PREFACE

The chapters in this volume derive from a symposium held in Madrid, Spain, from 6-8 November, 1998. Organized and supported by the Autónoma University of Madrid, the meeting was part of the activities of the Special Interest Group (SIG) on Conceptual Change of the European Association for Research on Learning and Instruction (EARLI), coordinated by the editors of this book.

The volume brings together contributions from leading researchers investigating the role of conceptual change to enhance meaningful learning in the classroom. The aim of the volume is to present the state of the art on a topic that has become very relevant to explaining how students, and people in general, build their knowledge and incorporate new concepts and ideas.

The volume keeps the four main sessions in which the symposium was articulated. They were structured around both theoretical and practical issues of conceptual change. Particular attention was paid to discussing the characteristics of individuals' prior knowledge and to the more recent topic of how to integrate social, motivational and contextual aspects of learning within conceptual change research (Parts 1 and 2).

Most research on conceptual change has been carried out about science. Thus, the open question of whether conceptual change models and findings about the science domain are valid for other subject-matter domains, such as mathematics or history, was addressed in the meeting (Part 3). Finally, implications for instructional practices to promote knowledge revision, as well as crucial aspects that emerge when considering conceptual understanding in the real and complex context of the classroom, were debated in the symposium (Part 4).

Bringing to a wider audience the thorough treatment of the most significant questions on knowledge construction and revision, which were discussed during the SIG meeting in Madrid, this volume aims at contributing to stimulating further reflection and new research in the field of conceptual change. Enjoy reading!

ACKNOWLEDGMENTS

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The editors wish to thank the students of the Autónoma University who helped them during the meeting. They are also grateful to Rich Mayer and Paul Pintrich for supporting this project in the initial stage. Finally, the editors owe very special thanks to Luciano Fiorotto for his invaluable patience, help and generosity throughout the editing process, even during his holidays.

INTRODUCTION

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Since the middle of the 1970s research has shown that students have intuitive or naïve ideas about scientific phenomena, which have been labelled "misconceptions" in the literature. Since then, many efforts have focused on changing these ideas in ways that can lead students to a correct understanding of science concepts.

Three main findings can be highlighted from current findings. First, radical conceptual change is an effortful, gradual and time demanding outcome. Although instructional interventions are carefully designed to promote it, students' knowledge revision does not automatically occur. Literature has clearly pointed that often teaching practices are not very successful (e.g. Glynn & Duit, 1995; Mason, 2001; Schnotz, Vosniadou, & Carretero, 1999).

Second, it seems that not only purely cognitive aspects are involved in conceptual change processes. For individuals to be able to achieve the deep revision of their prior knowledge that radical conceptual change entails, it seems crucial that they also modify other aspects such as their beliefs about knowledge and knowing, their motivation, affect and achievement goals, and their learning attitudes (e.g. Pintrich, Marx, & Boyle, 1993; Pintrich, 1999).

Third, the social and cultural nature of the contexts in which the change of individuals' conceptions is desired to occur seems to play an essential role. Conceptual understanding and development can be seen as the product of shared social practices within a particular community, in which discourse practices are a cultural tool to construct knowledge (e.g. Kelly & Green, 1998).

More recently, the relevance of intentional learning for conceptual change processes has been pointed out (Sinatra & Pintrich, in press). To achieve a radical conceptual change individuals should be intentional, that is, they should be aware of the need to change their conceptions and beliefs, as well as be willing to change and self-regulate their process of knowledge revision (e.g. Limón, in press; Linnenbrink & Pintrich, in press; Pintrich, in press).

Moving from these findings, the volume aims at giving an account of the state of the art of both theoretical and practical issues that remain open in present day research on conceptual change. It is divided into four parts and each of them is commented by an invited discussant. The two first parts deal with theoretical perspectives on conceptual change. The last two focus more on implications that can

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be drawn from research and practical aspects to foster knowledge construction and re-construction, even if theoretical problems are also underlying in some chapters.

1. A STATE OF THE ART FOR UNDERSTANDING THEORETICAL PERSPECTIVES ON CONCEPTUAL CHANGE PROCESSES

Part I of this volume introduces four different theoretical views of conceptual change. The nature of individuals' prior representations and their characteristics as well as the nature of conceptual change itself have been discussed widely. Nevertheless, the discussion is far from closed as the chapters included in this part show. **DiSessa** points out the limitations of conceptual change research and criticises its current state. He considers that it lacks theoretical accountability concerning the nature of the mental entities involved in the process of conceptual change. The conceptual ecology approach he supports implies hypothesizing that conceptual change involves diverse kinds of knowledge organised and reorganised into complex systems. As an illustration of this approach he presents two very different kinds of mental entities: p-prims and coordination classes.

Vosniadou states that researchers in science education and cognitive science disagree on how to characterize naïve physics. She questions the kind of knowledge naïve physics consists of, how it is organised and how it develops. She argues that naïve physics is a complex conceptual system that includes perceptual information, beliefs, presuppositions and mental representations. Children's knowledge acquisition process starts by organising their sensory experiences, sieved by culture and language, into coherent explanatory frameworks. New information presented through instruction is assimilated to these initial explanatory frameworks creating synthetic models. She presents an empirical study about the development of the meaning of *force* to support the claim that children organise their physical experiences in narrow but coherent frameworks.

Chi also emphasises that even if the nature of misconceptions and conceptual change have been discussed for several decades, the literature only offers a fuzzy picture of what exactly misconceptions are, what constitutes conceptual change, and why it is difficult. She deals with these topics offering her view of these important matters.

Ivarsson, Shoultz and Säljö support a sociocultural view of conceptual change as an alternative to the cognitive view supported by the other three chapters of the section. They argue that to deal with conceptual development questions, it is necessary for researchers to clarify their position with respect to the more general question of how to conceive human cognition. Their paper presents a contribution to this age-old debate. They also present their results of a study on how very young children interpret a map. The authors show that using it as a mediational tool, these children can accomplish rather complicated reasoning about the shape of the earth and gravity, demonstrating the flexible and tool-dependent nature of cognition.

Finally, **Mayer** comments on the four chapters of this section. He compares these four views in terms of what changes during conceptual change, who changes, how the change occurs, where the change takes place, the role of prior knowledge, and whether there is research evidence to support each one of these views. As a conclusion, he offers a proposal for reconciling alternative views of conceptual change.

2. MOTIVATIONAL, SOCIAL AND CONTEXTUAL ASPECTS

To widen the cognitive perspective from which mainstream research on conceptual change has been carried out, **Part II** of the volume deals with the social, contextual and motivational aspects of conceptual change processes. **Linnenbrink and Pintrich** focus on students' motivation by examining the direct and mediated effects of achievement goal, affect and cognitive strategy use on students' understanding in physics. On the basis of findings from two empirical studies, they highlight the importance of students' purpose of understanding when approaching their schoolwork. Mastery goals appear directly related to the development of current conceptual understandings.

In order to shed light on the controversy between the constructivist and sociocultural approaches, **Halldén et al.** propose an alternative model for conceptual development and change. Their investigation on children's conceptions of the shape of the earth leads them to look at a child's emerging conception as a compound model, which includes facts experienced from different sources contextualized in different models. In this chapter contexts are understood as conceptual contexts, that is, conceptual systems.

The social and cultural specific contexts in which knowledge construction and re-construction occurs are addressed by **Gorodestky and Keiny**. By dealing with another conceptual framework alternative to that of traditional research in the field, they explore learning and conceptual change processes as participatory processes. Through excerpts from the ongoing discourse in a team of teachers, the authors show the process, continuity and evolution of learning within this community. The dialogical interaction between the "outer" (the social context) and the "inner" (the individual learner) illustrates the construction of common meanings.

Rodrigo, Triana and Simón indicate the importance of considering cognitive variability in a model of conceptual change, that is, people's understanding at a given age does not correspond to a single knowledge stage. Variety of knowledge states are documented through an empirical study on the development of the concept of family. Both transitional and consolidated states as well as changes in distribution of discordant and concordant states are discussed in the light of gradualist and contextualist views of developmental change.

The four chapters of this section are finally commentated by **Sinatra** who identifies three main themes across them, that is, conceptual change involves more than cognition, appears to be an evolutionary rather than a revolutionary process and what it is discovered about it depends on the theoretical perspectives and research methods. She suggests directions for future research and draws implications for pedagogical practice.

3. DOMAIN SPECIFICITY AND LEARNING

Part 3 of the volume illustrates and discusses how the particularities of domain-specific learning and teaching may affect the processes of conceptual change. **Lehtinen and Merenluoto** address some special characteristics of mathematical knowledge that should be considered to understand the processes of conceptual change in this domain. They present a study to examine the difficulties adolescent students experience in achieving the conceptual change that involves enlargement of the concept of *number*. Their results show that students tend to use the logic of the natural numbers and their everyday intuition, even if they are working on more advanced numbers. Nevertheless, the majority of students also had fragmented pieces of more advanced numbers.

Stavy, Tsamir and Tirosh argue that students answer in a similar way some conceptually non-related tasks that differ with regard to either their content area and/or to the reasoning they require, but share some common external features. They have observed this student reaction in both science and mathematical domains. They consider these responses to be instances of a few intuitive rules that lead our responses in many situations, particularly in the domain of science and mathematics. In their chapter they illustrate one of these intuitive rules, "More A-more B", which is described and discussed. Instructional implications for conceptual change and science teaching are developed.

Leach and Lewis deal with the role of students' epistemological knowledge in the process of conceptual change in science. They support that students' conceptual knowledge in science has an epistemological dimension. Thus, they argue that models of conceptual change in science should refer to this epistemological dimension. Based on empirical data from their own research they develop two claims: a) a tendency to over-attribute relevance to empirical processes is manifested by many science students when they justify viewpoints on scientific topics or when they have to explain how to solve scientific disputes; and b) students show different epistemological knowledge in different situations. Thus, students' epistemological knowledge should not be considered in isolation from the context in which that knowledge is used. An agenda for future research on epistemological knowledge and conceptual change in science is outlined.

Limón also emphasises the role of epistemological knowledge and beliefs about history as a discipline and how they affect understanding of history. Her chapter questions the extent to which results from research on conceptual change in science education can be applied to the domain of history. Particular attention is paid to second-order concepts (evidence, cause, explanation, empathy, etc.) that seem to play a crucial role in history understanding. The peculiarities of history as a discipline and their implications for history teaching and learning are also reviewed. Finally, some conclusions for conceptual change in history are developed.

This section of the volume concludes with the commentary by **White**. He addresses two issues that appear in the four chapters. The first regards the discussion of what is idiosyncratic of each topic and what principles can apply across a number of them. The second questions if conceptual change requires a different type of knowledge that may enable learners to see a subject and the topics within it in a new way.

4. INSTRUCTIONAL PRACTICES TO PROMOTE CONCEPTUAL CHANGE IN THE CLASSROOM

Part IV of the volume focuses on instructional practices to foster conceptual change in the real and complex learning environment of the classroom. The four chapters deal with implications from different lines of research on conceptual understanding and development. **Mason** argues about the relationship between personal epistemologies and knowledge revision processes. Issues from research on students' beliefs in particular domains, i.e. science, maths and history, are introduced to highlight that they may facilitate or impede conceptual change. For each of the three domains an example of an effective instructional intervention, implemented in the learning environment of the classroom, on the refinement of students' epistemological thinking is also introduced. These examples highlight that the development of naïve beliefs is a crucial condition for knowledge re-construction.

Mikkilä-Erdmann examines the role of instructional texts on conceptual change by introducing an empirical study theoretically motivated by research findings on text comprehension and development of conceptions. She compared a traditional text design on photosynthesis with a conceptual text design aimed at producing cognitive conflict in students with varying reading skills, and stimulating their metaconceptual awareness of how to understand this scientific phenomenon. Results highlight that in the complex process of conceptual change, texts play a role more important than we think.

Wiser and Amin focus on the use of computer-based conceptual models in learning physics. They refer to a "situated" approach to understanding in that they refer to the developing conceptualisation of things as a relational construct when thinking about students' sense-making of computer models and internalisation of them as a cognitive tool to construe the physical world. Excerpts from students' protocols illustrate how computer models, as components of students' increasing participation in the scientific practice, are the object of student-student and student-teacher interactions and negotiations of meaning.

Alonso-Tapia deals with assessment of conceptual understanding and its implications for conceptual change. The main characteristics of tools, procedures, contexts and processes to adequately assess students' conceptual representations are introduced. Examples taken from his own research on assessment in high school are given to illustrate how alternative conceptions and knowledge gaps can be identified. Moreover, features and benefits of portfolio assessment for assessing conceptual understanding and development are outlined. The need to pay attention not only to particular aspects of teachers' assessment practices, but to modifying the whole assessment practice is emphasised.

The four chapters of this section are finally commentated by **Boscolo**. He considers them from two perspectives. The first regards the object of change, the second regards the types of interventions that are implemented in the classroom. By

THE PROCESSES AND CHALLENGES OF CONCEPTUAL CHANGE

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Abstract. Students engaged in learning a large body of related knowledge often possess some incorrect naïve knowledge about the domain. These "misconceptions" must be removed and/or the correct conception must be built in order for students to achieve a deep understanding. This repair process is generally referred to as "conceptual change." However, although conceptual change has been discussed for several decades within different research contexts, the literature nevertheless presents a somewhat blurry picture of what exactly misconceptions are, what constitutes conceptual change, and why conceptual change is difficult. In this chapter, we suggest that one should think of misconceptions as *ontological miscategorizations* of concepts. From this perspective, conceptual change can be viewed as a simple shift of a concept across lateral (as opposed to hierarchical) categories. We argue that this process is difficult if students lack awareness of when a shift is necessary and/or lack an alternative category to shift into. These ideas are explored using a detailed example (i.e. diffusion) from a broad class of science concepts (i.e. emergent processes) that are often robustly misunderstood by students.

1. INTRODUCTION

When students engage in the task of learning some large body of related knowledge, such as a specific topic within a science domain (e.g. electricity or the human circulatory system), they are faced with two main obstacles. First, a great deal of information is simply missing from their initial understanding, and this new information must be acquired. However, it is not the case that students enter a learning situation with a blank slate. Instead, students often have some naïve knowledge or prior conceptions about the domain.

Naïve knowledge has two properties: it is often incorrect (when compared to formal knowledge) and it often (but not always) impedes the learning of formal knowledge with deep understanding. However, some type of naive knowledge can be readily revised or removed through instruction (for simplicity, instruction in this chapter refers to the presentation of knowledge through written text). We will refer to this type of naive knowledge simply as "preconceptions". On the other hand, some other type of naive knowledge seems highly resistant to change. These misunderstandings persist strongly even when they are confronted by ingenious forms of instruction. We refer to these *robust* ones as "misconceptions." In the following list of prior conceptions, the final four items are thought to be examples of misconceptions:

1) Insects are not a type of animal (Osborne & Wittrock, 1983)

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2) The heart is responsible for reoxygenating the blood (Chi, de Leeuw, Chiu, & LaVancher, 1994)
3) The earth is spherical, and people stand on top or inside of it (Vosniadou & Brewer, 1992)
4) Whales are a type of fish
5) A thrown object acquires or contains some internal force
6) An object and the shadow it casts are made of the same kind of substance
7) Electrical current is stored inside the battery
8) Coldness from the ice flows into the water, making the water colder

All naive knowledge needs to be repaired in order to promote deep understanding. The challenge is to understand why misconceptions in particular are resistant to change. Thus, although all processes of revising or removing prior conceptions can be generically construed as "conceptual change", the terms "conceptual change" are often reserved for referring to the processes of repairing misconceptions (Hewson, 1981; Posner, Strike, Hewson, & Gertzog, 1982). For emphasis, sometimes the specific processes of repairing misconceptions have been referred to as "radical" conceptual change (Keil, 1979), "genuine" conceptual change (Gunstone, Champagne & Klopfer, 1981), conceptual change "of the extreme sort" (Carey, 1991, p. 259), or nonconservative conceptual change (Thagard, 1996); whereas the processes of repairing non-robust preconceptions have been described as belief revision (Carey, 1991), mundane (Thagard, 1990), and ordinary (de Leeuw & Chi, in preparation). We will refer to the processes of repairing misconceptions as "conceptual change" and the processes of repairing preconceptions as "conceptual reorganization".

Although conceptual change has been discussed for several decades in the context of developmental research, science education research, and in the philosophy of science, the literature nevertheless presents a somewhat blurry picture of *what exactly misconceptions are, what constitutes conceptual change,* and *why it is difficult.* The goal of this chapter is to address these three related questions of process and difficulty in conceptual change. Because we define conceptual change as the processes of removing misconceptions, this definition is circular unless we can first establish what constitutes a misconception. To preview, we base our definition of misconceptions on the assumption that misconceptions are, in fact, miscategorizations of concepts. Thus, our first claim is that misconceptions are concepts categorized into an ("ontologically") inappropriate category.

From such a definition of misconceptions, our second claim follows, that conceptual change is merely the process of reassigning or "shifting" a miscategorized concept from one "ontological" category to another "ontological" category. "Ontological" categories have a lateral relationship to each other. In contrast, reconceptualizations that occur within the same ontology or hierarchy are better referred to as "conceptual reorganization" (Chi, 1992). Our third claim then is that this conceptual shift process itself is not inherently difficult, but is instead challenging mainly when students lack *awareness* of their misconceptions (i.e., they lack the knowledge that they need to shift) and/or lack the alternative ("ontologically" distinct) categories (*missing categories)* to which they should reassign their misconceptions. We are not denying that conceptual change can also be difficult because the concepts involved are complex or "incommensurate" (Carey, 1991); instead, we propose that these issues of *awareness* and *missing categories* are an important, new perspective that has not been considered. Thus, these three claims purport to answer the three questions posed above about the nature of misconceptions, the processes of conceptual change, and why it is difficult. These claims are detailed in the remaining part of this paper. Moreover, we will discuss how an ontological category view provides clear and testable definitions of misconceptions and informs unresolved issues in other perspectives. As part of our overall argument, we will provide a detailed analysis of misconceptions of a special class of scientific concepts (e.g. diffusion).

2. PRECONCEPTIONS AT THE "PROPOSITION" AND THE "MENTAL MODEL" LEVELS

2.1. The Proposition Level and Removing Incorrect Beliefs

A system of knowledge can be evaluated at the level of single ideas that can be stated as a sentence, or "propositions". These mentally-represented propositions are beliefs that students assume to be true, such as "Air is not made of matter" (Carey, 1991). If one assumes that beliefs are composed of concepts, then can mistaken beliefs be considered "misconceptions?"

When one examines a student's initial beliefs, and compares this set of propositions to a student's final beliefs (after reading a text), two classes of beliefs seem to emerge. In one case, beliefs that are incorrect at the outset are replaced by the correct knowledge after instruction. However, in a second case, a student's initial, inaccurate beliefs remain even after instruction. We might label beliefs of the first sort as "incorrect beliefs," and those of the second sort as "alternative beliefs."

Are alternative beliefs misconceptions, since they were not removed? It turns out that if we examine the text sentences in detail, and assess whether each individual initial belief was refuted or not by the text sentences, then it became clear that incorrect beliefs were the ones that the text sentences directly or indirectly refuted; whereas alternative beliefs were the ones that the text never addressed. For example, a student may initially believe that *all blood vessels have valves*.

However, after reading the text, which never mentions valves in the context of the arteries but only in the context of veins, then such indirect refutation can revise a student's initial belief to the correct proposition that *veins are the only blood vessels with valves*. It is tempting to say that alternative beliefs, since they seem to resist instruction, must be examples of misconceptions. However, our analysis has shown that the difference between incorrect and alternative beliefs relies not on qualitatively different knowledge, but on how they are addressed by the text. Specifically, incorrect beliefs are readily revised because the text tends to contradict them either directly or indirectly, at the individual proposition level. On the other hand, "alternative beliefs") are not addressed by the text at all, such as *the liver restores blood* or that *veins are like nerves that transmits signals from the brain* (these alternative beliefs are taken from the protocols of Chi, Siler, Jeong, Yamauchi, & Hausmann, in press). Such results were shown in our study on learning about the human circulatory system (de Leeuw, 1993). In that study, middle school children (8th graders) were asked to define 23 terms, diagram the path of blood through the circulatory system, and answer 42 questions, prior to instruction. In such pre-tests, students typically expressed about 15.8 propositions of preconceptions. From these 15.8 cases, only "stable" propositions (those that were repeated at least once, and that were not generated online in response to the content of the 42 questions) were considered. This filtering method reduced the number of preconceptions to 2.8 per student, giving a total of 31 across 12 subjects. In the post-tests, 77% of the 31 propositions were correctly revised if the text addressed them (these can be considered the incorrect beliefs). Five of the preconceptions remained. However, these five were not revised because *the text never addressed them*. We can consider these to be alternative beliefs.

The results above lead to a conclusion and a query. Clearly, both "incorrect beliefs" and "alternative beliefs" in this domain are preconceptions in that they can be removed with instruction, and not removed if instruction does not address them. This ease of removal for preconceptions is qualitatively different from misconceptions, which are retained even after much instructional confrontation. For example, if students believed that *Electrical current is stored in the battery*, then correct understanding cannot be easily achieved by merely confronting students at the proposition level with direct refutation, such as telling them that *electrical current is not stored anywhere*. It suggests that conceptual change of "false beliefs" require changes at a larger grain size. The query from the results above is why were all the preconceptions removable, once a text refutes them? That is, why were misconceptions not manifested in this domain? The answer alluded to in the preview, will be more obvious and revisited once we detail more clearly what misconceptions are.

2.2. The Mental Model Level and Repairing Flawed Models

Instead of representing knowledge at a piecemeal level, one can represent knowledge as a set of interrelated propositions, or a "mental model". What this adds to a discussion of proposition level beliefs is a structure in which the propositions are embedded. Examples of research that represent students' initial knowledge in terms of mental models are Vosniadou and Brewer's (1992) studies of young children's concepts of the shape of the earth, and Chi's (2000b) work with middle school students' understanding of the human circulatory system.

Like propositions, distinctions can be made about the nature of naïve mental models. One such distinction is made on the basis of coherence. An incoherent, or "fragmented," mental model can be conceived of as one in which propositions are not interconnected in some systematic way. Such a model cannot be used to give consistent and predictable explanations. Furthermore, because many parts may be unconnected, students are often aware that they lack a complete understanding. Alternatively, mental models can be coherent, meaning that the constituent propositions are related in an organized manner. Unlike fragmented models, such representations can be used to generate explanations, make predictions, and answer questions in a consistent and systematic fashion.

A coherent model can be correct or flawed. By "flawed" we mean a mental model whose coherent structure is organized around a set of beliefs or a principle that is incorrect. Note that this level of "correctness" is distinct from the correctness of individual propositions. A flawed mental model may share a number of propositions with a correct mental model, but they are interconnected according to an incorrect organizing principle. In addition, though students with fragmented mental models are often aware of their lack of understanding, this is not true for students with flawed, but coherent models. Because these students are able to answer questions adequately and consistently, they may be blind to their lack of deep understanding. Two studies clearly illustrate what we mean by a flawed mental model.

Vosniadou and Brewer (1992) have explored young children's naïve conceptions of the earth and it's shape. One common misconception they've identified is the belief that the earth is shaped like a round, flat pancake. However, children can make sense of their world using this flawed, disk-earth model. For example, the flatness of the earth is compatible with their everyday perceptions, in the sense that the ground appears level. They can use this simplistic model to answer questions and generate explanations that are meaningful to them.

Another example is provided by research on middle school students' naïve conceptions of the circulatory system (Chi, 2000b; Chi et al., 1994). On average, about half of the students think of the human circulatory system as a "single-loop," in which the blood leaves the heart, travels to all parts of the body, and then returns to the heart (see upper left diagram of Figure 1). This is in contrast to the correct pathway, a "double-loop," that involves both systemic (heart-to-body) and pulmonary (heart-to-lungs) circulation (see upper right diagram of Figure 1). However, the single-loop model is coherent. We can demonstrate this because it differs from the correct, double-loop model in systematic ways: the source of oxygen, the purpose of blood flow to the lungs, and the number of loops. Specifically, a single loop model is organized by a principle, consisting of the beliefs that the heart (rather than the lungs) is the source of oxygen, that blood goes to the lungs to deliver oxygen (rather than to exchange carbon dioxide and oxygen), and that there is just one loop. Thus, a flawed mental model is one that is organized around an alternative principle, consisting of a set of beliefs shown in the left column of Figure 1, whereas the correct double loop model is organized around another set of beliefs, shown in the right column of Figure 1. With a flawed single loop model, students will give systematic and predicable answers to questions like the following examples (student replies are in parentheses; Chi et al., 1994):

1. Why does blood have to go to the heart? ("to get oxygenated")
2. Why does blood go to the lungs? ("to deliver oxygen to the lungs")

In data collected, but not reported, by Chi et al. (1994), over half of the students (8 out 14 students in the prompted group) had easily and consistently identifiable mental models that were coherent, but flawed.

WHY "CONCEPTUAL ECOLOGY" IS A GOOD IDEA

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Abstract. This paper motivates the idea of "conceptual ecology" by critiquing the current mainstream of conceptual change research. Most research on conceptual change suffers from too little theoretical accountability concerning the nature of the mental entities involved and too little use of the details of process data to support its theoretical view. Part of the consequences of these limitations is a vast underestimate of the complexity and diversity of conceptual change phenomena. In contrast, a conceptual ecology approach involves hypothesizing that conceptual change involves a large number of diverse kinds of knowledge, organized and re-organized into complex systems. To illustrate a conceptual ecology approach, we explain two very different kinds of mental entities, p-prims and coordination classes. P-prims are small and numerous intuitive elements that are often quite context specific in their activation. Coordination classes, by contrast, are large systems whose very existence entails a high degree of coordination across diverse contexts. We claim that both p-prims and coordination classes are much more explicit and precise in their assumptions than is typically the case, and they both survive substantial empirical test in the form of analysis of process data.

1. INTRODUCTION

My aim in this chapter is to provide a critique of the current state of conceptual change research and a brief account of how I believe better progress may be achieved. In particular, much prior research in conceptual change has taken a vastly oversimplified view of the process. Figure 1 provides a graphical backdrop on which to illustrate these oversimplifications. The figure shows a naïve concept, A, and its trajectory of development into expert concept, B. What could be wrong with such a picture?

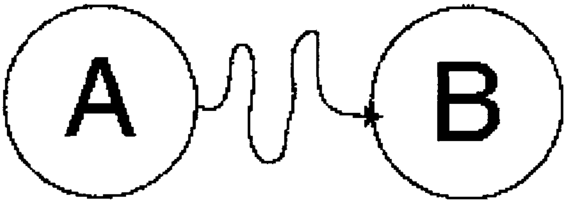

Figure 1. A graphic illustrating "conceptual change."

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To begin, we must ask, what are the entities, A and B? The answer most often given is "concepts," although other types of mental entities are sometimes given, say, ontologies (Chi, this volume), beliefs (Hofer & Pintrich, in press), models (Vosniadou & Brewer, 1992), or theories (McCloskey, 1983; Gopnik & Meltzoff, 1996). (To simplify exposition, for the most part I will use "concepts" as an exemplar type of mental entity, although my arguments are essentially unchanged if other types are substituted or if a few are added to a list of types.) To say A and B are concepts begs the question, what is a concept (or any of these other mental entities)? How do we know a concept when we see one? Might it not be necessary to distinguish different kinds of concepts? In this chapter I will strongly motivate the need for a significant variety of types of mental entities to replace the few listed in the literature. More significantly, I will argue that prior work has typically lacked theoretical accountability; it has, indeed, failed to tell us what concepts are, and how to distinguish them from other actual or possible types of mental entities.

Figure 1 shows only two examples of concepts, A and B. Might it not be true, however, that many mental entities contribute to the construction of B? Might it not be true that B is, in fact, a complex system consisting of many interacting parts? My belief is that it is essentially certain that scientific concepts are best considered as complex systems, and prior research has not systematically addressed this possibility seriously. For example, current practice in conceptual change research is far from being able to (and rarely attempts to) match system elements and processes against the details of student reasoning and learning data.

The logical extension of Figure 1 has exactly one naïve concept for every expert concept, and it does not make room for the distinct possibility that naïve concepts have rather different properties than expert ones. Empirical data with respect to these possibilities are easy to come by. Beginning students have many ideas that do not come close to matching expert ideas on a one-by-one basis. It well may be that the naïve conceptual ecology has no exemplar whatsoever that approaches the qualities exhibited by expert concepts.

With an impoverished view of the nature of concepts, it is no wonder that the long, winding path from naiveté to expertise has little exposed detail in the literature. Instead, one finds a variety of unhelpful, definition-begging and probably unfalsifiable terms, like "partial construction," "mixed models," and "confused ideas." And yet, in the classroom, teachers easily find rich and complex intermediate states with which they have to deal; clinical interviews of students essentially always reveal a textured mix of naiveté and learned knowledge, which, however, has had few, if any, systematic descriptions to date.

Figure 2 shows a graphic—obviously simplified—that illustrates the view of conceptual change I advocate in this paper. The naïve state consists of a large number of conceptual elements of varying types. Those elements are modified and combined in complex ways, possibly in levels and into subsystems that, together, constitute the "final" configuration of an expert concept. For reference, I call this a "complex knowledge systems" view of conceptual change—informally, "conceptual ecology."

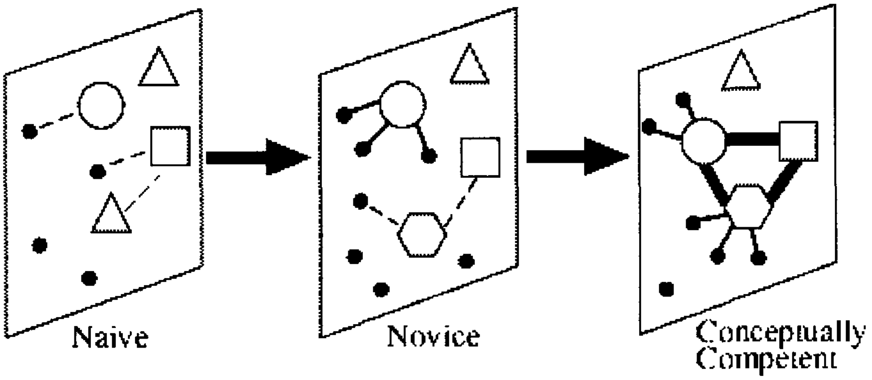

Figure 2. Illustrating a complex systems view, where many exemplars of many different types of knowledge develop and become reorganized in the process of "conceptual change." An "expert concept" draws on many different elements of naïve knowledge (some not belonging to "the naïve concept") that get gradually changed, augmented with new elements, and organized into a new configuration.

The term conceptual ecology has been used by others. In particular, in their influential work on conceptual change, Strike and Posner (1992) speak of conceptual ecology in a similar spirit.[1] More generally, there have been other advocates and allies of the complex knowledge systems view, some implicitly in the details of their analysis of learning complexities, and some more explicitly in the richness of their theoretical framing (e.g., Thagard, 1992). Indeed, in a summary chapter for a section of book on reasoning (Vosniadou & Ortony, 1989), Bill Brewer reports his synthetic conclusion that "in the long run, a proper understanding of the human mind will require that we recognize a large number of very different forms of knowledge and associated psychological processes." (p. 537) Despite sporadic recognition of the importance of a complex systems view, the mainstream of conceptual change research has persisted with vague and oversimplified assumptions about the entities and processes involved in conceptual change. In addition, of course, I intend my contribution to point out particular ways of pursuing a complex systems view that I expect will be most fruitful.

The remainder of this paper elaborates and systemizes the difficulties I see in the contemporary landscape of conceptual change research. Following, I illustrate my approach to improving on the present state.

2. DIFFICULTIES ELABORATED

Broadly, I divide the difficulties in the core of contemporary conceptual change landscape into theoretical and empirical subsets.

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[1] *However, Strike and Posner did not seem to intend the level of detail in articulating and modeling knowledge types and architectures implicated here.*

2.1. *Theoretical Considerations*

A lot could be said about the lack of cogent theoretical framing for the issue of conceptual change. However, in this chapter, I underscore only one issue: the lack of well-developed technical terms.

Dictionary meanings can almost never serve the purposes of science. Instead, whenever science is successful, it refines existing terms or adds supplemental ones that can bear a stronger burden. Everyday words are known to be polysemous, combining multiple senses in useful (if ambiguous) packages. Furthermore, even the various senses of everyday words serve only everyday purposes in everyday ways. "Concept" (or one of its various senses or connotations), in particular, seems clear and useful in common usage. However, in the following section, I argue that it is hopelessly vague, covering multitudes of kinds of mental entities with a common coat.

At this point in cognitive studies, we can hope to apply high analytical (as opposed to purely empirical) standards to our technical terms. We could, for example, attempt process models that explain technical terms. Although I won't press far in this direction here, it is good to realize that the literature on conceptual change has rarely attempted process models, nor has it entertained substitute methods of making technical terms' meanings precise.

Besides "concept," other common candidates for useful technical terms suffer similar difficulties to varying degrees. We all have a vague sense of what a theory is. Yet, even if the term is sufficiently well-defined within the social conduct of professional science, in transporting the term to individual learning, a host of changes are likely necessary.[2] In particular, I believe there is convincing data that many naïve scientific ideas are inarticulate, are not easily expressible in words. This, alone, is a dramatic difference from professional science, where complex, careful and symbolically augmented expression (e.g., using algebra) is almost always evident. It seems indubitable that externalizing ideas is more than for archival purposes in professional science. Externalizing allows extraordinary reflective scrutiny and careful reformulation. In contrast, "naïve theories" are never seen directly in the words of subjects, or we might simply be able to ask students for their theories, the way we do with scientists.

"Ontology" has longstanding philosophical roots. To my knowledge, however, no researcher of conceptual change has attempted a process model of ontologies. I don't need to criticize empirical work that implicates shifting ontologies to point out that such work is weakened unless we know what an ontology is, unless we understand how such mental entities may come to exist in some detail and how they function in reasoning and learning. For ontology, as well as for concept, we want to know how we can surpass images like Figure 1 in detail and cogency.

Unless we develop theoretically well-elaborated technical terms, major empirical problems follow. Unless we know what a theory is, how do we distinguish it from a small collection of concepts, or even from a sentence one may utter and toward which one might express some commitment? Tellingly, researchers preferring one

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[2] *With regard to social vs. individual perspectives on theory development, see Harris (1989).*

term of another (concept, theory, belief, ontology) essentially never use data to show students' reasoning and learning are inconsistent with other theoretical assumptions. diSessa & Sherin (1998) examine the literature of conceptual change. They argue that even the best and most widely-recognized researchers use inexplicit definitions that implicate ill-defined meanings, and they show what difficulties follow in attempting to interpret data in such vague terms.

The deep problems of conceptual change remain unscathed when we cling to vague, unelaborated terms. What aspects of "theory" are really critical in theory change, and why, after all, is conceptual change difficult when some kinds of learning proceed effortlessly?

In this chapter, I won't propose general criteria for cogency of technical terms in cognitive studies. However, I will illustrate steps toward more adequate terms with two categories among several I have developed in my own studies of conceptual change.

2.2. Empirical and Quasi-Empirical Considerations

This section views the current state of conceptual change research through an empirical lens. I will argue that researchers have used very weak empirical strategies that avoid the real complexity of conceptual change. In particular, I make the case that, without much effort, we can strongly motivate, if not prove, that the appropriate default approach to studying conceptual change recognizes diversity in mental entities.

Several trends that I take to be paths of improving our study of conceptual change will become evident in this section. The first, already mentioned, concerns *types*. In particular, I advocate a trend toward *multiplicity*, a greater number of (more accountable) types of mental entities. A second trend concerns *grain size*. Here, the trend should be toward *a greater number of smaller scale elements*. Concomitantly with the second trend, in investigating large-scale accomplishments like "conceptual change" we are necessarily studying *systems of interacting elements*. A final trend concerns increased care in dealing with *invariance*, that is, the issue of when two situations evoke the same conceptual elements. With a rich selection of knowledge elements, we are forced into much more specific consideration of context. If a conceptual ecology contains thousands of elements, certainly the issue of when which are activated is highlighted. In fact, we should expect a greater degree of *context dependency*. Combining trends toward increased contextual dependency, toward multiplicity and toward smaller grain size suggests that an application of a concept is likely to be better viewed as the selected activation of particular concept subcomponents, depending on context. This particular observation will become a core concern when we turn to one of my sample knowledge types, "coordination class."

ON THE NATURE OF NAÏVE PHYSICS

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Abstract The argument will be advanced in this paper that naive physics is neither a collection of unstructured knowledge elements nor a collection of stable misconceptions that need to be replaced, but rather a complex conceptual system that organises children's perceptual experiences and information they receive from the culture into coherent explanatory frameworks that make it possible for them to function in the physical world. The process of learning science appears to be a slow and gradual one during which aspects of the scientific information are added on to the initial explanatory framework destroying its coherence until (and if) it is restructured in ways to make it consistent with currently accepted scientific views.

1. INTRODUCTION

Researchers in science education and cognitive science seem to agree that naive physics exerts a great deal of influence on the way new information is understood and science concepts are acquired, but disagree on how to characterize the exact nature of naïve physics. What kinds of knowledge elements naive physics consists of, how is it organized, and how does it develop? This disagreement has important implications for the teaching of science. Are there persistent misconceptions that represent relatively stable and internally consistent beliefs that interfere with the teaching of science, or is it the case that naïve physics consists of a multiplicity of knowledge pieces that are mainly unstructured and unsystematic? And, is the process of knowledge acquisition in science a process that increases the systematicity of initially fragmented pieces of knowledge or a process of replacing stable and resistant misconceptions with currently accepted scientific theories?

In this paper we will try to outline a different theoretical framework within which this debate can be reframed. We will argue that children start the knowledge acquisition process by organizing the multiplicity of their sensory experiences under the influence of everyday culture and language into narrow but coherent explanatory frameworks that are different from the currently accepted science. Naïve physics thus does not consist of a collection of unstructured knowledge elements or of stable misconceptions but constitutes a complex system that includes perceptual information, beliefs, presuppositions, and mental representations. This knowledge

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system represents children's attempts to organize their perceptual experiences and information they receive from the culture into coherent explanatory frameworks. The process of learning science appears to be a slow and gradual one during which elements of the scientific theory become assimilated to the initial explanatory framework destroying its coherence and creating synthetic models. This is the case because currently accepted scientific explanations and concepts have evolved over thousands of years of scientific discovery to become rather elaborate, counter-intuitive theories that differ in their structure and in the phenomena they explain from initial explanations of the physical world based on everyday experience.

In the pages that follow we will describe the misconceptions and knowledge in pieces positions in greater detail. We will continue by discussing the theoretical framework we have developed. An empirical study investigating the development of the meaning of the term *force*[1] will be presented to provide an example of conceptual change as we see it. We will argue that the results of this study add further evidence to those earlier conducted in our lab (Vosniadou, 1994; Vosniadou and Brewer, 1992, 1994) in showing that from an early age children organize their physical experiences in narrow but coherent explanatory frameworks. During development, we observe neither a sudden change from an impetus misconception to Newtonian physics nor the gradual development of more coherent and systematic networks of knowledge. Rather, information received through instruction seems to become assimilated to the initial explanatory framework creating synthetic or internally inconsistent models.

2. THE "MISCONCEPTIONS" VERSUS "KNOWLEDGE IN PIECES" POSITIONS IN SCIENCE EDUCATION

The proposal that the learning of science involves the replacement of persistent misconceptions has its roots in the work of science educators like Novak (1977), Driver and Easley (1978), Viennot (1979) and McCloskey (1983a, 1983b). They were among the first to pay attention to the fact that students bring to the science learning task alternative frameworks, preconceptions, or misconceptions that are robust and difficult to extinguish through teaching. Misconceptions are defined as student conceptions that produce systematic patterns of error. Misconceptions can be the result of instruction or they may originate prior to instruction. Posner, Strike, Hewson and Gertzog (1982) drew an analogy between Piaget's concepts of assimilation and accommodation and the concepts of "normal science" and "scientific revolution" offered by philosophers of science such as Kuhn (1970) and derived from this analogy an instructional theory to promote "accommodation" in students' learning of science. The work of Posner et al. (1982) became the leading paradigm that guided research and practice in science education for many years.

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[1] *This study is based on a dissertation submitted by Christos Ioannides and is reported in detail in C. Ioannides and S. Vosniadou, Exploring the Changing Meanings of Force, Cognitive Science Quarterly (in press).*

Smith, diSessa, & Rochelle (1993) have criticized the misconceptions position on the grounds that it presents a narrow view of learning that focuses only on the mistaken qualities of students' prior knowledge and ignores their productive ideas that can become the basis for achieving a more sophisticated mathematical or scientific understanding. Smith et al (1993) argue that misconceptions should be reconceived as faulty extensions of productive knowledge, that misconceptions are not always resistant to change, and that instruction that "confronts misconceptions with a view to replacing them is misguided and unlikely to succeed" (p. 153). Other research has shown that it is very difficult to identify internally consistent misconceptions in mechanics and kinematics in high school or college students who had little exposure to formal physics (e.g. Ranney, 1994)

diSessa (1988; 1993) has put forward a different proposal for conceptualizing the development of physical knowledge. He argues that the knowledge system of novices consists of an unstructured collection of many simple elements known as phenomenological primitives (p-prims for short) that originate from superficial interpretations of physical reality. P-prims appear to be organized in a conceptual network and to be activated through a mechanism of recognition that depends on the connections that p-prims have to the other elements of the system. According to this position, the process of learning science is one of collecting and systematizing the pieces of knowledge into larger wholes. This happens as p-prims change their function from relatively isolated, self-explanatory entities to become pieces of a larger system of complex knowledge structures such as physics laws. In the knowledge system of the expert, p-prims "can no longer be self-explanatory, but must refer to much more complex knowledge structures, physics laws, etc. for justification (diSessa, 1993, p. 114).

We appreciate the efforts of diSessa (1993) and Smith et al (1993) to provide an account of the knowledge acquisition process that captures the continuity one expects with development and has the possibility of locating knowledge elements in novices' prior knowledge that can be used to build more complex knowledge systems. We also agree that we need to move from single units of knowledge to systems of knowledge that consist of complex substructures that may change gradually indifferent ways. Finally, we agree with Smith et al's (1993) urge to researchers to "move beyond the identification of misconceptions" towards research that focuses on the evolution of expert understandings and particularly on "detailed descriptions of the evolution of knowledge systems over much longer durations than has been typical of recent detailed studies (p. 154).

In the last few years we have been involved in a program of research that attempts to provide detailed descriptions of the development of knowledge in specific subject-matter areas mainly of the physical sciences, such as astronomy (Vosniadou and Brewer, 1992; 1994; Vosniadou 1994; 1998), mechanics (Ioannides and Vosniadou, in press; Megalakaki, Ioannides, & Vosniadou, & Tiberghien, 1997), geophysics (Ioannidou & Vosniadou, in press) chemistry (Kouka, Vosniadou & Tsaparlis, in press), and biology (Kyrkos & Vosniadou, 1997).

The above-mentioned studies are all cross-sectional developmental studies investigating the knowledge acquisition process in subjects ranging from 5 to 20 years of age. We have also used the results of our research to develop curricula and instruction that has been tried in schools in Greece (see Vosniadou et al., in press). The results of these studies show that young children answer questions about force, matter, heat, the day/night cycle, etc. in a relatively consistent way revealing the existence of narrow but coherent explanatory frameworks. These explanatory frameworks are usually different in their structure, in the phenomena they explain, and in their individual concepts from the scientific theories to which children are exposed through instruction.

The position we have been developing is similar in many respects to the views developed by Carey (1985), according to which even very young children form "theories" that embody causal notions, allow distinct types of explanations and predictions, reflect basic ontological commitments, and are subject to modification and radical revision. In our work (Vosniadou, 1994; 2000), we have used the term "framework theory" to refer to the conceptual system that young children form to interpret their observations about the physical world, as well as their interpretations of the information provided by the culture. The term "theory" is used relatively freely to denote an explanatory system with some coherence. Unlike Gopnik (1996) it is assumed that this system differs in many respects from a scientific theory. It lacks the systematicity of a scientific theory as well as other characteristics of scientific theories such as their abstractness, and social/institutional nature. It is also assumed that children differ from scientists in important ways, for example in the strategies they use to evaluate evidence (e.g., Kuhn, Amsel, & O'Loughlin, 1988), or in that they lack metaconceptual awareness of their naive theories, and therefore do not seek to verify or falsify them.

While this kind of developmental research has so far concentrated on very young children, the research we have pursued investigates older children and young adults as well, in an effort to find out what happens after they are exposed to systematic science instruction in school settings. Our results show that in the process of learning science, children add or delete beliefs and presuppositions to their explanatory frameworks destroying their coherence, while at the same time distorting the scientific concepts to which they are exposed.

More specifically, we assume that in physics children's initial explanatory framework (their "framework theory") consists of certain basic ontological and epistemological presuppositions about the nature of physical objects and the way they function in the physical world. Some of the ontological presuppositions are that physical objects are solid and stable, that space is organized in terms of the directions of up and down and that unsupported objects fall in a downward direction. Children also seem hold certain epistemological presuppositions, such as that rest is the natural state of inanimate objects and motion needs to be explained, and that entities such as force, heat and weight are properties of physical objects.

Children's continuing observations and the information they receive from the culture are interpreted under the constraints of presuppositions such as the above to create specific explanations of phenomena. For example, as shown in Figure 1, there can be various specific explanations of the day/night cycle such as that the sun goes behind the mountains, or that the sun goes down to the other side of the earth. These specific explanations are embedded within the above-mentioned explanatory framework because the earth is considered to be a physical object (as opposed to an astronomical object), and thus to be constrained by all the presuppositions that apply to physical objects in general. In other words, children assume that on the earth space is organized in terms of the directions of up and down and gravity works in an up/down direction. These presuppositions can stand in the way of children's understanding of the spherical shape of the earth and of the earth's axis rotation, which in turn are necessary for understanding the scientific explanation of the day/night cycle.

It could be argued here that our attempts to explain conceptual change are similar to the explanations proposed by Chi and her colleagues (Chi, 1992; Reinner et al., 2000). Chi argues that misconceptions arise when a person associates the wrong ontology with a scientific concept, such as *force* or *heat*. She notes that many concepts in physics are wrongly associated with a *substance* ontology when in fact they belong to a *process* (or *acausal*) ontology. Chi seems to believe that conceptual change is a radical process that happens in a short period of time.

There are, however, important differences between our position and the one put forward by Chi and her colleagues. Unlike Chi, Vosniadou (1994) argues that conceptual change does not happen suddenly but is a gradual and time consuming process. This is the case because we are dealing with a complex knowledge system that consists of a network of beliefs or presuppositions that take a long time to change. We agree with Chi and her colleagues that conceptual confusions often arise in science learning from the assignment of scientifically incorrect ontological presuppositions to concepts such as force, heat, the earth, etc. However, ontological change is only one of the many kinds of changes that need to take place in the process of changing theories. Furthermore, we believe that Chi's theoretical framework does not provide an adequate account of the nature of ontological categories and their development. There is no theory about where ontological categories come from, how they develop, how new ontological categories are formed and why, etc. In our theoretical framework we try to account for how children slowly construct the explanatory framework within which their observations about the physical world are interpreted (see also Vosniadou, 1994; 1998). Information from infancy studies substantiates our claims that children start from very young to organize their perceptual experiences in conceptual structures, such as the concept of the physical object (e.g., Spelke, 1991). Ontological and epistemological presuppositions are attached to these conceptual structures. Perceptual information, as well as beliefs, and mental representations also constrain the knowledge acquisition process.

Our position is not inconsistent with the view that something like diSessa's p-prims constitute an element of the knowledge system of novices and experts. We believe that p-prims can be interpreted to refer to the multiplicity of perceptual and sensory experiences that are obtained through our observations of physical objects and our interactions with them. In the conceptual system we propose, diSessa's p-prims would take the place of the perceptual information obtained through observation. These perceptual experiences provide the basis for forming beliefs, presuppositions, and mental models. The proposal that the conceptual system consists of different kinds of knowledge elements (such as beliefs, presuppositions and mental models) is also consistent with diSessa's proposal that we need to focus

MAP READING VERSUS MIND READING

Revisiting children's understanding of the shape of the earth

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Abstract. Any study pursuing questions of conceptual development has to position itself with respect to the more general questions of how to conceive human cognition. At one level this study thus presents a contribution to this age-old debate about the nature of human thinking and learning. At another level – the empirical – it provides a discussion of the difficulties that children face when reasoning about the shape of the earth and gravity. The study reported is part of a project that explores issues of how people use physical artefacts, embodying conceptual distinctions of considerable complexity, when thinking and reasoning.

The results suggest that even very young children are familiar with sophisticated knowledge about how to interpret a map. Furthermore, using it as a mediational tool, they can accomplish rather complicated reasoning about the shape of the earth and gravity. This is a demonstration of the flexible and tool-dependent nature of cognition. It is, however, inconsistent with a more formal stage theory or a theory in which children's reasoning is characterised by means of distinctively different conceptions. It is also at odds with a dualist perspective on human cognition in which the embeddedness of physical tools in human reasoning is not taken seriously.

1. INTRODUCTION

For centuries, the question of how to conceive human cognition was an issue that mainly concerned philosophers. During the 19th and 20th century, however, new disciplines emerged, and researchers within areas such as psychology, anthropology, linguistics, neuroscience, artificial intelligence and educational science joined this lively debate. Although its roots go further back, the one perspective that has been dominant in recent decades, or at least up until recently, is the one represented by cognitive psychology. The traditional focus of cognitive psychology is to posit cognition as a fundamentally individual process. The assumption is that human mental functions are located in individuals and can be modelled accordingly as mental entities such as memory systems, thought processes, and cognitive structures.

The empirical approach that resonates with this conception usually explores allegedly basic cognitive and perceptual processes (thinking, memory, problem-solving, perception, etc.) by attempting to unpack the basic mechanisms of mental processes and/or the conceptions of the world that people hold when reasoning. The focus is on cognitive systems and thought processes that – as the metaphor goes –

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underlie reasoning at the level at which it is visible externally in linguistic and physical activities.

A major challenge to this tradition comes from a sociocultural and discursive perspective inspired by Vygotskian and Wittgensteinian views of human cognition and communication (Wertsch, 1991, 1998; Vygotsky, 1986). The sociocultural tradition places human cognition in a historical and situated perspective. Cognition is conceived as a problem of how people use tools – physical as well as conceptual/discursive. This is as much an interactive process as an individual one; in fact, it is very much in the middle as joint and mediated action. And even when reasoning on their own, people do not do this in social isolation - human action is always situated. An important assumption is that such cultural tools form an integrated part of cognitive processes. There is no sense, following such perspectives, in assuming that there is a level of thinking that is "pure" and that underlies reasoning in human practices. We cannot separate thought processes, say in the context of doing geometry or playing chess, from the conceptual tools that are applicable to such activities. Thinking is the use of tools. Or, as Wittgenstein so suggestively put it in the context of the use of language; "When I think in language, there aren't 'meanings' going through my mind in addition to the verbal expressions: the language is itself the vehicle of thought" (Wittgenstein, 1953, § 329).

Although it would be tempting to create syntheses between traditions, our preference is to keep them apart. They build on conflicting assumptions regarding the nature of human cognition and action that have a long history in western philosophy, and the difference between them is of a paradigmatic nature that cannot be easily resolved by appealing to empirical data. However, on some issues the critical differences between these traditions should be explored. The particular area that we will be considering in this context is that of learning and conceptual reasoning. In these areas, the views of these traditions differ very clearly, and these differences have apparent implications for how one conceives human learning and conceptual knowledge and also for establishing what is difficult in such activities.

2. STUDYING HUMAN COGNITION

A critical point of departure in any research on human cognition, and one which deserves to be taken seriously, is that the object of inquiry is somewhat elusive. As scholars we are forced to consider that the observations we are attending to in our analyses are symptomatic and have, as it were, an indirect relationship to what we are interested in. Cognitive phenomena can be described at many different levels, for instance, in terms of neural signals and reactions, blood flow in the brain and all the way up to how people reason and interact in complicated everyday situations. The relationships between these levels are complex, to say the least.

Since the object of inquiry is contested and ambiguous, one has to consider how various paradigms construe their studies, design experiments and relate theory to observation. Rather than arguing about thinking and learning in general, one should scrutinise precisely how the empirical studies are carried out in various paradigms in order to establish in what sense the observations can be seen as valid indicators of human thought processes and reasoning. When looking at the area that we shall be exploring – children's understanding of the shape of the earth and certain concepts from elementary astronomy (such as gravitation) – these differences between theoretical traditions are obvious. In the following, we shall give a brief introduction to research in this area from a cognitive psychology and sociocultural perspective, respectively. We do not pretend to cover all the research. Rather, in order to address our main question about how children understand the shape of the earth and some related matters, we will give a brief summary of relevant studies with the ambition of illustrating the clear differences in how children's competences and learning trajectories are portrayed. But before embarking on this presentation, we shall say a few words on the notion of conceptual change.

2.1. Conceptual Change in a Sociocultural Perspective

Central to a sociocultural tradition is the idea of mediation and tool-mediated action (Wertsch, 1991). Language, and its conceptual resources, is the most important tool, and it is also unique to the human species – it is the "tool of tools". Concepts and categories thus mediate the world for us in real world activities, and they are, in fact, basic to our perception, reasoning, remembering, and any kind of cognitive activity. Seeing an object as "a square" or "a circle" relies on, and reproduces, a certain, socioculturally generated, set of categories for describing and thinking about objects. However, concepts are not just mental entities that reside inside our heads, they are part of human social practices. People use concepts to do things in a world of physical and intellectual actions; discourse is an important aspect of practical action. The judge uses the concepts of the legal system such as "intent", "fraud", and "assault" when passing a sentence on a suspect. The construction engineer uses the conceptual tools of mathematics, mechanics and other specialised scientific areas when designing a new engine. Thus, and this is one of Vygotsky's (1986) fundamental insights, concepts (or as he referred to them: psychological or intellectual tools) are used by people when thinking (i.e. intramentally) as well as when communicating with each other (i.e. intermentally); thinking in this perspective is conceived as a kind of silent and private dialogue where people use the conceptual resources of their society for reasoning. In this sense, our thinking is sociohistorically produced as we have already alluded to.

So, how does one conceive conceptual development in such a perspective? When regarding concepts as tools (and not just abstract, internal representations of the world), a critical feature of conceptual development is how people come into contact with various kinds of tools that exist in a society. Concepts are elements of discourses that are used in various practices in society. Everyday reasoning relies on conceptual tools as much as does any other kind of activity. But an important arena for the communication of more specialised kinds of conceptual tools is schooling. It is here that the individual encounters scientific (or, more generally, institutional) forms of reasoning that may not be familiar or widely used outside institutional settings. When learning physics, for instance, we have to familiarise ourselves with new modes of reasoning that build on concepts such as force, velocity, momentum, acceleration and so on that are defined in particular manners. And learning to use these in an insightful manner (which is not the same as being able to define them in a formal sense) can be a long and complicated learning process.

But what, then, is the nature of this process? This is a critical question from a psychological and communicative point of view. Vygotsky (1986) originally suggested that learning and conceptual development could be seen as a process of internalisation by individuals of conceptual tools. However, this is a problematic position, since this formulation somehow recreates a boundary between thinking and communication that Vygotsky was eager to do away with. The point of much of his argumentation is that conceptual tools are used in both these types of human actions, and it therefore seems more fruitful to avoid reintroducing the Cartesian split between "the outside" (communication and physical action) and "the inside" (thinking).

Alternative modes of formulating the processes of conceptual development have been suggested by, for instance, Rogoff (1990) and Wertsch (1998). The traditional preference has been to view learning and conceptual development in terms of appropriation of mediational means. Appropriation, as used here, implies that the individual gradually familiarises herself with a set of conceptual tools and begins to realise how they are used. For instance, Saxe (1991), who studied Brazilian children acting as candy sellers, observed how the young children with a low or no formal education performed complex calculations that involved the awareness not only of proportional relationships between goods and price, but also included consideration of the problems imposed on the activities of selling and buying by hyper-inflation. Appropriation thus implies that the individual is able to reason and act in situations by means of a certain conceptual tool. This does not imply that the tool is appropriated in all its details. This is probably rarely the case. Even if one understands and is able to use the concepts of force or energy when solving physics problems, there are many aspects and potential uses that may take years of further study to appropriate. In a similar vein, the candy-sellers in Saxe's study had not appropriated the concept of inflation in the same sense as an academically trained economist. Yet, in some settings they were able to take this highly complex phenomenon into account in quite a sophisticated manner. In this sense, appropriation implies an increasing familiarity with how a tool can be used for different purposes. Recently, Wertsch (1998) has suggested that it might be useful to make a distinction between appropriation and mastery, a suggestion which is interesting in this context. The latter concept is developed in the context of observations made by the Estonian psychologist Peeter Tulviste (e.g., 1994), who studied the learning of history in Estonia under Soviet rule. In these studies it was shown that the students in school and at universities learned the officially sanctioned explanations and accounts of history and historical development in the Soviet-Marxist tradition without appropriating the conceptual tools or the worldviews these accounts implied. Sometimes the students even mastered these accounts to perfection, but they never used them in any other settings as conceptual tools. So, mastery of a particular kind of tool may be seen as something different from appropriating a tool in order to actively use it. This is a fascinating perspective on human cognition, but we shall not go deeper into this matter here.

There is another layer to this argument about the tool-dependent nature of thinking, which is essential to the research reported here and has to do with conceptual knowledge. In a sociocultural perspective, the intimate relationship between concepts (i.e. intellectual tools) and physical tools (i.e. artefacts) is emphasised (Bliss & Säljö, 1999; Säljö, 1998). Thus, calculators, calendars, computers, instruments for measuring entities such as distance, volume, pressure, etc. are seen as physical embodiments of human conceptual constructions such as number systems, units of measurement and so on. This implies that when reasoning with artefacts, the tool serves as an aid to thinking in the sense that it represents the world in relevant conceptual categories. This is an important aspect of the role that artefacts play as support and prosthetic devices for thinking, which we will come back to below (see also Wyndham & Säljö, 1998). But before going into this, let us review some of the work done on the particular issue of children's understanding of some elementary astronomical and/or geographical concepts.

3. STUDIES OF CHILDREN'S UNDERSTANDING OF THE SHAPE OF THE EARTH AND GRAVITATION: A COGNITIVIST PERSPECTIVE

The interest in studying children's learning and understanding these matters goes back quite some time. In the cognitivist, and Piagetian, tradition a series of empirical studies have examined the nature of the conceptual problems that children have in this area, and the conceptual change that takes place as they develop (Mali & Howe, 1979; Nussbaum, 1979; Nussbaum & Novak, 1976; Sneider & Pulos, 1983; Vosniadou, 1994; Vosniadou & Brewer, 1992, 1994). A major theme of this line of research has been the illustration of the apparent difficulties children have in understanding that the earth is a sphere. These difficulties were clearly outlined in the pioneering studies by Nussbaum and colleagues during the 1970s. Their findings have later been refined and elaborated but are still, by and large, confirmed by more recent studies. Since these early observations, considerable effort has been put into describing in detail the different constructs children hold (see below), and the transitions in conceptual understanding that take place during ontogenesis. Vosniadou and Brewer (1992), two of the recent leading specialists in this area, suggest that the reason for the problems children have is that information about the shape of the earth contradicts the child's basic ontological presuppositions. That is, the scientifically appropriate model is contradictory to the beliefs held by the children, beliefs based on years of convincing everyday experiences. According to Vosniadou (1994) these experiences form the foundation of our knowledge base. A revision of this base is not easily achieved, and, when this happens, it will have profound implications for subsequent knowledge structures.

UNDERSTANDING CONCEPTUAL CHANGE: A COMMENTARY

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Abstract In this essay, I compare and contrast four views of conceptual change--Vosniadou's *synthetic meaning* view, Chi and Roscoe's *misconception repair* view, diSessa's *knowledge-in-pieces* view, and Ivarsson, Schoultz, and Säljö's *sociocultural* view. In particular, I compare these four views in terms of what changes during conceptual change, who changes, how the change occurs, where the change takes place, the role of prior knowledge, and whether their is research evidence. As a conclusion, I offer a proposal for reconciling alternative views of conceptual change.

1. INTRODUCTION

How does a learner come to understand how force and motion work, how the human respiratory system works, or how gravity keeps objects on the earth? In each case, the learner undergoes a process of conceptual change in which he or she builds a coherent mental representation capable of explaining the target phenomenon.

Conceptual change is the mechanism underlying meaningful learning. Conceptual change occurs when a learner moves from not understanding how something works to understanding it. For decades scholars have recognized that conceptual change is at the heart of meaningful learning. Over the years, conceptual change has been represented as a process of achieving structural insight, accommodative learning, understanding of relations, deep learning, or--more recently--mental model building (Mayer, 2000).

Conceptual change has long been recognized as a fundamental aspect of science learning, and as a key process in learning in other domains. If scholars could understand how conceptual change works they would make important contributions both to learning theory and to educational practice. Throughout the first half of the 20th century researchers sought to build general theories of learning that could account for all forms of learning, but by mid-century it became clear that such efforts had failed (Mayer, 2001). Instead, today scholars focus on domain-specific theories of learning, such as trying to understand how people learn how something works or how to carry out a given procedure. Gone are the days when grand theories of learning dominated psychology and education, replaced today with more focused

M. Limón & L. Mason (Eds.), *Reconsidering Conceptual Change. Issues in Theory and Practice*, 101-111.

4. DISESSA'S KNOWLEDGE-IN-PIECES VIEW OF CONCEPTUAL CHANGE: CHANGE AS ORGANIZING

What changes? In diSessa's view--expressed in his chapter and elsewhere (diSessa, 2001)--the learner organizes many fragments of naive knowledge into a structured mental representation of complex system. Learning involves the construction of what diSessa calls a *complex knowledge system* (or *conceptual ecology*) consisting of a large number of different kinds of conceptual elements that are modified and combined in complex ways such as levels and subsystems. What changes, then, is the way that knowledge is organized--from fragmented to structured.

Who changes? Learners are knowledge organizers who strive to build connections among the diverse elements in their knowledge base.

How does change occur? The process of conceptual change relies on mentally reorganizing one's knowledge: "Conceptual change involves a large number of diverse kinds of knowledge organized and re-organized into complex systems." Learners begin with intuitive knowledge called *p-prims* (for *phenomenological primitives*)--small, simple, plentiful, natural-feeling pieces of knowledge used to help understand one's experience. For example, in intuitive physics, a p-prim is the idea that "induced motion just dies away", that is, an object in motion requires a force acting on it to stay in motion. However, in the course of conceptual change, p-prims are integrated into more complex explanatory systems. P-prims no longer function as isolated monolithic explanations but rather become part of a larger system. DiSessa notes that "many p-prims find useful places in the complex system" and might "come to be known as an effective special case of a scientific principle." Thus, the mechanism underlying conceptual change is not a simple process of deletion or replacement of p-prims, as in contrasting views of conceptual change, but rather a complex process of integration and reorganization.

Where does change occur? Conceptual change is a cognitive process that occurs in the learner's mind.

What is the role of prior knowledge in conceptual change? Prior knowledge--such as p-prims--form the basis for conceptual change. Prior knowledge enables conceptual change because conceptual change involves organizing existing pieces of knowledge.

Is there research evidence? The supporting empirical evidence for diSessa's argument comes from selected segments of the protocol of a structured clinical interview about physics problems with one child called J. However, diSessa correctly warns that "I don't intend to prove or demonstrate here."

5. IVARSSON, SCHOULTZ, AND SÄLJÖ'S SOCIOCULTURAL VIEW OF CONCEPTUAL CHANGE: CHANGE AS TOOL APPROPRIATION

What changes? In conceptual change, learners appropriate intellectual tools (i.e., agreed-upon concepts such as the concept of gravity) and physical tools (i.e., agreed-upon representations such as maps and globes). The authors claim that cognition is the use of tools, so conceptual change involves the development of tool-and modest theories of learning. The search for a research-based theory of conceptual change represents a major component in this focused strategy.

My assignment in this piece is to compare and contrast four views of conceptual change: Vosniadou's (this volume) *synthetic meaning* view, Chi and Roscoe's (this volume) *misconception repair* view, diSessa's (this volume) *knowledge-in-pieces* view, and Ivarsson, Schoultz, and Säljö's (this volume) *sociocultural* view. In each of four respective sections, I analyze the views in terms of what changes during conceptual change, who changes, how the change occurs, where the change takes place, the role of prior knowledge, and whether their is research evidence. Finally, in the last section, I attempt to synthesize a vision of conceptual change based on the ideas in these four views.

2. VOSNIADOU'S SYNTHETIC MEANING VIEW OF CONCEPTUAL CHANGE: CHANGE AS SYNTHESIS

What changes? In Vosniadou's theory, the learner seeks to builds a coherent explanatory framework (or mental model) of how some system works. In short, what changes is the learner's mental model.

Who changes? In Vosniadou's theory, learners are synthesizers who attempt to reconcile inconsistent models of how something works. The learner is a model builder who creates conflict by acquiring inconsistent new knowledge but who seeks to build internally consistent models.

How does change occur? Learners build a mental model by integrating new material from science instruction with their existing explanatory frameworks: "Information received through instruction seems to become assimilated to the initial explanatory framework creating synthetic or internally inconsistent models." Conceptual change begins with the learner's existing explanatory framework, that is, a naive theory of how something works based on personal experience: "Children construct a narrow but coherent explanatory framework that guides the process of acquiring knowledge about the physical world from early on." The next step in conceptual change occurs when learners are exposed to science instruction that is inconsistent with their existing mental representations; as they assimilate this new knowledge with existing mental representations they form synthetic meanings that lack coherence and stability. The final step is to resolve the internal inconsistencies, so "conceptual change occurs from the need to solve internal inconsistencies." This process of resolving internal inconsistencies in the learner's knowledge is a gradual one which can result in a progression of mental models. Rather than involving sudden replacement of misconceptions, conceptual change involves assimilating new scientific knowledge to existing explanatory frameworks, thereby creating internal inconsistencies that must be gradually reconciled. Rather than involving the process of organizing isolated knowledge fragments, conceptual change is a process of assimilating knowledge to existing structures, which must then be reorganized.

Where does change occur? Vosniadou presents a cognitive account of conceptual change in which the changes occur within the learner's mind.

What is role of prior knowledge in conceptual change? In Vosniadou's view of conceptual change, prior knowledge is both an obstacle for change--because it must be revised--and a vehicle for change--because new conflicting knowledge is assimilated to it.

Is there research evidence? In an exemplary study, kindergarteners, 4th graders, 6th graders, and 9th graders were asked in an interview to answer a series of questions about force. For example, in one question they were shown a drawing of a stone standing on the ground and asked, "Is there a force exerted on the stone? Why?" For most of the students, it was possible to classify their answers as consistent with one out of a small number of mental models of force. The most common model for kindergarteners was *internal force*, the idea that objects have internal force based on their weight or size. The internal force model is an example of an initial explanatory framework based on personal experience. The most common model for 4th graders was *internal and acquired force*, the idea that objects have internal force based on their weight or size, but there is also an acquired force within moving objects only. There is an internal inconsistency in the synthetic meaning of combining internal force and acquired force. The most common model for 6th graders was *acquired force*, the idea that there is an acquired force within moving objects only. The reliance on acquired force, which is another explanatory framework, can be seen as an attempt to resolve the inconsistency inherent in the internal and acquired force model. The most common model for 9th graders was *gravitational and other forces*, the idea that forces in objects come from gravity, from being pushed or pulled, and from moving. Students appear to be assimilating Newtonian concepts within their existing framework based on acquired force. By adding the force of gravity and the force of push/pull to the force of movement, learners create various synthetic meanings that eventually need to be resolved.

3. CHI AND ROSCOE'S MISCONCEPTION REPAIR VIEW OF CONCEPTUAL CHANGE: CHANGE AS REPLACEMENT

What changes? In Chi and Roscoe's view, the learner seeks to construct an accurate mental model of how something works. When mental models initially are based on incorrect conceptions (as in *naive knowledge*), these conceptions must be replaced: "All naive knowledge needs to be repaired in order to promote deep understanding." Thus, what changes is the learner's mental model and the conceptions from which it is built. In particular, a misconception is defined as a miscategorized concept, so what changes is the placement of a concept from an incorrect category to a correct category. The resulting mental model changes from being flawed to being correct.

Who changes? Learners are fixers who repair erroneous conceptions in their mental models. Learners engage in the repair process by recognizing misconceptions (i.e., miscategorized concepts) and creating or finding new categories into which the miscategorized concepts can be placed.

How does change occur? Conceptual change occurs when a learner identifies a faulty conception in his or her mental model, and repairs it. Learners begin with naive knowledge--or existing conceptions--that are often incorrect. Naive knowledge can consistent of *preconceptions*, which easily can be revised or removed through instruction, and *misconceptions*, which are misunderstandings that persist even when confronted with focused instruction. In short, "cognitive change is the process of removing misconceptions." The mechanism by which misconceptions are repaired involves recategorizating a concept from an incorrect category to a correct category: "Misconceptions are, in fact, miscategorizations of concepts" so "conceptual change is merely a process of reassigning or shifting a miscategorized concept from one ... category to another." To accomplish conceptual change, learners must become aware that they have miscategorized a concept and must invent or find an appropriate category to which it can be reassigned. Conceptual change means to change from a flawed (or incomplete) mental model to a correct mental model through assimilation (i.e., adding new pieces of knowledge) and revision (i.e., correcting pieces of knowledge). This is an incremental process--of changing many small pieces of knowledge--rather than a process of sudden accommodation.

Where does change occur? Conceptual change is a cognitive process that occurs within the learner's mind.

What is the role of prior knowledge in conceptual change? Prior knowledge--when it contains misconceptions--is an obstacle to conceptual change: "Naive knowledge ...often (but not always) impedes the learning of formal knowledge with deep understanding."

Is there research evidence? First, Chi and Roscoe describe previous research on 8th graders' preconceptions about how the human circulatory system works (Chi, 2000). Based on in-depth interviews, a collection of incorrect conceptions was identified (such as "all blood vessels have valves"). Then, students read a text about the human circulatory system and were interviewed again as a post-test. Many of the preconceptions that were addressed in the text were correctly revised on the post-test (such as "veins are the only vessels to have valves"), but those not addressed in the text were not correctly revised on the post-test. This research shows that some incorrect conceptions can be changed easily through instruction--namely, preconceptions.

The authors also describe a more recent study in which students read a text about the human circulatory system and explain to themselves what various sentences mean. Interviews with students show that the self-explanation process fosters incremental revisions of individual propositions about how the human circulatory system works, enabling students to change from a single loop model (in which only the heart is involved in pumping oxygen to the body) to a double-loop model (in which the lungs and heart are involved). This research shows that what appears to be a major conceptual change (from a single-loop to double-loop model) can be created by repairing individual pieces of knowledge about the circulatory system.