from cognitive development are *cars are alive* or *air is immaterial.* It seems unlikely that preschool children who insist that cars are alive could have the same concept of life as the adult and merely be mistaken about cars, and indeed, they do not. Rather, preschool children have constructed a very different theoretical framework from that held by adults, in which they have embedded their understanding of animals, just as children of elementary school age have constructed a different framework theory in which they embed their understanding of the material world. These beliefs of young children are true beliefs, formulated over concepts that differ from those that underlie the intuitive or scientific theories that adults use to understand the world.

What constitutes a different concept of life or a different concept of matter? Concepts of the same entities may differ along many dimensions, and many of these differences are matters of degree. Consider the following points:

1. Properties that are peripheral to a particular concept in the context of one framework may be core properties in another. For example, in understanding reproduction, the child comes to see that smallness and helplessness are derivative properties of babies, rather than their essential properties (see Carey, 1985, 1988).
2. Concepts are subsumed into newly created ontological categories of existence. For example, two classes of celestial bodies—stars and planets—come to be conceptualized with the sun and the earth as examples. Acquiring the concept of celestial body supports conceptual change in the concept of the earth (see Vosniadu & Brewer, 1992).
3. Concepts become embedded in theories that are lacking a basis for comparison. The beliefs in one theory cannot be expressed in terms of the concepts of the other. Examples are the concepts of the phlogiston and oxygen theories of burning (see Kuhn, 1962).

Individual concepts can change in many different ways. One type of change is differentiation, as when Galileo differentiated the general concept of *speed* into two more specific concepts of *average velocity* and *instantaneous velocity.* Concepts can also be coalesced or integrated, as when Galileo merged the Aristotelian concepts of *natural motion* and *violent motion* into a single concept of *motion.* Concepts may be reassessed and their basic structure reanalyzed, as when Newton realized that *weight* is a relation between objects rather than a simple property of a single object.

A Sketch of an Example

The respective literature on science and math learning provide many detailed analyses of the alternative conceptual frameworks that students bring to the classroom and of the conceptual changes necessary for students to learn the concepts that are the targets of instruction. At the elementary and junior high school levels, there are examples from students' understanding of numbers, astronomy, biology, and matter; at the high school and college levels, there are examples from students' understanding of mechanics, chemistry, thermal phenomena, and evolution. One example is described: changes that occur roughly between ages 4 and 12 in children's notions of the ontologically central concepts of *person* and *animal.* For the average student, the conceptual changes sketched here are not completed until well into the second decade of life.

Infants and preschoolers have an elaborate concept of *person*, as the extensive literature on theory of mind attests (Leslie, 1994; Spelke, Phillips, & Woodward, 1995; Wellman & Gelman, 1992). Preschool children, even infants, also have a concept of *animal* which serves as the basis for accumulating encyclopedic knowledge about different kinds of animals. Preschoolers distinguish animals from nonanimals and use this distinction productively to make inferences based on similarities. Nevertheless, there is ample evidence that the preschooler's concepts of *animal* and *person* are embedded in very different framework theories than those of a 10-year old; these theories are designated here T1 and T2 (Carey, 1985, 1988, 1995).

According to my analysis, the core of the preschooler's concept of *animal* is that of a behaving being, in essence a simplified variant on people, the prototypical behaving beings. The young child understands and interprets the body in terms of the role that body parts play in supporting behavior. That is, the preschooler's framework theory (T1), in which the concepts of *person* and *animal* are embedded, is a theory of mind, or intuitive psychology, rather than an intuitive biology. Others disagree, characterizing T1 as an intuitive biology, organized around central explanatory concepts such as essentialism (the idea that the essential hidden properties of each animal or each species determines its surface characteristics) or functional explanation (the idea that properties and parts of animals have purposes; Gelman, Coley, & Gottfried, 1994; Keil, 1994). Under either characterization of T1, the preschooler's extensive encyclopedic knowledge about animals includes many facts not yet integrated into any causal framework. By age 10 (recent work has revised this estimate downward, closer to 7 or 8; see Carey, 1995, for a review), the child has constructed a new intuitive framework theory of biology (T2), with *animal* and *plant* coalesced into the single core category of *living thing.* This new theory is organized around the core concepts of the life cycle of organisms and the function of body parts in maintaining life rather than supporting behavior. Inagaki and Hatano (1993) called this new biology *vitalist biology.* Crider (1981) characterized it as the *container theory of the body.*

Just as the concepts of *person* and *animal* change in fundamental ways throughout childhood, so do a host of interrelated concepts also undergo conceptual change (see Carey, 1985, 1988, 1995; Keil, 1989). These other changes include the differentiation of the preschooler's concept of *not alive* into the adult's concepts of *dead, inanimate, unreal,* and *nonexistent,* and the differentiation of the child's concept of *family* into separate concepts of *biologic family and social family.* Others include the reanalysis of *death* from motionless behavior to the collapse of the body machine, and the reanalysis of *baby* from *small, helpless animal* to *reproductive offspring.* The core features of the concept of *species kind* shift away from physical and behavioral characteristics toward origins of the animal. Finally, the concept of *person* is reanalyzed from *prototypical behaving being* to *one-animal-among-many.*

A redesign of the elementary school biology curriculum should be based on an understanding of the structure of T1 and the ways in which T1 differs from the concepts of biology taught in elementary schools. Seeing the elementary school child as a "concrete thinker" misses the point in two different directions. The elementary school child is a theory-bound thinker, just like the scientist or another adult, and is quite capable of being engaged at a theoretical level. But the initial theory of the elementary school child is vastly more different from the target theory of elementary biology than we may suppose, which implies that the young elementary school child faces a very difficult task in grasping that theory.

Educational Implications

The view that science educators are up against the problem of conceptual change has many implications for educational research, classroom practice, and teacher training. Several of these are listed, but space precludes arguing for or elaborating on them.

First, the goal of education, teaching for understanding, cannot be achieved without a diagnosis of students' initial understanding of content knowledge. Teachers must become aware of the progress made by the science education community and must learn to incorporate such diagnosis into their teaching and evaluation techniques. There must be an emphasis on qualitative as well as quantitative expression of understanding.

Second, a very important goal for science education research is to study the mechanisms underlying conceptual change. We must face the analytic challenges sketched above and understand the failure of seemingly excellent curricula to bring about conceptual change. Many of the components of standard curricula are based on a logical sequence of the concepts to be built up; they expose students to phenomena that illustrate the target theory, formal expressions that capture it, and problems that give students practice in using its machinery. These components are *part* of the solution, but as has been demonstrated again and again, they are not sufficient. The good news is that there are now many demonstrations of curricular interventions that work, often by supplementing the above-mentioned components with various modeling techniques, such as limiting case analyses or reasoning by analogy. (To develop a sense of how these modeling techniques work, imagine that a teacher is trying to help older elementary school children develop a conception of matter that will support the differentiation of weight and density. Using a strategy of limiting case analysis, the teacher may ask the students to imagine the weight of a pile of rice, a piece of rice, half a piece of rice, half of that, and so on. Most of the students will agree that one reaches a point where the rice weighs 0 grams. Then the puzzling question can be raised: how can a pile of rice weighing 2 grams be composed of many pieces weighing 0 grams? Using a strategy of reasoning by an analogy in the same domain, the teacher may first ask students to explore a visual model showing the relationship between two extensive quantities (the number of boxes in a multibox figure and the total number of dots) and an intensive quantity (the number of dots per box), and then ask the students to consider the analogous relationship between the two extensive quantities of volume and weight and the intensive quantity of density (weight per unit volume). See Smith, Maclin, Grosslight, & Davis (1997) for evidence of the effectiveness of curriculum built on such modeling techniques compared with a closely matched curriculum that does not incorporate them.

Third, the culture of the classroom must be changed. Children must be engaged in building explanations and in constructing explanatory understanding.

Fourth, parallel issues arise in the study of how students understand the nature of scientific knowledge in general. As the middle school child sees it, gathering scientific knowledge presents no problem—we simply experiment to see what happens. Students must be made aware of the role of interpretive frameworks in guiding experimentation and of the nature of conceptual change.

Fifth, teachers and science educators should be made aware of the important and perhaps surprising consequences of looking at the problem of science education in terms of conceptual change. For example, I have often heard teachers and science educators blame student misconceptions on faulty education at an earlier stage in the curriculum. Rather, student misconceptions are inevitable. Not having the target concepts is not an undesirable stage in students but an absolutely necessary one. Indeed, students *will* construct intermediate steps and misconceptions that do not conform with the views of developed science, and educators should recognize when these steps constitute progress, not problems. Also, students who appropriately understand what science education is all about will seize on a lack of understanding as an opportunity—a reflection of a need for conceptual work—rather than as a humiliation.

Sixth, this picture has profound implications for the education of science teachers. They must experience the kind of teaching being advocated. They need to experience and reflect on the process of conceptual change, to experience and reflect on social structures in which each participant is contributing to the group's explanatory understanding of scientific phenomena. They must themselves have the epistemological knowledge of science they need to instill in their students. They must know their subject matter deeply and be aware of the range of alternative conceptual frameworks held by students of the age they teach.

We have our work cut out for us.

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