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Abstract

This paper outlines an approach to the problem of knowledge acquisition. We argue that knowledge acquisition can be conceptualized as the articulation and restructuring of generative theory-like structures which we call schemata. We propose that the domain of observational astronomy is a particularly promising content domain for studying knowledge restructuring. Finally, we discuss some of the implications of these ideas for instruction.

The Problem of Knowledge Acquisition

The purpose of this paper is to review some of the literature that deals with the problem of how new knowledge is acquired, and to outline our own theoretical approach to this topic. Our position is that knowledge is organized in global conceptual constructs which we call schemata, and that the process of knowledge acquisition can be conceptualized as the articulation and restructuring of these schemata. We suggest that the domain of observational astronomy (i.e., the knowledge about the sun, moon, and stars in relation to the earth) would be an appropriate domain to test these ideas. Finally, we sketch some of the implications of our theoretical framework for instruction.

Knowledge Restructuring

In the *Meno*, Plato raises the fundamental question of how it is possible to acquire new knowledge. He puts the issue in the form of a dilemma: either one already knows what one is trying to learn, in which case there is no reason to learn anything; or one does not, in which case one will not know when he or she has been successful in the attempt. While Plato's formulation of the problem may be a bit too extreme, it does serve the purpose of raising the question of how it is possible to acquire new knowledge from experience, a question which has occupied philosophers and psychologists ever since (see Hamlyn, 1978; and Petrie, 1981, for recent philosophical treatments of this issue).

While some learning may consist of the acquisition of "totally" new knowledge (e.g., Campbell, 1974; Petrie, 1981), most of the learning that occurs in life is either assimilated to or accommodates (to use Piaget's terms) prior knowledge. Indeed, the acquisition of new knowledge from experience makes little sense without assuming that there exists some prior knowledge within which the new experience is interpreted. Otherwise the new experience will be unintelligible. There is now a substantial body of psychological literature that demonstrates the importance of prior knowledge in learning (see Bransford, 1981, for a review).

In an important paper on the topic of learning, Rumelhart and Norman (1981a) distinguish three possible ways in which existing knowledge can be modified by new experience: accretion, tuning, and restructuring. Accretion refers to the gradual accumulation of factual information. Tuning refers to the evolutionary change in the categories we use for interpreting information. These evolutionary changes are the result of a number of different processes. They may involve generalizing or constraining the extent of a concept's applicability, determining its default values, or otherwise improving the accuracy of the concept so that it best fits the actual data. The third type of learning is restructuring. Restructuring refers to the creation of new structures which are devised either to re-interpret old information or to account for new information. Restructuring

represents the most radical form of knowledge acquisition within a prior-knowledge framework. This type of process is frequently postulated by investigators attempting to account for the radical changes in knowledge that appear to occur with age or with expertise. In the work of Piaget, for instance, developmental change is attributed to global restructurings known as stages.

For Piaget, restructuring is conceptualized as a change in the very structures that determine the nature of the representational format available to the child. These changes are brought about by the growth of the child's logical capabilities. Thus the child's ability for representational thinking marks the difference between sensori-motor and preoperational and operational structures. This type of restructuring is said to constrain children's ability to acquire knowledge in all domains and thus has been referred to as global restructuring (Carey, in press).

Piaget's theory of global restructuring has been criticized on the grounds that it is not supported by the available evidence (Carey, 1980; Gelman & Baillergeon, 1983; Mandler, 1983). Recently, Carey (in press) has suggested that it could be replaced by what she refers to as domain-specific restructuring. Carey argues that developmental change can be viewed as domain-specific theory change. According to this view, children begin with a few theory-like conceptual structures (i.e., a naive psychology and a naive physics) which, through differentiation, develop to others (i.e., biology, a theory of mechanics, a theory of heat, etc.).

The domain-specific view of restructuring has emerged out of the study of the differences between novices and experts in various domains of human expertise such as physics (Chi, Glaser, & Rees, 1982; Larkin, McDermott, Simon & Simon, 1981; McCloskey, Caramazza & Green, 1980; Clement, 1983), chess (Chase & Simon, 1973a, 1973b), radiology (Lesgold, Feltovitch, Glaser, & Wang, 1981), and the social sciences (Voss, Greene, Post, & Penner, 1983) among others. This research has produced two different interpretations of the kind of restructuring that can occur with knowledge acquisition.

Some researchers investigating the novice/expert shift (e.g., Chi, Glaser & Rees, 1982; Larkin, 1979, 1981) have argued that the knowledge representations of expert physicists are different from those of novices both in terms of their content (i.e., a greater amount of more abstract information), and in terms of their structure (i.e., what could be characterized as a basic category for the expert is a superordinate category for the novice, Chi, Feltovich & Glaser, 1981, and Chi et al., 1982). These researchers appear to view the knowledge acquisition

press) on the acquisition of expertise in the social sciences. This position has been referred to as the "weak" restructuring position, as contrasted to the "radical" restructuring view of the novice/expert shift, which is represented in the work of Disessa (1982), McCloskey (1983), Wiser and Carey (1983), among others. According to this latter view, the novice/expert shift involves a change in theory, similar in many respects to the kind of theory change observed in the history of science (Hanson, 1958; Kuhn, 1957, 1962).

According to the radical restructuring position, the novice does not simply have an impoverished theory as compared to the expert; the novice has a different theory, different in terms of its structure, different in the domain of phenomena it explains, and different in its individual concepts. Many researchers who hold the radical restructuring position point to correspondences between theory changes in the history of science and changes in an individual's theories as the individual acquires knowledge in a domain. These correspondences raise interesting questions about the extent to which ontogeny may recapitulate phylogeny. Thus, Disessa (1982) and White (1983) seem to be making the claim that novices in physics hold theories which resemble more those

Views that incorporate a process of radical restructuring of domain-specific knowledge have been recently proposed by a number of researchers working in the area of science education (e.g., Driver & Easley, 1978; Fensham, 1983; Novak, 1977a, 1976; Osborne & Wittrock, 1983; Posner, Strike, Hewson, & Gertzog, 1982). For example, Novak (1977a) argued that it was time for a shift in views regarding cognitive development, from a stage dependent view to a view that cognitive development is dependent "on the framework of specific concepts and integrations between these concepts acquired during the active life span of the individual" (p. 473). Driver and Easley (1978) in review of the literature on concept development in science criticize Piaget's notion of global restructuring but encourage educators to view Piaget's accounts of children's thinking in various content areas as important sources of information about children's alternate conceptual frameworks, "some of which reflect analogies with historically held views" (p. 80), that children bring to the science learning task. Furthermore, it is usually recognized in these writings, that the process of conceptual change involves not the simple addition of information to an existing but underdeveloped conceptual structure, but, rather, the formation of new conceptual models (something that Wittrock, 1981, and Osborne & Wittrock, 1983, call "generative learning").

Mechanisms for Knowledge Restructuring

So far, most of the work that has been done in the area of knowledge acquisition is of a descriptive nature. Little or nothing has been said about the mechanisms thereby which these changes are brought about. Some discussion about mechanisms can be found in the work of Rumelhart (Rumelhart & Norman, 1981a, 1981b; and Rumelhart & Ortony, 1977), in the work from the area of Artificial Intelligence, (e.g., Carbonell, 1983; Langley, Zytkow, Simon & Bradshaw, 1983; Larkin, 1981; Winston, 1981, 1983) and in the work on the instructional implications of cognitive science (e.g., Anderson, 1977; Champagne, Klopfer, Gunstone, 1982; Greeno, 1980).

One major mechanism for restructuring is learning by analogies (metaphors or models). In learning by analogy the restructured schema is patterned on an existing schema from a different domain with the necessary modifications. Analogy has been found to be a potent mechanism for schema acquisition in the area of artificial intelligence (e.g., Burstein, 1983; Carbonell, 1983; Schank, 1982; Winston, 1981), and in studies of how scientists solve problems (Clement, 1982; Darden, 1983; Oppenheimer, 1956). Experimental work has shown that the use of explicit analogies facilitates learning in a new domain in adults (Gentner, 1981; Gick & Holyoak, 1980, 1983; Rumelhart & Norman, 1981b) and in children (Vosniadou & Ortony, 1983; Vosniadou & Schommer, in preparation).

Other possible mechanisms for restructuring that have been discussed in the literature are schema induction, which involves the discovery of the regularities in the co-occurrences of certain phenomena (Rumelhart & Norman, 1981b), generalization and specialization (Rumelhart & Ortony, 1977) and Socratic dialogues (Anderson, 1977; Champagne, Klopfer & Gunstone, 1982; Collins, 1977). However, it seems to us that schema induction, generalization, and specialization describe the product of a change which involves restructuring, but do not describe the mechanisms thereby which this change is achieved. Socratic dialogues are also mechanisms for restructuring only to the extent that they facilitate the awareness of inconsistencies which motivate the search for a new schema. They do not describe how the new schema itself is acquired.

Our Theoretical Position

Our position has many similarities with the radical restructuring view. A basic tenet of our position is that knowledge is organized in schemata, and that schemata are theoretical entities that describe "the mental structures and processes underlying the molar aspects of human knowledge" (Brewer & Nakamura, 1984, p. 42). A major defining characteristic of schemata is what Brewer and Nakamura (1984) refer to as the "molar assumption." The "molar assumption" is the assumption that the theory of human cognition cannot be an atomistic theory which postulates that the more complex aspects

of human activity can always be derived from combinations of basic mental elements, but that one frequently needs to postulate larger theoretical entities which operate as units in the theory (see also Anderson, 1980; Minsky, 1975; Rumelhart & Ortony, 1977).

A second assumption is that a schema, like a scientific theory, is a generative structure; generative in the sense that it can be used as a mechanism for understanding new phenomena and for predicting things that are not known. For example, a cosmological schema which places the earth at the center of the solar system has a wide range of implications which go beyond the particular facts that a child has been taught.

Thirdly, it is assumed that the process of knowledge acquisition can be characterized as one that involves both the articulation and the restructuring of a schema. What we mean by "articulation of a schema" is analogous in many respects to what Rumelhart and Norman (1981) call "tuning," with what Kuhn (1970) calls "the articulation of a theory," and with the "weak restructuring" view of the novice/expert shift. Assuming that a schema is a generative structure with implications beyond what is immediately known, the working out of these implications is the kind of learning which we refer to as the articulation of the schema. On the other hand, restructuring is the kind of learning that involves fundamental changes in the nature of the schema itself, changes similar to those referred to as "radical restructuring" in the novice/expert literature.

The distinction between schema articulation and restructuring is similar in many respects to the distinction drawn by Kuhn regarding theory change as compared to change in paradigms. According to Kuhn (1970), the exercise of "normal science" consists mostly in the articulation of the existing paradigms which may result in theory changes. Only when these attempts at articulation fail repeatedly does the motivation for a paradigm shift arises. Paradigm shifts happen in an effort to resolve the anomalies that exist in the relation of existing theory to nature (Kuhn, 1970, p. 97).

The process of developmental change can be seen in similar terms, namely as a process which consists mainly in the articulation of existing schemata. Occasionally the child is faced with major anomalies an existing schema cannot account for and restructuring is required. Seeing the child as a scientist can be useful in the present framework (see also Carey & Block, 1976, Karmiloff-Smith & Inhelder, 1975) for it provides a way to reconcile the kind of learning which consists mainly in the elaboration of existing structures as compared to the more radical restructurings.

However, there are also important differences between children and scientists which have to be considered. For example, while restructuring in the case of the scientist

requires the creation of an internally consistent new paradigm, this is not usually the case in the child. Unlike the scientist, the problem for the developing child is that of integrating current scientific views (from the adult world) with the child's phenomenal experience. Children's misconceptions often reflect quite clearly these attempts at integration. For example, the information that the earth is round is interpreted by elementary school children whose phenomenal experience is that of a flat earth to mean that the earth is flat with a circular shape, or that there is another earth somewhere in the sky that is a round sphere (see Nussbaum & Novak, 1976).

Knowledge Acquisition in the Domain of Astronomy

We are now in the process of testing our theoretical views in a project that deals with children's acquisition of knowledge in the domain of astronomy, or more specifically, that of planetary mechanics. The question of interest is how children acquire knowledge about the size, shape, distance and motion of the sun, the moon and the stars in relation to the earth and how this knowledge changes with age. The domain of astronomy was selected because it is one of the few knowledge domains that met a set of criteria which we believe are necessary to test our theoretical position. First, it is based on information which is, for the most part, accessible to the child. The child's knowledge of the everyday world already contains many of the phenomena which are explained by theories of the solar system and its motion (e.g., the day/night cycle; the changing seasons; the phases of the moon). In addition, it is a conceptually rich domain which has undergone major theoretical restructurings in its historical development. The successive theories in the area of planetary mechanics have been taken to be classic examples of revolutions in the history of science (e.g., Kuhn, 1957, 1970). One of the basic issues we are interested in studying is the nature of schema restructuring, and it appears that by choosing a knowledge domain in which the scientists have undergone major paradigm shifts would maximize our chances of finding similar shifts on the part of the children acquiring the domain.

We believe that it is possible to identify a limited set of generative schemata which will characterize children's knowledge of planetary mechanics at different ages although a great deal of individual variation within the same age range is also expected. It is hypothesized that the first schemata will be based mainly on the phenomenal appearance of the everyday world and that the later ones will be more and more influenced by adult scientific theories. While it is not possible to give a full account of these schemata without comprehensive data, tentative hypotheses can, nevertheless, be suggested on the basis of the available developmental evidence and on the basis of the theories that have been held in the history of astronomy.

We think that young children will adopt the "common sense" view that the earth is flat and motionless, and that gravity

operates along an up/down gradient. This has been called the "Flat Earth Animistic Schema." A series of recent studies in the area of science education (Nussbaum, 1979; Nussbaum & Novack, 1976; Sneider & Pulos, 1983) have argued that children around ages 6-8 believe the earth is flat. Almost all children at this age say the earth is round when asked, but under more detailed questioning ("Where does the sun go at night?"; "What does the earth look like when you look at it from very far away?") give answers consistent with a flat earth view.

At this time children will also adopt a stationary geocentric view of the sun-earth relation and will provide animistic accounts of the apparent motion of the moon and the sun. Piaget's (1929, 1930) studies of the young child's conceptions of the physical world suggest that the young child frequently provides animistic explanations of the motion of the sun and moon. Piaget proposes that often young children (ages 4-5) assume that inanimate objects that move possess human attributes. Thus, children say "yes" to questions such as, "Could the sun stop shining if it wanted to?" (Piaget, 1929, p. 226) or "Is the sun alive?" (Piaget, 1930, p. 82). Later in development children shift to a mechanistic account of astronomical phenomena. For example, they say that the moon moves because "It is pushed by the wind" (Haupt, 1950, p. 226), that at night "It's the air which becomes black" (Piaget, 1929; p. 293), and that the phases of the moon are caused by clouds which "cover the moon and make it different shapes" (Haupt, 1948, p. 259).

The change from the animistic to the mechanistic account of celestial phenomena represents the first major restructuring in the children's knowledge of astronomy. This second schema has been called "The Flat Earth Mechanistic Schema." This schema combines the view of a motionless, flat earth with a geocentric but mechanistic account of the celestial phenomena. Thus, at the time when children hold this schema they might give an explanation of the day-night cycle by claiming that the sun moves under the ground during the night, or explain the phases of the moon by saying that clouds cover part of it.

It is hypothesized that the next major restructuring will involve a change from a flat earth to a round earth position and that the concept of a round earth will not be fully understood until children know that gravity operates toward the center of a spherical earth. The studies of Nussbaum (1979) and Nussbaum and Novack (1976) show that children shift from a view that gravity operates along an up/down gradient (i.e., things fall from high places to low places) to a position that gravity operates toward the center of large objects such as the earth. Thus children with the first view argue that if there were people on the other side of the earth they would fall off, whereas older children say that they would not. We call this the "Round Earth Stationary Geocentric Schema" because it also assumes that the children have

a geocentric view of the earth-sun relation (they assume that the sun rotates around the earth).

The geocentric view is again more consistent with the phenomenal evidence. The Copernican shift and the adoption of heliocentric view, we predict, will not come until much later on. There is currently little explicit developmental data on this shift but clearly this is a plausible sequence of knowledge acquisition. In fact, Piaget (1930) argues that the heliocentric view is so far removed from children's conceptualization of the earth-sun relation that it would be quite fruitless to attempt to teach young children this view (p. 85). We call this last schema the "Heliocentric Round Earth Schema."

These schemata are considered generative because they can be used to explain phenomena or to predict things currently not known. For example, children with a flat earth animistic schema will tend to explain the day/night cycle in terms of the sun's voluntary movement (the sun was tired and went to bed, or hid behind the moon, etc.), even though they (hopefully) never heard similar explanations of the day/night cycle from adults. Conversely, children with a round earth geocentric schema will tend to explain the day/night cycle in terms of the movement of the sun around the earth, again despite the fact that they were not given such explanations by their parents or teachers.

In this framework, schema articulation can be conceptualized as the kind of learning which is consistent with the implications of the current schema, but extends and enriches that schema. For example, even some adults with a heliocentric schema do not know how to explain how the seasons work or what causes the phases of the moon. The acquisition of this type of knowledge would certainly enrich their heliocentric schema without requiring any restructuring.

Following Kuhn (1970), Carey (in press) and Wiser and Carey (1983), we have focused on three criteria for distinguishing the radical restructuring of a previous schema. That the two schemata should be different in terms of (a) the domain of phenomena they explain, (b) their structure, and (c) their individual concepts. All the restructurings we have described meet these three criteria. For example, the shift from an animistic to a mechanistic explanation of the movement of the sun and the moon can be conceptualized as representing the separation of astronomy from a psychological schema, similar to the separation of biology from a psychological schema, described by Carey (in press). Clearly, the explanatory framework for phenomena such as the day/night cycle is completely different in an animistic cosmology than a mechanistic one. Moreover, the relationship between the movement of the celestial objects and phenomena such as the day/night cycle cannot be understood in the context of animistic causality.

The shift from an animistic to a mechanistic causality also represents a change in the structure of the domain. In an

animistic framework astronomical phenomena are one part of the larger psychological theory that children have developed on the basis of their experiences. What children know about these phenomena is information such as that they go to sleep during the night, that they wake up during the day, that the sun is in the sky during the day and so on. When children start providing mechanistic accounts of astronomical phenomena we have evidence that a new schema has been formed, a schema with its own structure and explanatory domain. Finally, this shift brings about changes in individual concepts. The concept of an animistic sun, a sun who goes to bed at night, or who disappears behind the mountains so that we can go to sleep, is clearly different from the concept of a mechanistic sun.

Implications for Instruction

The relation of old knowledge and new knowledge. One of the major results of recent work in cognitive science has been an awareness of the importance of old knowledge in the acquisition of new knowledge (Anderson, Spiro, & Montague, 1977; Bransford, 1981). Clearly, to the degree that is possible one wants to elaborate old schemata and to construct new schemata out of old ones. The process of learning is one of constantly relating incoming information to what is already known, and of actively testing hypotheses generated by one's current schemata. One implication of this for instruction is that one needs a careful description of the child's present knowledge in order to know how to relate new information to this base. Yet, most adults do not take into consideration children's existing knowledge when trying to teach them something new. For example, in most elementary science programs the heliocentric model is assumed when teaching children about astronomy, without consideration that the child may be operating from a very different knowledge base. It seems likely that teaching and instructional programs could be considerably improved if we had a deeper understanding of children's existing knowledge base.

The use of old knowledge to support new knowledge appears to operate differently in the case of schema articulation than it does in schema restructuring. Clearly, the relations of prior knowledge to new one is important for schema articulation. One cannot enrich and elaborate existing structures without first identifying them. Correspondingly, when the purpose of instruction is to promote the kind of learning that we have described as schema articulation it is important to build the instruction around the child's existing schema. However, it is not clear how important domain-specific knowledge is when it comes to schema restructuring. This problem is particularly acute in the domain of astronomy, a domain which is characterized by a number of radical shifts of view. There has been much debate in recent philosophy of science on this topic as it relates to the historical development of scientific theories. Thus, Kuhn (1962) initially argued that new scientific theories did not tend

to incorporate or be built on the basis of earlier theories, but involved a completely new way of construing the world. In his later work, Kuhn (1970, 1977) moderated his position somewhat and suggested that to some extent one can see new theories as building on the results of earlier ones.

This suggests that it may be profitable to identify which aspects the earlier schema are compatible with the new schema and to use this information during the acquisition process. Another important question this discussion raises is that of the sequencing of knowledge. Should children be taught the most advanced schemata from the beginning, or not? For instance, should young children be taught the heliocentric position from the beginning, or should this view be delayed so that children can work from a fully developed geocentric schema?

The recognition of anomaly. On the basis of study of the history of science Kuhn (1962) has argued that the recognition of anomalies that do not fit into the current paradigm is one of the major motivating forces for radical conceptual shifts on the part of scientists. Recently a number of researchers in the area of developmental psychology (i.e., Kamiloff-Smith & Inhelder, 1975), and science education, have argued for the use of anomalies as a mechanism to drive knowledge acquisition in science domains (Anderson, 1977; Champagne, Klopfer, & Gunstone, 1982; Posner, Strike, Hewson, & Gertzog, 1982).

We believe that the recognition of anomalies can serve an important function in schema restructuring, but we question its adequacy as the only mechanism for restructuring. While much spontaneous restructuring may occur in development, it may not be profitable to leave children alone to restructure their knowledge of physics or astronomy, particularly when it is known what theory the child must eventually develop. Here the child is in a different situation than the scientist. The scientist who is faced with an anomaly is forced into a re-examination of basic assumptions without any guidance as to where this will lead. However, it is not clear that this "pure discovery" method is the optimal way for the child to acquire new knowledge. Clearly, research is needed to study the impact of the recognition of anomalies and of the "discovery method" on schema restructuring.

The use of analogies, metaphors and physical models. We have argued that the mechanism of relating new knowledge to an existing schema from the same domain may not be a good mechanism for restructuring. However, one way old knowledge can be brought to bear on the construction of a new schema is by using analogies and metaphors from a different domain. Analogies can play different roles in restructuring. They can facilitate both the spontaneous discovery of a new schema, and the teaching of a new schema to children or adults. In their efforts to understand the anomalies that have forced them to seek a restructuring of a domain scientists often notice an analogy to an already existing

schema. The spontaneous use of analogy is a powerful mechanism for theory construction in the case of individual scientists (see Darden & Maull, 1977; Gentner, 1980; Hesse, 1966; Oppenheimer, 1956) but very difficult to achieve in experimental situations both with children (Vosniadou, 1984; Vosniadou, Brown & Bernstein, in preparation), and in adults (Gick & Holyoak, 1980, 1983). Analogies can be very effective, however, when used for the purpose of teaching a new schema. Both adults and children can transfer information from a known domain to help schema construction in a new area (Gentner, 1981; Vosniadou & Ortony, 1983; Vosniadou & Schommer, in preparation).

Physical models can often do the work of analogies when an easily identifiable generative analogy is not present. Physical models are particularly appropriate in a domain like that of planetary mechanics in which the structure of the solar system and its operation can be easily captured in a physical representation. A schema can then be constructed by internalizing this physical model, whose implications can then be further elaborated.

Summary and Conclusions

We have argued that knowledge acquisition can be conceptualized as the articulation and restructuring of generative schemata. Assuming that a schema is a generative structure with implications beyond what it is immediately known, the working out of these implications is what we refer to as schema articulation. Schema restructuring is the kind of learning that involves fundamental changes in the nature of the schema itself, changes similar to those referred to as "radical restructuring" in the novice/expert literature, or as "paradigm shift" by Kuhn. We have argued that when the purpose of instruction is to promote schema articulation it is very important to build instruction around the child's already existing schema. When the purpose of instruction is to promote knowledge restructuring, it is important to foster recognition of the anomalies in the existing schema. It is also important to use explanatory analogies and/or physical models to bring relevant knowledge from a different domain to help schema restructuring. These theoretical ideas are currently being tested in a research program that investigates the development of knowledge in the domain of astronomy.

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