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CAPTURING AND MODELING THE PROCESS OF CONCEPTUAL CHANGE

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Abstract

A theoretical framework is outlined in this article that attempts to explain the nature of conceptual change that takes place in the learning of physical science. It is argued that a naive framework theory of physics is established early on in infancy and forms the basis of individuals' ontology and epistemology. The presuppositions of this framework theory act as constraints on the way individuals interpret their observations and the information they receive from the culture to construct specific theories about the physical world. The specific theories formed through this process are continuously enriched and modified. Some kinds of conceptual change require the simple addition of new information to an existing conceptual structure. Others are accomplished only when existing beliefs and presuppositions are revised. It is proposed that conceptual change is particularly difficult to achieve and very likely to give rise to misconceptions when it requires the revision of fundamental presuppositions of the framework theory. Misconceptions are interpreted as individuals' attempts to assimilate new information into existing conceptual structures that contain information contradictory to the scientific view.

Introduction

This article describes a theoretical framework that attempts to capture and model the kind of conceptual change that takes place in the process of acquiring knowledge about the physical world. This theoretical framework is based on extensive research on students' models and explanations of phenomena in the area of observational astronomy, and more recently in the areas of mechanics and thermal physics. The aim is to describe changes in students' representations of the physical world as their qualitative understanding of the domain changes. The problem of learning physics equations and the representational changes this may entail is not being addressed.

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It is argued that concepts are embedded into larger theoretical structures which constrain them. A distinction is drawn between a *naive framework theory of physics*, which is built early in infancy and which consists of certain fundamental ontological and epistemological presuppositions, and various *specific theories* which are meant to describe the internal structure of the conceptual domain within which concepts are embedded. It is assumed that conceptual change proceeds through the gradual modification of one's mental models of the physical world, achieved either through *enrichment* or through *revision*. Enrichment involves the addition of information to existing conceptual structures. Revision may involve changes in individual beliefs or presuppositions or changes in the relational structure of a theory. Revision may happen at the level of the *specific theory* or at the level of the *framework theory*. Revision at the level of the framework theory is considered to be the most difficult type of conceptual change and the one most likely to cause misconceptions. Misconceptions are viewed as students' attempts to interpret scientific information within an existing framework theory that contains information contradictory to the scientific view.

The article starts with a general description of the theoretical approach and proceeds to show how this approach can be used to explain conceptual change in the areas of astronomy, mechanics, and thermal physics. The relations between the present approach and a number of related approaches is examined next. The article ends with a brief discussion of instructional issues and considerations in the learning of physical science.

A Theoretical Approach to the Problem of Conceptual Change

Background

Concepts are Embedded in Theories

In recent years there has been an interesting reversal of the commonsense view that people start the knowledge acquisition process by forming atomistic concepts which then get connected on the basis of similarity to create more complex conceptual structures. A number of researchers have made persuasive arguments in support of the position that concepts are embedded in larger theoretical structures from the start (see Carey, 1983; Murphy & Medin, 1985; Vosniadou & Ortony, 1989).

One of the reasons for this reversal has to do with the realization that the notion of similarity is insufficient to explain how atomistic concepts are grouped together to form categories. For example, in a series of experiments, Rips (1989) has shown that it is possible to alter similarity judgements without affecting category membership and to alter category judgements without affecting similarity. Murphy and Medin (1985) have also argued that similarity cannot be the only mechanism on which we form categories, because we often form categories which are not based on similarity and which nevertheless cohere — for example, the biblical category of clean and unclean animals. They propose that what determines category membership is not similarity but a complex explanatory framework or theory within which concepts are embedded.

The view that concepts are embedded in theories is also supported by the results of recent research with infants. These results have challenged Piaget's view that infants start the knowledge acquisition process equipped only with a set of sensory reflexes and some domain-general processes and have suggested that the human mind is more specified innately, to deal with the complexity of environmental stimulation (Gelman, 1991; Karmiloff-Smith, 1992).

Reconciliation of Nativism with Constructivism

It is important to emphasize here that, in contrast to the claim of many nativists (e.g., Chomsky, 1988; Fodor, 1984), the results of current research on infancy are not necessarily irreconcilable with Piaget's constructivist epistemology. As argued by Karmiloff-Smith (1992), it is not necessary to equate the notion of innate predispositions with a static, genetic blueprint for maturation that the initial, innate, endowment of the infant appears to be much less detailed than the nativists have proposed, leaving enough room for flexibility and creativity in cognitive development.

Theoretical Constructs

A Naive Framework Theory of Physics

A number of persuasive arguments have been made to support the view that the human mind operates on the basis of a small number of domain-specific constraints, reflecting the structure of the specific adaptive problems humans needed to solve over a long period of time in the course of evolution (e.g., Atran & Sperber, 1987; Cosmides & Tooby, in press; Gelman, 1991). One area of knowledge for which it is likely that domain-specific principles have been developed is the domain of knowledge about the physical world. Recent work with infants (e.g., Spelke, 1991; Baillargeon, 1990) has succeeded in describing some of the basic principles that seem to guide the process of acquiring knowledge about the physical world. For example, Spelke (1991) has described five constraints about the behavior of physical objects which infants appear to appreciate from early on, such as *continuity, solidity, no action at a distance, gravity* and *inertia*.

In earlier papers (Vosniadou, 1989; Vosniadou, in press) it was argued that such constraints, or *entrenched presuppositions*, are organized in a global or *framework theory of naive physics** which is not available to conscious awareness and hypothesis testing. This framework theory of physics constrains the process of acquiring knowledge about the physical world in ways analogous to those that research programs and paradigms have been thought to constrain the development of scientific theories (Kuhn, 1977; Lakatos, 1970).

Specific Theories

A specific theory consists of a set of interrelated propositions or beliefs that describe the properties and behavior of physical objects. Specific theories are generated through

*The term *theory* is used to denote a relational, explanatory, structure and not an explicit, well-formed scientific theory. No specific assumptions are made here about the particular way such theoretical information may be organized in the knowledge base. Even connectionist models would be acceptable for as long as they are capable of generating symbolic representations that are theory-like and which can produce explanations.

observation or through information presented by the culture under the constraints of the framework theory. One can describe the beliefs which constitute a specific theory as second-order constraints which emerge out of the structure of the acquired knowledge itself, as this structure comes to impose its own unique influence on the knowledge acquisition process (see Keil, 1991). For example, the statement "hotness can transfer from one object to another which is less hot by direct contact" is one of the beliefs of a specific theory of heat transfer. This belief is constrained by the underlying presupposition that "hotness is a transferable property of physical objects" that is part of a naive framework theory of physics. Additional examples that clarify the distinction between a framework theory and a specific theory will be provided later.

Mental Models

The construct of the mental model has been used by different researchers in different ways (e.g., Johnson-Laird, 1983; Gentner & Stevens, 1983). It is used here to refer to a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning, and which has the special characteristic that it preserves the structure of the thing it is supposed to represent.

Mental models are dynamic and generative representations which can be manipulated mentally to provide causal explanations of physical phenomena and make predictions about the state of affairs in the physical world. It is assumed that most mental models are created on the spot to deal with the demands of specific problem-solving situations. Nevertheless, it is possible that some mental models, or parts of them, which have proven useful in the past, are stored as separate structures and retrieved from long-term memory when needed.

It is argued here (specific examples will be given later) that the mental models individuals generate or retrieve during cognitive functioning are the points at which new information is incorporated into the knowledge base. As such, a mental model can constrain the knowledge acquisition process in ways similar to beliefs and presuppositions. In addition to acting as constraints themselves, mental models can provide important information about the underlying knowledge structures (specific and framework theories) from which they are generated. For example, the mental model of the location of a hammer invited by a sentence such as "Harry dropped the hammer," is constrained by an underlying structure related to the assumed properties of gravity. While a single, specific, mental model may be undetermined with respect to the underlying conceptual structure generating it, understanding the *generic* mental models individuals use to answer a variety of different questions related to a given concept can provide important information regarding the framework theories and specific theories that constrain the knowledge acquisition process.

Conceptual Change

Kinds of Conceptual Change

In the context of the present theoretical framework, the simplest form of conceptual change is the *enrichment* of an existing conceptual structure. Enrichment is conceptualized as the simple addition of new information to an existing theoretical framework through the mechanism of accretion. It is assumed that this is a relatively easy form of conceptual change. Our studies of elementary school children's comprehension of science texts have shown that children do not find it difficult to add facts to an existing conceptual structure when these facts are consistent with the knowledge that is there already. For example, after reading a text about the moon, most of the elementary school children in our sample learned that the moon has craters (Vosniadou & Matthews, 1992).

Revision is required when the information to be acquired is inconsistent with existing beliefs or presuppositions, or with the relational structure of a theory. It is argued that the revision of a specific theory is easier than the revision of a framework theory. This argument is supported by several findings in studies conducted in our lab. For instance, young children who usually assume that there is water and air on the moon do not find it difficult to change this belief when they are told that the astronauts who went to the moon had to carry water and oxygen with them (Vosniadou & Matthews, 1992). We believe this is the case because children's specific theories about the moon are not directly constrained by a naive framework of physics but are based on an analogy between the earth and the moon (see Vosniadou & Ortony, 1989, for a more extensive discussion of this point).

When the beliefs of a specific theory are constrained by a framework theory, conceptual change can be very difficult to achieve. As it has been argued elsewhere, children find it very difficult to believe that the earth is a sphere because this information contradicts basic ontological presuppositions which are part of a naive framework theory of physics, such as the presupposition that space is organized in terms of the directions of up and down with respect to a flat ground and that unsupported objects, including the earth, fall "down" (Vosniadou & Brewer, 1992).

The change of a framework theory is difficult because the presuppositions of the framework theory represent relatively coherent systems of explanation, based on everyday experience and tied to years of confirmation. In addition, ontological and epistemological presuppositions form the foundations of our knowledge base and their revision is likely to have serious implications for all the subsequent knowledge structures which have been constructed on them.

Failures in Learning

Learning failures can happen at any time during the knowledge acquisition process and for many reasons. In the context of the present theoretical framework, it is claimed that learning failures are more likely to happen when the acquisition process requires the revision of entrenched presuppositions that belong to the framework theory, than when it does not. In these cases we are likely to witness *inconsistency, inert knowledge*, or the creation of *misconceptions*.

Inconsistencies are produced when conflicting pieces of information are simply added to existing knowledge structures. In a study of third grader's comprehension of expository text explaining the day/night cycle, we found that many children added to their knowledge base the information that the sun does not move, which was explicitly stated in the text. When these children were later asked to explain the day/night cycle, many continued to provide the explanation they used before they read the text, namely that the sun goes down behind the mountains. These children were clearly confused and mixed up after reading the text (Vosniadou, 1991b).

Inert knowledge is produced when the inconsistent information is stored in a separate microstructure and is used only on certain occasions (e.g., school-type tasks or verbal problems — see Chi, 1988). Misconceptions are produced when students try to reconcile the inconsistent pieces of information and to produce a synthetic mental model. Examples of misconceptions will be given later.

Methodological Issues

In our studies of conceptual change we have adopted a methodology that consists of asking many questions about the concept in question. Some of these questions require a verbal response, others elicit drawings, and others require the construction of physical models. It is assumed that students access the relevant knowledge and use it to construct a mental model that allows them to answer our questions. We try to understand and describe these mental models and use them to generate inferences about the nature of the specific and framework theories that constrain them. There are two aspects of this methodology that deserve particular attention: the kinds of questions used, and the text of internal consistency.

Kinds of Questions

The results of our experiments have shown that certain kinds of questions have a greater potential for providing information about underlying conceptual structures than others. For example, the factual questions "What is the shape of the Earth?", or "Does the Earth move?" require children to repeat information to which they have usually been exposed through instruction. Scientifically correct responses to these questions do not necessarily mean that the students have understood the concept in question, because students often repeat the information they have received through instruction without fully understanding it.

Generative questions confront children with phenomena about which they do not have any direct experience and about which they have not yet received any explicit instruction. Because generative questions cannot be answered through the simple repetition of unassimilated information, they have a greater potential for unraveling underlying conceptual structures. Consider, for example, the questions, "If you were to walk for many days in a straight line, where would you end up?", "Would you ever reach the end or edge of the Earth?", or "Does the Earth have an end or an edge?" Students are not usually provided with explicit information regarding the end or edge of the Earth. We assume that when they are asked such a question, they retrieve the relevant information from the knowledge base and use it to construct a mental model of the Earth. They then use this model to answer the question. Therefore, responses to generative questions have a greater potential than factual questions to unravel the mental models students use during creative problem solving and to provide information about the underlying theoretical structures that constrain them.

Test of Internal Consistency

The second important characteristic of our methodology is a test of internal consistency. This consists of determining for each child whether the pattern of his or her responses to all of the questions investigating a given concept can be explained by the consistent use of a single, underlying, "generic" mental model. Consider, for example, the following sequence of responses:

Kristi (first grade)
E: What is the shape of the Earth?
Child: Round.
E: Can you make a drawing which shows the real shape of the Earth?
C: (*Child draws a circle.*)
E: If you walked and walked for many days in a straight line, where would you end up?
C: You would end up in a different town.
E: Well, what if you kept on walking and walking?
C: In a bunch of different towns, states, and then, if you were here and you kept on walking here (child points with her finger to the "edge" of the circle which she had drawn to depict the Earth) you walk right out of the Earth.
E: You'd walk right out of the Earth?
C: Yes, because you just go that way and you reach the edge and you gotta be kinda careful.
E: Could you fall off the edge of the Earth?
C: Yes, if you were playing on the edge of it.
E: Where would you fall?
C: You'd fall on this edge if you were playing here. And you fall down on other planets.

Notice in this example that although Kristi said that the Earth is round to the factual question regarding the shape of the Earth, her overall responses are not consistent with the mental model of a spherical Earth. Nevertheless, Kirsti's responses could be consistent with the mental model of the Earth as a suspended disc or as a truncated sphere.

Consider now the following example:

Venica (3rd grade)
(*Venica has said that the Earth is round but that it has an end/edge in the previous questions.*)
E: Can people fall off the end or edge of the Earth?
Child: No.
E: Why wouldn't they fall off?
C: Because they are inside the Earth.
E: What do you mean inside?
C: They don't fall, they have sidewalks, things down like on the bottom.
E: Is the Earth round like a ball or round like a pancake?
C: Round like a ball.

E: When you say that they live inside the Earth do you mean they live inside the ball?
C: Inside the ball. In the middle of it.

From responses such as these we could infer that Venica has constructed the mental model of the Earth as a hollow sphere with people living on flat ground inside it.

Students are placed in a "mental model" category on the basis of their responses to all the questions designed to investigate a given concept. Placement in a model category is decided using strict criteria and requires no more than one deviation from the expected pattern of responses, and only if this deviation occurs in a non-defining item for this category. More information about the specific ways in which internal consistency is determined and children are assigned to mental models can be found in Vosniadou and Brewer (1992).

It is important to emphasize here the novelty of this methodological approach to the study of conceptual development, both for the importance it places on describing students' mental representations, and for the systematic search for internally consistent "alternative representations." Many researchers assume that students are internally inconsistent if they use a scientific concept correctly in some cases but not in others. The possibility that a student who sounds inconsistent may in fact be using a mental model which is different from the scientific one, but which is nevertheless well-defined and internally consistent, is usually not explored in a systematic way.

Our studies of conceptual change have shown that it is possible to identify a small number of mental models related to the concepts in question which students use in a consistent fashion to answer the questions posed to them within the space of an interview. For example, the studies of the concept of the Earth have shown that 80% of the children in our sample used in a consistent fashion one out of a small number of well-defined mental models of the Earth. Identifying the mental models students use to answer our questions provides the information we need to start unraveling the underlying theoretical structures that constrain them and to understand the process of conceptual change.

Examples of Conceptual Change in Childhood

The Concept of the Earth

In this section an example will be given to demonstrate how the theoretical framework outlined previously can explain a set of data produced by a series of cross-cultural studies that investigated the development of the concept of the Earth in elementary school children in the U.S.A. (Vosniadou & Brewer, 1992), in Greece (Vosniadou, Archodidou, & Kalogiannidou, in press), in India (Samarapungavan & Vosniadou, 1989), and in Samoa (Brewer, Herdrich, & Vosniadou, 1987).

Figure 1 presents a graphic representation of the mental models of the Earth obtained in the study conducted in the U.S.A. (from Vosniadou & Brewer, 1992). The mental models of the Earth constructed by the younger children in our sample were the models of the rectangular or disc Earth. According to these models the Earth is shaped like a flat rectangle or like a disc, is supported by ground underneath, and is surrounded by sky and solar objects above its flat top. We call these models "initial" because they

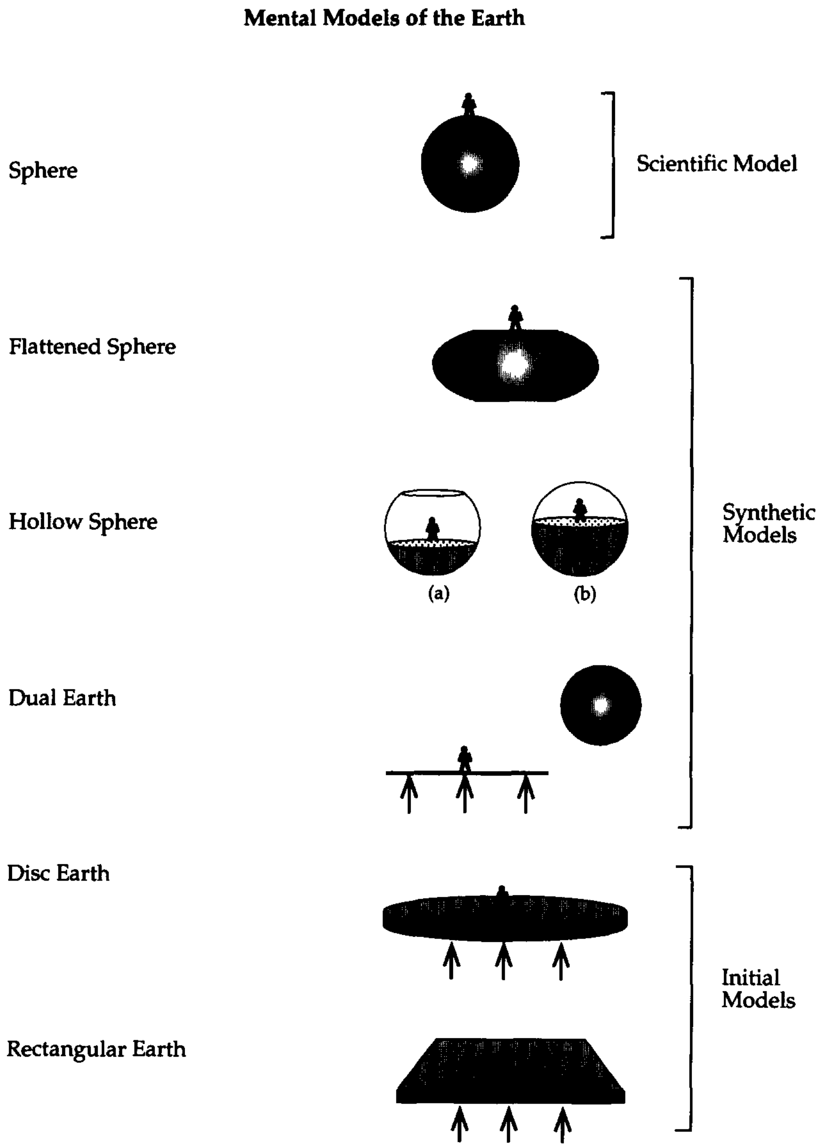

Figure 1. Mental models of the Earth.

seem to be based on everyday experience and do not show any influence from the culturally-accepted, scientific model of the spherical Earth.

The older children in our sample were more likely to form models which combined aspects of the initial model with aspects of the culturally-accepted spherical model. We called these models synthetic. There was only a small set of synthetic mental models of the Earth which children used in a consistent manner to answer our questions, even in our cross-cultural sample (see Vosniadou, in press, for a discussion of the cross-cultural findings). The synthetic models for the American sample were the following: (a) *the dual*

Table 1
Frequency of Earth Shape Models as a Function of Grade

	Earth shape models	Grade 1	Grade 3	Grade 5	Total
1.	Sphere	3	8	12	23
2.	Flattened sphere	1	3	0	4
3.	Hollow sphere	2	4	6	12
4.	Dual Earth	6	2	0	8
5.	Disc Earth	0	1	0	1
6.	Rectangular Earth	1	0	0	1
7.	Mixed	7	2	2	11
Total		20	20	20	60

Earth model, according to which there are two Earths — a flat one on which people live and a spherical one which is a planet up in the sky; (b) *the hollow sphere model*, according to which the Earth is a hollow sphere with people living on flat ground deep inside it; and (c) *the flattened sphere model*, according to which the Earth is sphere flattened at the top and the bottom parts, where people live.

The distribution of these models by age is shown in Table 1. As can be seen only 23 out of 60 children had formed the culturally-accepted spherical model of the Earth. The remaining children had formed a synthetic or an initial model or were mixed up.

Why is the Spherical Earth Model Difficult for Children to Construct?

It appears that children find it difficult to construct the mental model of the Earth because this model violates certain entrenched presuppositions of the naive framework theory of physics within which the concept of the Earth is embedded (Vosniadou & Brewer, 1992). More specifically, children seem to start by categorizing the Earth as a physical object — rather than as an astronomical object — and apply to it all the presuppositions that apply to physical objects in general. The hypothetical conceptual structure underlying children's initial models of the Earth is described in Figure 2.

It is hypothesized that children's initial models of the Earth have their origin in a related set of beliefs (specific theory) about the Earth that are based on interpretations of observations and cultural information under the constraints of a naive framework of physics. Two of the presuppositions of the framework theory are particularly important because they have the potential to explain the formation of the initial and synthetic models of the Earth children construct. They are: (a) the presupposition that space is organized in terms of the directions of up and down with respect to a flat ground, and (b) the presupposition that unsupported objects fall in a downward direction. The assumption that children are operating under the constraints of these two presuppositions can explain the formation of the initial and synthetic models of the Earth obtained in our studies. Initial models present the Earth as a flat, supported, and stable physical object with the sky and solar objects located above its top. Synthetic models represent attempts on the part of the children to reconcile the culturally-accepted model of the spherical Earth with this initial model.

For example, the synthetic model of the dual Earth provides a good way to resolve the conflict between the flat and spherical Earth models without giving up any of the

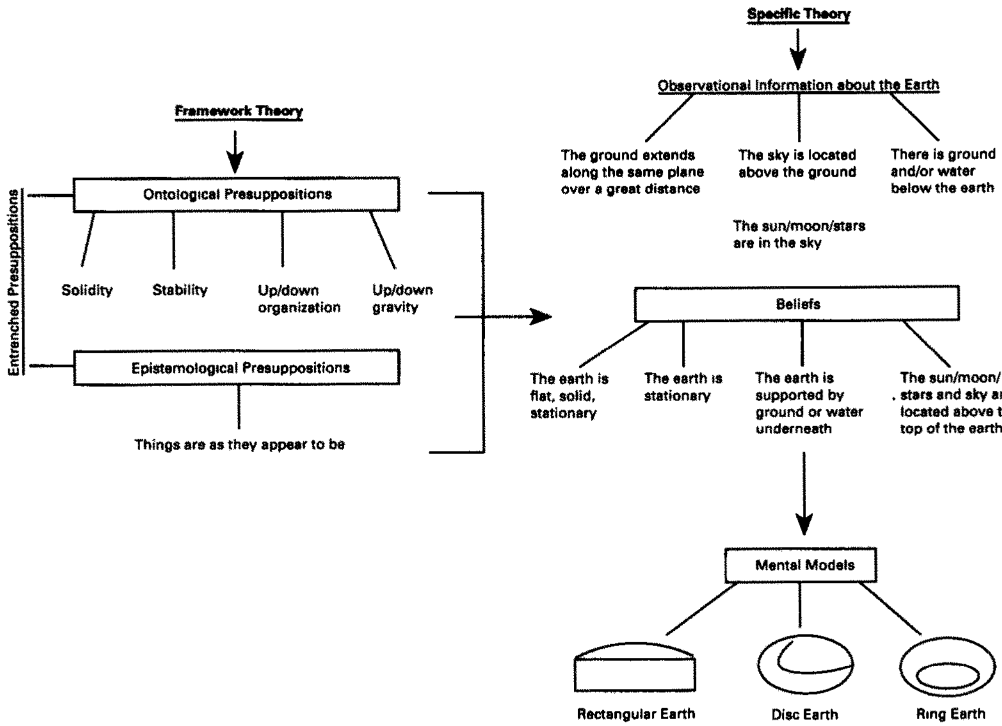

Figure 2. Hypothetical conceptual structure underlying initial mental models of the Earth.

presuppositions of the framework theory. In this model the information regarding the spherical shape of the Earth is interpreted to refer to another Earth, a planet, which is "up in the sky," and not to the flat, supported ground on which people live. By forming the dual Earth model students add the scientific information to their existing conceptual structures without changing their underlying beliefs and presuppositions. Models such as the dual Earth one are clear demonstrations of how the mechanism of *accretion* can produce a misconception, when the information added to the knowledge base is inconsistent with what is already there.

Unlike the dual Earth model, the models of the hollow sphere and of the flattened sphere are misconceptions which seem to have been produced by partial changes in underlying beliefs and presuppositions. For example, the hollow sphere model requires giving up the belief that the Earth needs to be supported. The children who form this model seem to have "suspended" the up/down gravity presupposition as far as it applies to the Earth itself. Presupposition suspension is the mechanism by which the range of applicability of a presupposition is restricted, so that this presupposition does not constrain a certain class of entities that belong to the domain. In the present case, the suspension of the presupposition of up/down gravity on the Earth itself is the first step that children seem to take in their differentiation of the concept of the Earth from the concept of the physical object to which it is originally seen to belong.

The children who form the hollow sphere model accept the notion that the Earth is a sphere surrounded by space but continue to operate under the constraints of the up/down gravity presupposition when they consider the physical objects located on the Earth. As a result, they cannot understand how it is possible for the people and objects on the Earth to stand on the outside of this sphere without falling "down." In order to solve this problem, they create a model according to which the spherical Earth is hollow and people live on flat ground inside it.

Finally, the synthetic model of the flattened sphere is an example of a misconception that can be created when some but not all of the presuppositions which the scientific model rejects are revised. The children who have formed the flattened sphere model have revised their up/down gravity presupposition but still believe that the ground on which people walk is flat. As can be seen, our theoretical framework can account for the kinds of mental representations of the Earth that elementary school children construct at different ages and for the difficulty they have in understanding the culturally-accepted concept of a spherical Earth.

In summary, it has been argued that the concept of the Earth is initially conceptualized to belong to the class of physical objects and to be constrained by a larger, naive framework theory of physics. Information about the Earth which is contradictory to the presuppositions of the framework theory is assimilated into the existing conceptual structure creating synthetic mental models or misconceptions. The process of conceptual change appears to be slow and to proceed through the gradual suspension and revision of the presuppositions of the framework theory and their replacement with a different explanatory framework. By the end of the elementary school years, most children seem to have constructed the concept of a spherical Earth, as an astronomical object, suspended in the sky and surrounded by space and solar objects.

Explanations of the Day/Night Cycle

The theoretical framework earlier described makes a number of clear predictions regarding the nature of children's initial explanations of the day/night cycle and their development. First, it predicts that children will produce only a small class of initial explanations of the day/night cycle and that these explanations would be consistent with the presuppositions of a naive framework theory of physics. Since, according to such a theory, the Earth is a solid, stationary, supported, physical object, with the sky and solar objects located only above its top, initial explanations of the day/night cycle should be given only in terms of the movement of the sun and its occlusion behind mountains or clouds. For a more extensive discussion of the specific and framework theories that constrain children's explanations of the day/night cycle, see Vosniadou and Brewer (in press).

Second, the theoretical framework predicts that the process of conceptual change will be gradual and will give rise to misconceptions. As was the case in the development of the concept of the Earth, we would expect misconceptions to represent attempts on the part of the children to reconcile the culturally accepted scientific explanation of the day/night cycle with their initial explanations, without giving up the beliefs and presuppositions that constrain them.

The results of the research on children's explanations of the day/night cycle (Vosniadou & Brewer, in press) have confirmed all of the above-mentioned predictions. We were able to account for children's responses to our questions and explain the surface inconsistency found in these responses on the basis of a small number of mental models of the day/night cycle. The most frequent of these models are described in Figure 3.

As was expected, children's initial explanations of the day/night cycle are embedded within a naive theory of physics according to which the Earth is a flat, stationary, and supported physical object and the Sun and the Moon are located above its top. The alternation of the day/night cycle is explained in terms of the movement of the Sun and the Moon behind the mountains of this flat Earth or behind clouds (models 1, 2, and 3, in Figure 3).

A number of synthetic models of the day/night cycle were also obtained, such as the model of the Sun and the Moon revolving around the Earth once every 24 hours, or the

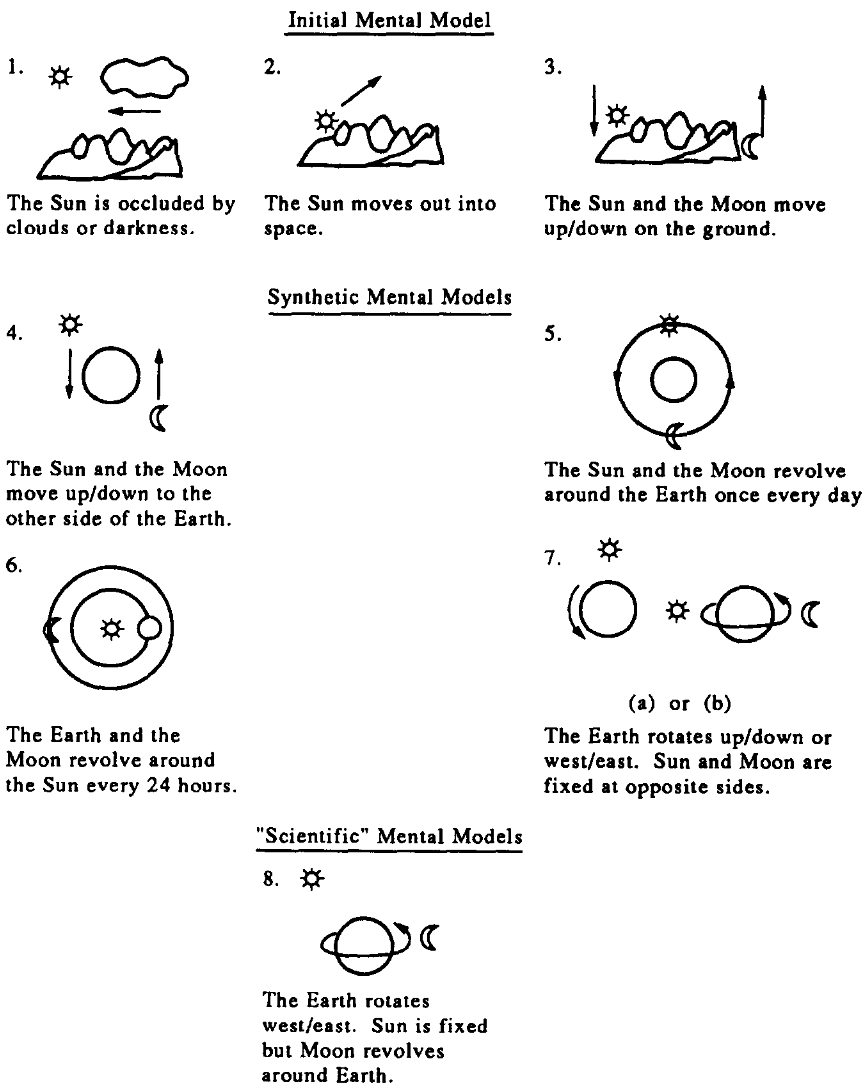

Figure 3. Mental models of the day/night cycle.

model of the Earth revolving around the Sun (models 7 and 8 in Figure 3), which are clear attempts on the part of the children to assimilate aspects of the scientific model to their existing conceptual structures.

The main constraint on children's understanding of the scientific explanation of the day/night cycle appears to be the initial mental model of a flat, stationary, and supported Earth, embedded in the ontology and epistemology of a naive theory of physics. For as long as the children retain this initial mental model of the Earth they are unable to understand the culturally-accepted, scientific explanations in terms of the Earth's axis rotation. As we had predicted, we did not observe any cases where a child with an initial mental model of the Earth had formed a scientific mental model of the day/night cycle (Vosniadou & Brewer, in press). The creation of a spherical or synthetic model of the Earth appears to be a necessary, although not a sufficient, condition for the acquisition of a mental model of the day/night cycle where the alternation of day and night is attributed to the rotational movement of the Earth.

In addition to supporting the theoretical framework earlier presented, the study of the development of children's explanations of the day/night cycle enriched our understanding of the process of conceptual change in two ways. First, it showed that there is a sequence in which concepts are acquired in a conceptual domain, such that the acquisition of some concepts (e.g., spherical Earth may be a prerequisite to the acquisition of other concepts (e.g., day/night cycle). Second, it demonstrated the importance of the mental model itself as a constraint on the knowledge acquisition process.

An example of how a mental model can constrain the knowledge acquisition process is the following. The results of our study of children's explanations of the day/night cycle (Vosniadou & Brewer, in press) have shown that the children who are operating on the basis of a spherical Earth model are very likely to interpret information related to the Earth's rotation as indicating that the Earth rotates up/down (Figure 4, Part 3) and not from west to east (Figure 4, Part 4). All the 13 children in our study of the day/night cycle with spherical Earth models, who explained the day/night cycle in terms of the Earth's rotational movement, interpreted the direction of the rotation to be an up/down one.

We have interpreted this misconception to indicate that children operate on the basis of the mental model of the Earth in which the Sun is located above the "top" of the spherical Earth rather than on the Earth's equator. The belief that the Sun is located above the top of the Earth could very well be a remnant of children's initial models of the day/night cycle, based on everyday experience (Figure 4, Parts 1 and 2). Given such a mental model of the Earth and the Sun, children must interpret the direction of the rotation to be up/down if they are to produce an explanation of the day/night cycle that is empirically accurate, that is, an explanation according to which the person located on the top part of the Earth, facing the Sun, will be away from the Sun when it is night.

On the other hand, the children who form the mental model of a hollow sphere, with people living on flat ground inside it, tend to prefer a west/east rotation of the Earth (Figure 4, Part 4). The west/east interpretation of the direction of the Earth's rotation is a better one for these children because it does not violate the up/down gravity presupposition which constraints the hollow Earth model. However, the model of a west/east rotating sphere is problematic because it does not explain well the disappearance of the Sun at night. In order to solve this problem, some children with

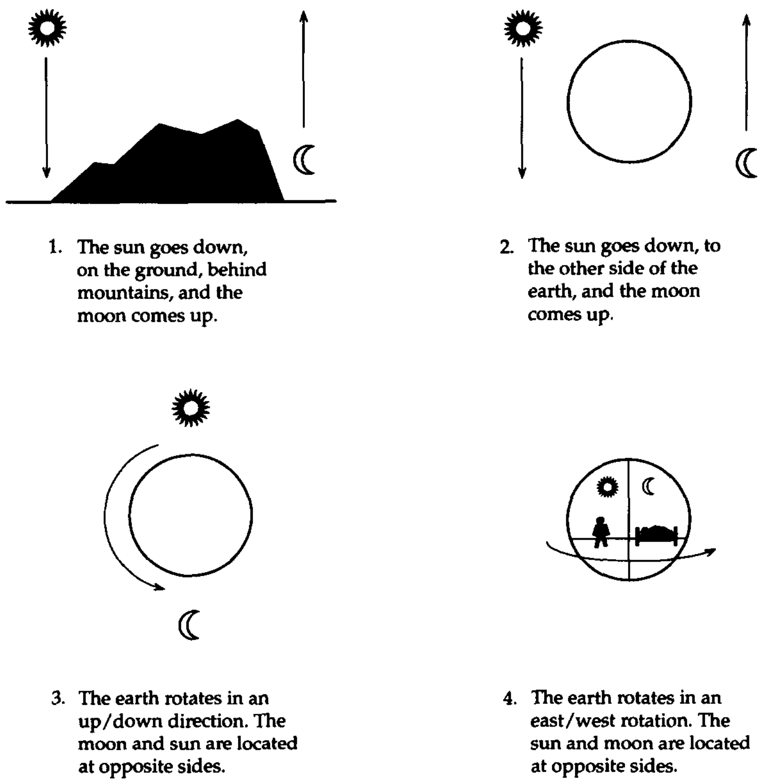

Figure 4. How students' mental models of the Earth influence their explanations of the day/night cycle.

hollow sphere models create a "day side" and a "night side" of the Earth (Figure 4, Part 4) and say that the Sun disappears from our sight as the Earth in its rotation from west to east moves from the day side to the night side! As can be seen in these examples, a generative mental model can constrain in very subtle ways the way new information is integrated in the knowledge base.

In the pages that follow some beginning attempts to test the predictive validity of the theoretical framework in the areas of mechanics and thermodynamics will be described.

The Concept of Force

A doctoral dissertation recently conducted in Greece (Ioannides, 1991; Ioannides & Vosniadou, 1991) has provided some evidence suggesting that the theoretical framework developed to explain conceptual change in the subject-area of astronomy can be applied in the area of mechanics. In this study, 105 students (ranging from 5 to 15 years old) were asked a series of questions related to their understanding of the concept of force.* The

*In the Greek language there is only word, "dynamics," which means both *strength* and *force*.

Table 2
Mental models of Force

Mental Models		Kind	Grade 4th	6th	9th
1.	There is an internal force within heavy objects — both stationary and moving	40%	6.7%	0%	0%
2.	There is an internal force within heavy and stationary objects. There is both an internal and an acquired force within moving objects	13.3%	26.7%	13.3%	0%
3.	There is an internal force within stationary objects	13.3%	6.7%	0%	0%
4.	There is only an acquired force within moving objects	0%	10%	43.3%	20.7%
5.	Force of gravity on stationary objects and on objects on a free fall. Force of gravity and acquired force within objects which have been thrown	0%	6.7%	6.7%	46.7%
6.	No force either within stationary or moving objects	0%	0%	0%	3.3%
7.	Force in waiting in stationary objects. Acquired force and force in waiting within moving objects	6.7%	10%	13.3%	6.7%
8.	Mixed	26.7%	33.3%	23.3%	23.3%

results showed that the responses of about 75% of these children could be explained by assuming that they used in a consistent fashion one of a small set of mental models of force. The most common of these mental models are described in Table 2.

The youngest children in our sample constructed an initial model of *force* according to which there is an *internal force* which is a property of objects that feel "heavy" (e.g., a big stone, but not a small stone or a balloon). This force is the same regardless of whether the object is stationary or moving. The assumed internal force appears to represent for these children the potential that these objects have to react to other external objects with which they come in contact. This force is distinct from another force, an *acquired force*, which is imparted to objects by an outside agent and is necessary to explain their motion. As can be seen in Table 2, the first four mental models of force represent various combinations of these two notions of force: the *internal* and the *acquired.* In mental model 4, students are exposed to information regarding "the force of gravity" and seem to replace the notion of internal force with the notion of gravity. At this point various misconceptions of gravity are formed, resembling the earlier notions regarding internal force. For example, some students believe that gravity is a property of the object itself. Others think that objects that fall have more gravity than stationary objects, or that gravity is not exerted upon stationary objects (see Ioannides & Vosniadou, 1991).

The hypothesized conceptual structure underlying children's initial models of force is outlined very schematically in Figure 5. It is assumed that there are two fundamental

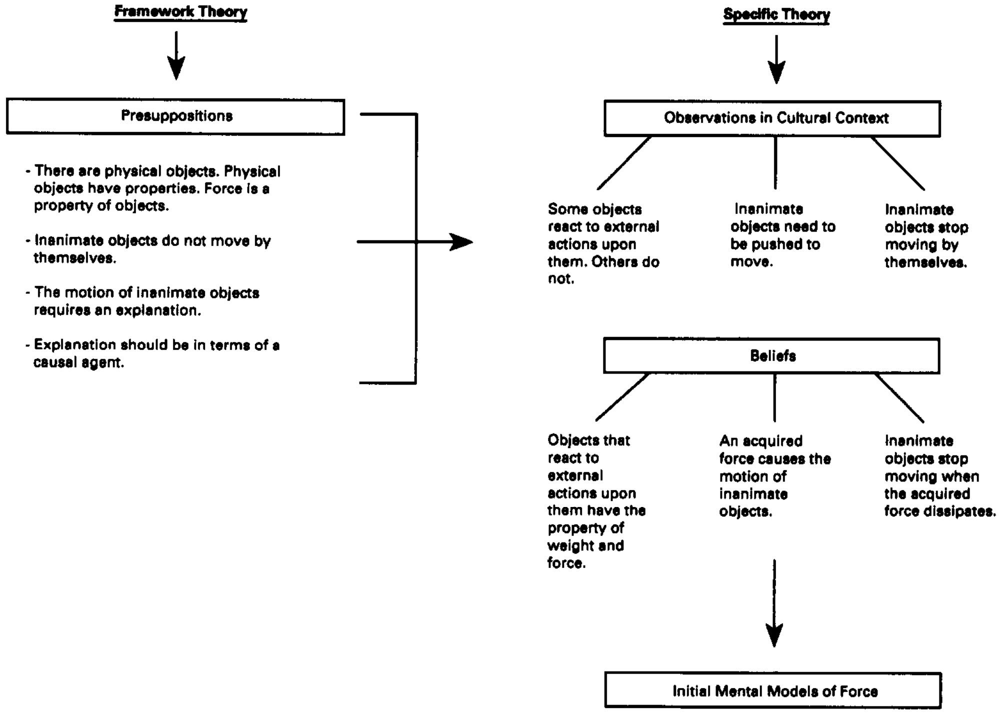

Figure 5. Hypothetical conceptual structure underlying initial mental models of force.

presuppositions of a naive framework theory of physics that constrain children's initial mental models of force: (a) that force is a property of physical objects, and (b) that force is the causal agent needed to explain the motion of physical objects.

As was the case with the concept of the Earth, the successive mental models of force obtained in our sample, can be explained as children's attempts to reconcile the information they receive by the culture with their underlying beliefs and presuppositions. The process of conceptual change proceeds through the gradual revision of the beliefs and presuppositions which are part of a naive theory of physics. For example, we see that the older children differentiate the concept of weight from the concept of force and replace the notion of an internal force with the notion of gravity. Despite these changes, the presupposition that force is a property of objects and that the motion of physical objects requires an explanation do not seem to be replaced in the conceptual system of the 9th graders in our sample, despite the fact that these students had been exposed to systematic instruction in Newtonian physics.

The Concept of Heat

Finally, some preliminary studies (Vosniadou & Kempner, 1993) show that the theoretical framework we have developed can also account for the development of the concept of heat in preschool and elementary school children. As in the case of the previous concepts we have studied, the initial concept of heat is very different from the currently-accepted scientific concept. It appears that children start with an experientially based distinction between felt hotness and coldness. Hotness and coldness are thought to be two distinct properties of physical objects which can transfer to other objects by direct contact. Children not only lack the differentiation between heat and temperature (see Wiser & Carey, 1983) but because they think that heat is a property of physical objects they are likely to confuse the amount of a given substance with the intensity of its hotness or coldness.

In modern thermodynamics heat has come to be understood in terms of the energy exchange when two objects at different temperatures come in contact. It is defined by the principle of thermal equilibrium — which states that energy will be exchanged when two objects at different temperatures are left in contact long enough until their temperature is the same — and by the differentiation between heat and temperature. Heat is an extensive quantity measured in calories or BTUs. Temperature is an intensive quantity measured with a thermometer.

Figure 6 describes very schematically aspects of the hypothetical conceptual structure that seems to underly children's initial models of heat. It is assumed that in the ontology of a young child, hotness and coldness are conceptualized to be properties of physical objects. This fundamental presupposition constrains the way children interpret their observations to generate a set of interrelated beliefs which are used to explain thermal phenomena.

Finally, Figure 7 shows some mental models of health which the elementary school children that participated in our experiments were found to have constructed. These various mental models of heat can be explained as attempts on the part of the children

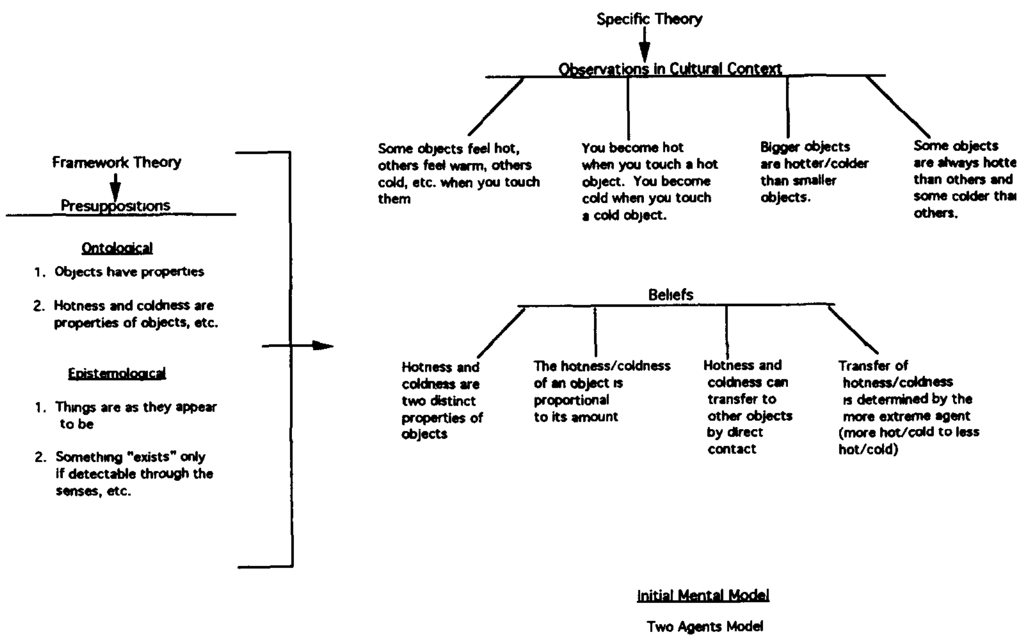

Figure 6. Hypothesized conceptual structure underlying initial mental models of heat.

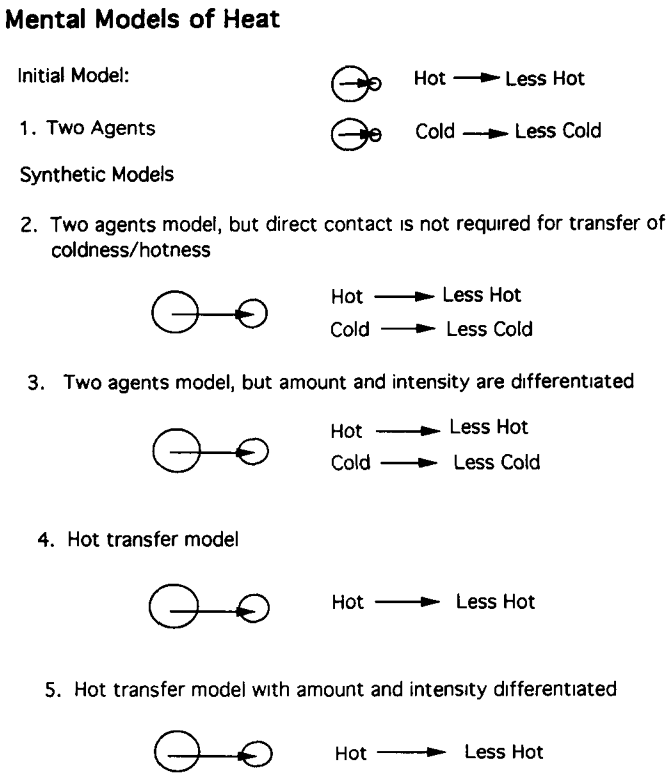

Figure 7. Mental models of heat.

to reconcile aspects of the scientific model to which they are exposed through instruction with their initial model. As in the previous cases, the process of conceptual change appears to proceed through a gradual revision of the presuppositions and beliefs of the specific and framework theories. As was the case with the concept of force, instruction does not succeed in making children to revise their underlying presupposition that heat is a property of physical objects. By the end of elementary school, most children continue to believe that heat is a property of objects.

Summary

It has been argued that concepts are embedded within larger theoretical structures that constrain them. A distinction has been drawn between *specific theories* that describe the internal structure of a given conceptual domain and a *naive framework theory* that provides the fundamental ontological and epistemological presuppositions that constrain the knowledge acquisition process in the domain of physics. Seen in this framework, conceptual change is most difficult when it requires the revision of the entrenched presuppositions of the framework theory. In these cases it is most likely that misconceptions will be formed.

Misconceptions, or synthetic models, as I call them, often represent students' attempts to reconcile the culturally-accepted, scientific views with the presuppositions of the naive framework theory of physics. Various examples of misconceptions in the subject-matter areas of astronomy, mechanics and thermal physics were discussed.

Other Theoretical Approaches

In this section, the similarities and differences of the theoretical approach to the problem of conceptual change described in this paper will be compared to some other, well-known approaches.

Knowledge in Pieces

In a recent paper diSessa (1993) proposes that the intuitive knowledge about the physical world is "knowledge in pieces." The pieces are certain primitive schemata called "p-prims" (phenomenological principles) which are "superficial interpretations of physical reality" and which serve important roles in explaining physical phenomena. Misconceptions are explained as being triggered by particular p-prims. For example, the impetus theory misconception is traced to a class of p-prims, such as "force is a mover," "dying away," "dynamic balance," etc., which are associated together to describe a small set of situations but which do not constitute a coherent and systematic theory. In this system, conceptual change occurs through the reorganization of p-prims or through increases in the internal coherence and systematicity of the collections of p-prims that serve as explanations. The most important kind of conceptual change, however, is described to be a change in the function of p-prims, which cease to be self-explanatory and become tied to more complex knowledge structures, such as physics laws and principles.

The notion of phenomenological primitives that capture aspects of the physical reality is analogous in many respects with the beliefs of a specific theory in the present theoretical framework. The main difference between diSessa's theoretical framework and the one presented in this paper centers around the point of whether p-prims, or beliefs, are self-explanatory or not. Unlike diSessa, I consider beliefs to be tied to and constrained by a set of ontological and epistemological presuppositions. As a result, beliefs do not operate "in pieces" but form a coherent structure. In this theoretical framework, the main difference between the novice and the expert is *not* that the novice's physical knowledge is in pieces and the experts tied to physical laws and principles, but that the novice's knowledge is tied to ontological and epistemological presuppositions that provide a radically different explanatory framework to fundamentally similar experiential beliefs than the principles and laws of physics. An additional important difference between novices and experts is that novices, unlike scientists, are not aware of the hypothetical status of the presuppositions and beliefs which constrain the way they interpret new information.

diSessa's theory cannot explain the findings of the experiments that show that most students operate on the basis of a small number of well-defined synthetic models, or misconceptions, and that these misconceptions can be explained as attempts on the part of the students to reconcile scientific information with the deeply held presuppositions of a naive framework theory of physics. Even a superficial look at the misconceptions of the Earth presented in Figure 1, is enough to persuade the most sceptic reader that they are all attempts to deal with the same fundamental problem: the inconsistency between the spherical shape of the Earth and the presupposition that gravity operates in an up/down fashion. Misconceptions are not caused by local, isolated, false beliefs or p-prims, which will wither away when students are exposed to systematic instruction. On the contrary, they are tied to fundamental ontological and epistemological presuppositions, which are constantly confirmed by everyday experience and which are very hard to revise.

Finally, it is also important to clarify, that unlike McCloskey (1983) and Carey (1983), we view misconceptions to be spontaneous constructions which are often generated on the spot, during the testing situation, and not deeply held specific theories. In the theoretical framework I described, misconceptions derive their resilience from their association with certain entrenched presuppositions that underly them. I am quite comfortable with the notion that students may change their local, situational models, move from one misconception to another, or even be internally inconsistent. I interpret all of these phenomena as failures to learn, produced by students' attempts to reconcile fundamentally contradictory explanatory frameworks. It is the presuppositions that are difficult to change and resistant to instruction and not the misconceptions *per se*.

Ontological Categories

The importance I have attributed to underlying ontological and epistemological presuppositions agrees in some respects with Chi, Slotta and de Leeuw's (this issue) argument that the ontological category to which a concept is assigned determines the meaning of that concept. According to Chi *et al.*, misconceptions arise because students assign science concepts to an ontological category to which they do not belong. For example, students may assign the concept of heat to the ontological category "matter," when, in fact, it belongs to the ontological category "process."

Despite some similarities, there are important differences between the two approaches. The explanation of conceptual change in terms of the reassignment of a concept from one category membership to another, does not explain why such change is difficult to occur or why some reassignments are difficult while others are not. Why is it so difficult to reassign the concept heat from the category "matter" to the category "process" and it is not so difficult to reassign the concept of "whale" from the category "fish" to the category "mammal?" Finally, some of the categories that Chi *et al.* use seem rather arbitrary. Why, for example, should "process" be an ontological category?

In the system here, concepts are embedded within a framework theory of the physical world that constrains them. The currently accepted, scientific, concepts of the Earth, of heat, of force, etc., violate basic presuppositions of this theory — i.e., the concept of the spherical Earth violates presuppositions regarding the organization of space and gravity, the scientific concept of heat violates presuppositions regarding the notion of matter and its properties. The richness of these theories and their entrenchment, tied to years of confirmation in the everyday world, must be taken into consideration in order to understand the nature and difficulty of conceptual change. The Chi *et al.* theoretical approach presents a "syntactic" rather than a "semantic" explanation of conceptual change and as such, it fails to account for the misconceptions children form in the case of the concept of the Earth, and the difficulty they have in restructuring their concept of gravity.

Domain-Specific Theories

The account of conceptual change presented in this paper shares important similarities with the account of conceptual change developed by Carey (1983, 1991) but also differs from it in important respects. Carey proposes that children start by holding a domain-specific theory A (e.g., a naive theory of thermal physics or a naive theory of matter) which at some point changes to a different domain-specific theory B, which differs from A in terms of its structure, the phenomena it explains, and the individual concepts it includes. In the present theoretical framework, however, a distinction is made between specific theories and a framework theory. Specific theories are constrained by a naive framework theory of physics and the difficulty of revising them may vary depending on what needs to be changed. Within such a theoretical framework, conceptual change is not conceptualized as a sudden shift from one theory to another, but a continuous process which happens gradually as the different kinds of constraints, and particularly those that belong to the framework theory, are reinterpreted. One of the advantages of the present approach is that it can explain not only why scientific concepts are difficult to acquire, but also the formation of synthetic models or misconceptions, the movement from one misconception to another, and, in general, the gradual nature of conceptual change.

Implications for Instruction

In this section some of the instructional implications that follow from the theoretical framework earlier presented will be briefly outlined.

Taking Students' Theories Into Account in the Design of Instruction

If strongly held presuppositions and beliefs lie at the roots of misconceptions in science learning and are not going to wither away on their own, it is important to understand them and to take them into consideration in the design of instruction. Unfortunately, the instructional materials that are currently available do not seem to take into consideration students' underlying theoretical constructions. In a detailed examination of the astronomy units in four leading science series in the U.S.A., as well as an analysis of the national curricula for elementary school science in Greece, we have noted serious limitations in the way information is presented and in the sequencing of this information (see Vosniadou, 1991a). For example, a discussion of gravity as it relates to the problem regarding the shape of the Earth was never found. As was mentioned earlier, one of the problems children have with the notion that the Earth is a sphere is their difficulty to understand how it is possible for the people and objects on the Earth to stand on the "sides" and "bottom" of this sphere without falling.

Instruction based on the presentation of counterintuitive facts (such as the information regarding the shape of the Earth) cannot by definition lead to conceptual change because it does not provide students with all the information they need to have in order to revise their naive theories. Such instruction can only lead to the accretion of inconsistent information in the knowledge base with all the unwanted implications earlier discussed.

It is interesting to note that many conceptual conflict producing situations used by science educators confront students' synthetic mental models rather than the presuppositions of the naive framework theory responsible for creating these mental models. If students' misconceptions are formed because of inadequate attempts to replace entrenched presuppositions with a different explanatory framework, as our analysis shows, the focus of instruction must be the presuppositions and not the misconceptions. For example, telling a child who believes that people live on flat ground inside a hollow sphere, that the Earth is *not* hollow, will not solve this child's problem with the notion of the spherical Earth. Children believe that the Earth is a hollow sphere because they cannot reconcile their perception of a flat Earth with the idea of roundness and with their presupposition that gravity operates in an up/down fashion. What children need in order to get rid of this misconception is a lesson on gravity and a lesson on how round things can sometimes appear to be flat. Otherwise, one misconception will be followed by another, and the students will remain confused.

Creating Metaconceptual Awareness

In the preceding pages, the theoretical nature of children's conceptual structures and the importance of underlying presuppositions and beliefs as constraints on the knowledge acquisition process have been discussed. As one looks at the implications their theoretical framework has for instruction, it becomes important to stress that while children may be good interpreters of their everyday experience, they are not aware of the theoretical nature of their interpretive activities. They do not realize that the presuppositions and beliefs of their naive theories are hypotheses that can be subjected to experimentation and falsification. Rather, they consider them to be unquestionable truths about the way the physical world operates.

Lack of metaconceptual awareness of this sort prevents children from understanding that their presuppositions and beliefs can be questioned and encourages the creation of misconceptions. Instructional programs that aim at enriching students' experiential knowledge without making them aware of their naive theory-building attempts, fail to create the necessary metaconceptual awareness. It is important to teach science in ways that make children aware that their beliefs and presuppositions are not true facts but theoretical interpretations which are subject to falsification.

It is not entirely clear how this can be best done, but the following are some possible suggestions:

- Provide children with situations in which they can engage in the active "doing" of science — present them with problem solving situations that require observation and experimentation and the testing of hypotheses.
- Encourage children to provide verbal explanations of phenomena, to share these

explanations with other students, to defend the against criticism, and to compare them to the explanations of experts.

— Take students' mental models seriously and create environments that allow students to express their representations of situations, to manipulate them, to test them, and to have the experience of revising them successfully.

Metaconceptual awareness and the cognitive flexibility that accompanies it will ultimately be based on students' successful experiences in theory restructuring.

Conclusions

It has been argued that individuals construct a naive framework theory about the physical world early in infancy. This theory facilitates but also constrains the knowledge acquisition process. Information consistent with existing conceptual structures can be easily incorporated into the conceptual system. Information inconsistent with existing presuppositions and beliefs is difficult to understand and likely to give rise to misconceptions. It is particularly difficult to achieve the kinds of conceptual change that require the revision of the ontological and epistemological presuppositions of the framework theory, because they represent relatively coherent systems of explanations tied to years of confirmation.

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