THE PROCESSES AND CHALLENGES OF CONCEPTUAL CHANGE

MICHELENE T. H. CHI & ROD D. ROSCOE

Learning Research and Development Center, University of Pittsburgh, USA

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)

M. Limón & L. Mason (Eds.), *Reconsidering Conceptual Change. Issues in Theory and Practice*, 3-27.

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 (8^{th} 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.

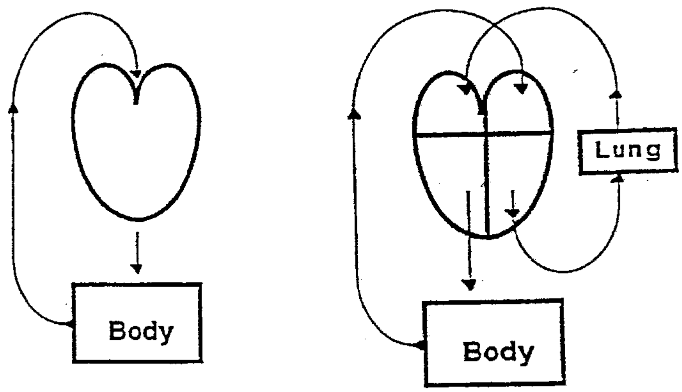
A coherent model can be correct or flawed. By "flawed" we mean a mental model whose coherent structure is organized around a set of beliefs or a principle that is incorrect. Note that this level of "correctness" is distinct from the correctness of individual propositions. A flawed mental model may share 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.

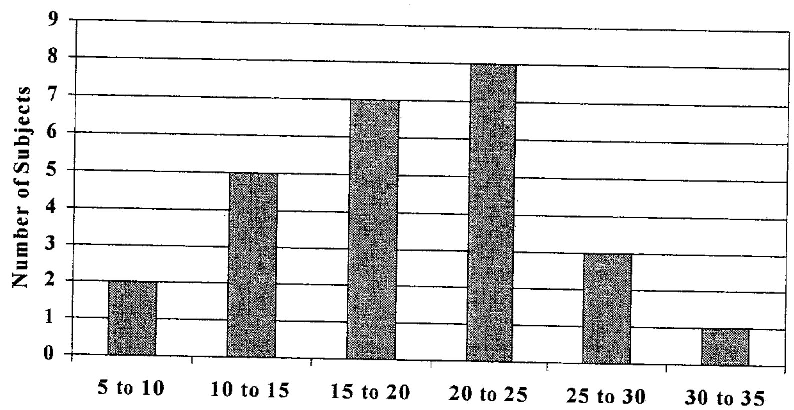


Assumptions	**Single Loop**	**Double Loop**
Source of oxygen	Heart	Lungs
Purpose of lungs	Destination of oxygen	Site of O_2 - CO_2 exchange
Number of loops	One	Two

Figure 1. Differences in the assumptions between a flawed single loop mental model and the correct double loop model

In addition to the factors of coherence and correctness, one can also consider completeness. A complete mental model has a majority of the key propositions. An incomplete model has many missing pieces. Completeness, however, is somewhat orthogonal to either coherence or correctness. Specifically, students may possess a very complete, but flawed mental model, or possess a basically correct model, but with sparse details. For example, a student may have a great deal of knowledge about the human circulatory system, organized according to the incorrect, single-loop principle. In contrast, a student might understand that the system is a double-loop, but not know how it works or the exact function of every component.

This is clearly shown when one looks at the variability in the number of correct propositions that students with a single-loop model hold. In data collected by Jeong (1998), but not reported, we coded students' prior conceptions at both the proposition and mental model level. Figure 2 shows the distribution of the number of correct propositions that students knew (either at the pre-test or at the post-test). The figure shows that there is a range of correct propositions that students knew, even though they all basically organized their propositions into a single loop model. For example, 5 students expressed between 10 and 15 correct propositions, and 3 students expressed 25-30 correct propositions. This figure shows that although some students may have more correct beliefs than others, they all share the same assumptions about the role of the heart and blood flow to the lungs consistent with the flawed understanding of a single loop model. Thus, mental models may not differ in terms of the number of correct propositions, but in how these beliefs cohere.



Data of 22 subjects from the pretest, 4 subjects from the post-test, taken from Jeong (1998).

Figure 2. No. of correct propositions per single loop model

As Figure 2 shows, a flawed mental model obviously is composed of many correct beliefs as well as incorrect and alternative beliefs. From the analysis presented earlier, we have shown that these preconceptions can be readily removed, at the piecemeal level, if they were addressed; and there does not appear to be any false beliefs or misconceptions for this domain, of the human circulatory system. Therefore, it follows, by definition, that no conceptual change is necessary to achieve the correct mental model. If not conceptual change, then what kind of learning processes can achieve this repair of a flawed mental model?

At least two "ordinary" learning processes can be proposed as mechanisms that can remove incorrect beliefs and repair flawed mental models. These two processes, "assimilation" and "revision," can result in significantly richer and more accurate knowledge about a domain. In the case of learning about the human circulatory system, these mechanisms seem to very adequately explain how students with an initial single-loop model develop the correct double-loop model through instruction in the following way (Chi, 2000). Suppose we assume that learning is the sequential encoding of propositions (sentences). Each new piece of information presented to the student can be considered either compatible with his or her existing knowledge or contradictory. Sentences that are compatible provide information that is consistent with the student's existing beliefs and consistent with student's mental model. If an incoming proposition is compatible, then learning consists of simply embedding this new information into the existing mental model. This process is called assimilation.

Assimilation can occur regardless of whether the student's mental model is correct or flawed. As long as the statement does not contradict what the student currently believes, it can be understood (or misunderstood) in the context of the existing knowledge structure. For example, consider the text sentence, "Pulmonary circulation is the movement of blood from the heart to the lungs and back to the heart." A student with a correct, double-loop model would understand this sentence as a description of the pulmonary loop of circulation. However, a student with an incorrect, single-loop model would interpret this sentence to mean "blood travels to the lungs to deliver oxygen, as it does to many organs." In both cases, the new information is assimilated. However, in the case of the initially flawed mental model, such assimilation would perpetuate its flawness. A similar case occurred in Vosniadou and Brewer's (1992) data. Children who possessed a flat, disk-earth model (pancake shape) understood and assimilated the statement "the earth is round like a globe" by interpreting it to mean that the flat disk is situated inside of the globe or on top of it. Thus, assimilation alone cannot repair mental models, although it can enrich them.

An incoming sentence can also contradict or refute what the student already knows. Suppose that a student originally thought "Systemic circulation is the movement of blood from the heart to the lungs back to the heart" (this is actually pulmonary circulation). The text sentence given above directly contradicts this belief. Upon reading such a contradiction, the student could simply revise his or her incorrect belief, as the results of the de Leeuw (1993) study showed. This process is called revision.

Taken together, the accumulation of assimilation and revision processes could lead to a major change in the students' understanding of a system of knowledge. Chi's (2000b) analysis detailed how the incremental accumulations of assimilations and revisions of individual propositions allowed a student to achieve the correct, double-loop model from a single-loop model. This repair of the mental model appears to be an example of "accommodation", a term used in the literature broadly to mean changes in the structure of a mental representation, as opposed to assimilation, in which the mental structure remains unchanged. But such mental model restructuring can evolve from the incremental buildup of ordinary learning processes occurring at the prepositional level, and not from conceptual change processes. Thus, one can achieve a major re-organization by repairing a flawed mental model with ordinary learning processes. No radical conceptual change was necessary since individual beliefs were readily removed and revised.

3. MISCONCEPTIONS AT THE "DOMAIN THEORY" LEVEL AND THEORY CHANGE

Some researchers prefer to represent initial knowledge at the level of the domain or discipline. These terms usually refer to a large body of knowledge corresponding to some field of science, such as biology, psychology (Carey, 1985), or mechanics (McCloskey, 1983). At this level, it seems natural to analogize naïve conceptions to naïve theories and thus to analogize conceptual change to theory change. However, to make this analogy work, one must first demonstrate how students' naïve knowledge is "theory-like" and what is theory change.

3.1. *Naïve Domain Theories*

The first problem of determining whether students' naive knowledge is theory-like is typically handled in one of two ways. The first method is to demonstrate how naïve conceptions share fundamental assumptions with well-known medieval theories. For example, McCloskey (1983) argued that students' naïve understanding of mechanical motion and the medieval "impetus theory" both assume that 1) an object set in motion acquires an internal force (impetus) and that this internal force is responsible for the object's motion, and 2) a moving object's impetus gradually dissipates (either spontaneously or as the result of external forces) causing it to gradually slow down and come to rest. This is the same approach we used to show that all single-loop models are basically similar because they share the same three basic assumptions (as shown in Figure 1).

The second means of showing naïve knowledge to be theory-like is done by capturing regularities in naïve conceptions, and determining any underlying guiding principles or laws (Viennot, 1979). This is also an acceptable way to determine that a set of beliefs is theory-like since it draws upon the nomological sense of a theory, in which laws play a significant role (Hempel, 1966) and explanations are deductively closed. In sum, determining that naive knowledge is theory-like does not pose an insurmountable challenge.

3.2. *Theory Change and Incommensurability*

A second more serious problem arises with the naïve theory analogy: How do we define theory change? Some researchers have argued that we can determine the process of theory change by looking at theory shifts in scientific revolutions (Carey, 1985; Posner, et al., 1982). Carey (1985) has done this by appealing to the "incommensurability" of certain concepts in science, and to the processes of differentiation and coalescence. Incommensurability is defined as irresolvable "differences" in the concepts, beliefs (or propositions), and explanations of the theories, as well the phenomena the theories explain. In other words, misconceived concepts may differ from the correct understanding in the sense that they are incommensurable. The problem with such a definition is that it is difficult to define "different" without being circular: Are concepts incommensurate because they participate in incommensurable theories, or are two theories incommensurable because their concepts are incommensurate? The issue boils down into figuring out how we can decide that two concepts or theories are incommensurate.

According to Carey (1991), concepts are incommensurate if they can be defined in the context of three processes: "replacement," "differentiation," and "coalescence." First, an initial concept can be replaced by an alternative concept. This does not mean, necessarily, that a correct belief replaces an incorrect belief. Rather, the two beliefs are so fundamentally different (i.e. are incommensurable) that acceptance of one belief precludes the existence of the other, and thus overwrites it. Differentiation is another replacement process, but also involves the splitting of the initial concept into two or more new concepts, which may be incommensurate to the initial concept or to each other. These new concepts take the place of the original. Coalescence is the opposite process: two or more original concepts are collapsed into a single concept that replaces the originals. Note that these replacement processes differ from cases of differentiation and coalescence *without* replacement. That is, a single concept, such as *dog*, may be differentiated into breeds such as *collie* or *terrier*. The concept of *dog* remains as a superordinate, however. Similarly, a child might originally see collies and terriers as two different types of animals. Later, these two concepts are coalesced into the concept of *dog*, but the original concepts remain.

To validate that differentiation and coalescence with replacement are processes of conceptual change involving incommensurate concepts, several examples of these replacement processes have been drawn from the history of science. In one case, the concept of *phlogiston* was replaced by the concept of *oxygen* in later theories of combustion. The interpretation is that theories relying on the concept of *phlogiston* cannot explain or handle the same phenomena that can be addressed by a theory based on *oxygen*. Similarly, a favorite example of differentiation is the replacement of the concept *degree of heat* with the modern concepts of *heat* and *temperature*. These new concepts are not subordinates to the original, but replacements (Wiser & Carey, 1983). An example of coalescence can be seen with Galileo's treatment of the concepts of *violent motion* and *natural motion*. He argued that there was no meaningful difference between the two concepts, and collapsed them into a single concept.

There are a couple of problems with the notions of incommensurability and replacement as they are described above. First, although one can identify any number of examples of change in the history of science, such historical examples as given above do not clearly specify *how* two concepts or theories are incommensurable, only *whether* they are incommensurate because they have been replaced. Such hindsight however, fails to explicate how the concepts are fundamentally different in the first place. Moreover, it is not clear whether replacement processes are conceptual change processes, or whether they are the outcome of reorganization, resulting from processes such as assimilation and revision, much as the way a double loop model replaces a single loop model (Chi, 2000).

In sum, without the hindsight of history, how can we tell that two theories are radically different or not? How do we identify conceptual changes that are occurring now, or need to occur (in terms of students' misconceptions)? For example, in contemporary science, the cause of heart disease has been traditionally attributed to the deposit of plaques. A more recent theory has suggested that it is the depositing of a mineral, iron, that may cause heart disease. It has also been proposed, very recently, that heart disease may be caused by bacterial infection and resulting inflammation. How can we determine if these shifts in thinking are radical or not without looking ahead one hundred years? Note that these alternate conceptions are *co-existing* – although they may eventually replace one another, differentiate, or coalesce at some point, but at the present they are competing theories. With a clearer definition of incommensurability, we could presumably predict which new theory is a radically different one and has the promise of revolutionizing the treatment of heart disease.

3.3. Misconceptions at the Ontological Category Level and Conceptual Change

Concepts, as defined by cognitive psychologists, are intricately linked with the notion of categories. Simply put, one can represent, understand, and interpret concepts in the context of their category membership. This means that once a concept is assigned to a given category, then that concept inherits all the features of that category. From this perspective, misconceptions can be viewed as instances of miscategorization, not hierarchically, but laterally. More specifically, misconceptions may involve the assignment of a concept to the wrong *ontological* category.

What are hierarchical categories and lateral categories? A concept, such as *cobra*, can be embedded in a subordinate category of *poisonous snakes*, which would also include concepts like *rattlesnake* or *adders*. *Cobra* may also be considered a member of the basic level category of *snakes*. Likewise, it is also a member of the superordinate category of *reptiles*. All three categories also belong to a more superordinate category called *living things*. Thus, these categories, *cobra, poisonous snakes, snakes,* and *living things*, are hierarchically-related. This type of hierarchically-related categories have been the major focus of research on categorization in cognitive psychology. Misclassification of a concept into a hierarchically-related category would not constitute a misconception.

Besides hierarchical relationships, however, one can also consider the lateral relationships among categories. Lateral categories are those that do not participate in any hierarchical relationship to one another. That is, neither category is a "parent," "grandparent," etc. to the other. Some lateral categories are "siblings" in the sense that they share a parent category. For example, *cobra* and *rattlesnake* are siblings sharing the parent concept of *poisonous snakes*. Some lateral categories are "cousins" in the sense that they share only a grandparent or higher superordinate category in the hierarchy (but not a parent category). For example, *snakes* and *chairs* are lateral categories (one is a *natural kind* and the other is a *man-made artifact*) but are only related at a higher level, perhaps at the superordinate category of *concrete things*. There are also concepts that do not share a category even at the highest levels, such as *substances* and *processes*. We say that such concepts exist on different or distinct hierarchies or "trees" (Chi, 1997).

We consider lateral categories, especially those that exist on different trees, to be "ontologically distinct." This distinction can be determined through the use of a predicate test (Keil, 1979; Sommers, 1971). This test consists of a number of sentences constructed so that either a compatible or incompatible statement modifies a given concept. Students make judgments about whether these sentences are valid (are plausible or make sense) or are invalid (are impossible or anomalous). For example, a concept belonging to the category of *concrete objects* such as *dog* or *chair*), cannot be modified sensibly by a predicate of the lateral category of *processes*. In other words, one cannot say that "The dog is an hour long" – students will judge such sentences to be invalid. On the other hand, one could accept a sentence such as "The dog is green" even though that is a very unlikely color for dogs. This is because "green" is an attribute or predicate that concrete objects can possess (color), whereas "an hour long" is a predicate that processes can possess (duration). Consider the opposite example of melting ice. The process of melting has a duration (a few minutes), but could not have a color (i.e. green).

To return to the topic of misconceptions and miscategorization, we consider a misconception to be a concept that has been miscategorized into an ontologically distinct category. Imagine that a learner assigned the concept of *electricity* to the category of *substances* rather than the lateral category of *processes*[11]. For these students, it would make sense to say that *electricity is "stored" in a battery,* the same way other substances are stored in boxes or cans. These students also understand the current of electricity flowing through a wire as an actual "flow," analogous to a liquid substance (e.g. water) moving through a pipe under pressure. This is why students would also say that *electricity "leaks" out of the battery.* Ignoring the fact that this analogy (electricity as water) is a common instructional tool, the point is that these students' difficulties in understanding electricity at a deep level, their misconceptions, stem from the miscategorization of the concept of *electricity*.

This miscategorization can be determined by the predicates that they use to describe the concept. Thus, using predicates such as "stores" and "leaks" confirm that the students conceive of electricity from the category of *substances* (Slotta, Chi, & Joram, 1995). In order to gain a formally correct understanding of "electricity", students must reassign the concept to its correct *process* category. This is not to say that once this shift is made that students will immediately and deeply understand electricity, merely that a key obstacle will have been removed. But it does allow the concept to inherit the proper categorical features, and provides the correct context (or the appropriate categorical perspective) from which ordinary learning processes can incrementally build a correct understanding.

One can immediately appreciate the simplicity and power of the ontological categorization view of misconceptions and conceptual change. This perspective provides a clear definition of what misconceptions are (miscategorization), suggests a simple process for conceptual change (reassignment, or shift), and a rule for what constitutes conceptual change (crossing ontological boundaries). We will take this

---

[1] *Misconceptions about electricity are actually much more complex than just a single miscategorization. There are several miscategorizations at work, and even the term "electricity" is broadly misapplied. For simplicity's sake, we will leave our simplification intact.*

opportunity to look back at the other perspectives and show how this view can resolve certain ambiguities.

4. ADDRESSING UNRESOLVED ISSUES

4.1. Old Questions

Recall that the issue was raised with respect to why misconceptions (or false beliefs) were not manifested in the case of the human circulatory system, so that a change from a single-loop model to a double-loop model did not constitute conceptual change. We now see that the reason is that the majority of the concepts underlying the beliefs of the circulatory system (such as the concepts of blood, valves, heart) were the same for both the single loop and the double loop models, therefore no ontological boundaries were crossed. Moreover, even at the mental model level, the two organizing set of beliefs "the circulatory system is a single-loop system" and "the circulatory system is a double-loop system" exist in the same ontology. Thus, because no misconceptions existed, the accommodation or reorganization that occurs can be accounted for by the incremental accumulation of assimilations and revisions, processes that are distinct and different from the process of conceptual change.

The domain theory perspective also left us with unanswered questions, even though we agree with the notion of incommensurability taken from examples in the history of sciences. Specifically, we had no way of determining if two concepts were incommensurate, and thus whether any of the replacement processes had resulted from conceptual change or conceptual reorganization. The issue of incommensurability is partially resolved if one considers conceptual differences in terms of ontological categories. Simply put, two concepts may be incommensurable if they exist in separate ontological (lateral) categories (or especially, different ontological trees). Such incommensurability can be determined using the predicate test described above. Concepts or beliefs for which few or no shared predicates can be found can be said to be incommensurate. Concepts with a high degree of overlap are not incommensurate. Unresolved issues of course remain, concerning the degree of overlap necessarily needed in order to consider two concepts (and their respective categories) as no longer ontologically distinct.

This definition allows us to address the question of whether the replacement processes in the history of science resulted from conceptual change or conceptual reorganization mechanisms. In the case of replacement, if the new concept is ontologically distinct from the original, then conceptual change has occurred. If the new concept is within the same ontology, then conceptual reorganization has occurred. Similarly for differentiation and coalescence, conceptual change has occurred if the original concepts are ontologically distinct from each other, the new concepts are distinct from each other, or the original concept(s) are distinct from the new. Thus, replacement processes may not be conceptual change processes per se, but may lead to, or result from, conceptual change. Using such a definition does allow us to make predictions. For example, if we consider the germ theory of heart disease to be an ontologically distinct perspective (germs being a kind of *living thing*) from both the plaques and the iron deposit perpective (plaques and iron are *non-living things*), then presumably the germ theory perspective might give us radically new insights that are not predictable from the plaques and iron deposit perspective.

4.2. *A New Question*

One question arises from the discussion of incommensurability and ontological categories: Are all lateral categories incommensurate, or only those that are more "distantly related" or on different ontological trees? For example, *artifacts* and *natural kinds* are not hierarchically related to each other, and thus can be considered ontologically distinct. One can also identify a predicate (whether the object can be "built" or "made") that discriminates between the two. This assumption is consistent with theories about these two concepts in the literature (e.g. Gelman, 1988; Sommers, 1971). However, although these concepts are ontologically distinct, are they incommensurate?

One could suggest that incommensurable categories and concepts would share no predicates, and commensurate categories would share many. This doesn't appear to be true for all cases, however. For example, *artifacts* and *natural kinds* can be discriminated by the predicates of "made," and possibly "discovered," but not by "duration," "color", or "emotion." How many distinguishing predicates must there be to label two concepts as "incommensurate?" Should there even be a cut-off point, or does incommensurability lie on a continuum? These remaining questions are beyond the scope of this chapter and require much research. For the time being, we can assume that certain categories (and their respective sub-categories) that are useful for thinking about science concepts, appear to be reliably incommensurate: *static* vs. *dynamic*, *substances* vs. *processes* vs. *mental states*, *time* vs. *space*, *linear systems* vs. *dynamic systems*, and so on (see also Chi, 1997).

4.3. *The Process of Conceptual Change*

In our discussion of ontological categories, we suggested an uncomplicated mechanism, "reassignment" or "conceptual shifting," as the main process of conceptual change. Other types of reconceptualization, or shifts *within* ontological categories, are considered examples of conceptual reorganization. We now elaborate on this reassignment process and begin to discuss why this process is difficult.

4.3.1. *Conceptual Shift*

In this chapter, we propose the mechanism of conceptual change to be the process of shifting across ontological categories. This process itself is straightforward, comparable to linking or associating a concept with another category. The same learning mechanism applies to all such shifts, regardless of whether the reassignment occurs across relatively similar categories (such as shifting the concept *whale* from the category of *fish* to *mammals*) or categories that are on different ontological trees (such shifting *electricity* from the *substance* category to the *process* category). Thus, this shift itself is a fundamental learning process, comparable to the process of linking or integrating new ideas with old, and can be applied to the learning of all concepts.

The proposed process is somewhat analogous to two conceptual change processes proposed by Thagard (1990), called "branch jumping" and "tree switching." In branch-jumping, one shifts a concept "from one branch of a hierarchical tree to another." Tree-switching involves "changing the organizing principle" of a class of concepts (Thagard, 1990, see Table 3.1). There terms sound superficially similar to our definition of conceptual change. However, Thagard (1996) primarily used the condition of replacement and/or abandonment as a criterion of conceptual change. For instance, an example of tree switching is one in which the concept of diseases was reconceptualized in terms of its causes to its symptoms. Without implicating the role of ontologies or ontological trees, such reorganization, resulting in the replacement of one organizing principle (causes of diseases) by another organizing principles (symptoms of diseases), may not require conceptual change, much as the replacement of a single loop model by a double loop model, which also requires changing the organizing principle only.

Note that the *fish-to-mammal* shift of *whales* and the *substance-to-process* shift of *electricity* are both considered here to be examples of conceptual change by our definition. Earlier, these two were distinguished because one seems easy, and can be addressed through simple instruction (whales) and one seemed robustly resistant to instruction (electricity). The first case was thought to be a simple preconception, whereas the robust case was given as an example of a misconception. In some sense, this distinction no longer applies because both cases are "misconceived" in the same manner – they are miscategorizations. However, this doesn't change the fact that one seems harder to repair than the other, which we will address shortly.

4.3.2. *Re-representation, or Perspective Shift*

Before we discuss the issue of difficulty, we must make it clear that not all "shift" processes are conceptual change. In other words, not all types of shift involve the reassignment of a concept. One example of such a process is "re-representation." This term has sometimes been used synonymously with conceptual change or conceptual shift, but according to the definition presented in this chapter, it is a distinctly different mechanism.

Suppose we ask students to solve the following two "insight" problems:

> 1. A man who lived in a small town married twenty different women in that town. All are still living and he never divorced a single one of them. Yet, he broke no laws. How can you explain this?
>
> 2. Two strings hang from a ceiling. They are hung far enough apart that a person cannot reach both strings at the same time. The goal is to tie the strings together. Lying on a nearby table are a hammer and a saw.

In order to solve the first problem, one has to represent "man" not as a bachelor, but as a clergyman. This does not require that the concept of *man* be reassigned to a new category. Instead, what must be shifted is one's *perspective* – one must emphasize or retrieve a subcategory of *bachelor*. In order to solve the second problem, one must view the hammer not as a "tool," but as a "heavy tool" (a subordinate category). This heavy weight can be tied to one of the strings to create a pendulum. One simply swings the pendulum, grabs the first string, and then catches the other string on its return – again, a shift in perspective. Thus, re-representation clearly consists of a hierarchical (non-ontological) shift, and thus should be considered reorganization rather than conceptual change. Again, our concept of re-representation may be analogous to Thagard's (1996) notion of "branch jumping", which he considered to be conceptual change.

4.4. The Difficulty of Conceptual Change

As we have described above, some naïve conceptions, or misconceptions, seem to be very difficult to revise, while others (preconceptions) respond very readily to instruction. Misconceptions have been proposed to be resistant to repair (i.e. resistant to conceptual change) for a variety of reasons, some of which we have not articulated here but are discussed elsewhere (Chi, 2000a), such as that they involve very hard-to-understand principles and component concepts. In this paper, we have raised additional possibilities, such as that misconceptions are difficult to remove because they are embedded in naive theories, and naïve theories and correct theories are incommensurate, or because shifting across categories is a difficult process. However, we have already stated that the nature of simple misconceptions (e.g. whales) and robust misconceptions is the same (they are miscategorizations), they are repaired through the same simple process (conceptual shift), and that this process is not affected by whether local or distant ontological boundaries are crossed. Thus, it is our claim that the difficulty of conceptual change in many cases does not arise from any of these factors. Instead, we argue that the challenge comes from mainly the fact that students may lack awareness of when they need to shift, and may lack an alternative category to shift into.

4.4.1. Lack of Awareness

In our earlier discussion of mental models, we pointed out that one feature of coherent, flawed models is that students are often unaware that their understanding is incorrect. Because students are able to generate predictable responses to questions and systematic explanations of phenomena, they don't notice that their model is incorrect. This is in contrast to students with fragmented models, in which students are clued-in to their lack of knowledge by the fact that they cannot answer certain questions or generate consistent explanations. A similar situation applies from the perspective of categorization. That is, students may not be aware of their misconceptions if the miscategorized concept can be interpreted in systematic ways.

For example, we described before how students may misclassify the concept *electricity* as a *substance* rather than a *process*. Because of this miscategorization, students believe that electricity can be stored in batteries and moves through a wire like water. Although incorrect, this misconception still allows students to function quite well in day-to-day living. For example, students can explain why batteries are needed to operate electronic toys by saying that the battery provides a source of electricity. Similarly, the electricity-as-water analogy can be used to explain why the lights go out if the wire is broken (i.e. the electricity cannot get to the light bulb). Thus, the ability to make sense of everyday events gives students the feeling that their deeper understanding is correct. They are unaware of a need to shift.

The issue of awareness is easily addressed, in theory. All one would have to do is tell the student that he or she is wrong, and confront them with information and demonstrations that show the student's understanding to be flawed. One can even explain the correct principles to the students. However, in practice, this does not always lead to a more accurate, deeper understanding. As described earlier, one may directly refute or contradict a misconception with little or no effect. The problem is that unless students have an alternate category to reassign the concept to, such instruction will not be effective.

4.4.2. Lack of Alternative Categories

It is this second obstacle that gives rise to much of the "robustness" of misconceptions. Consider two examples of misconceptions, one in which whales are miscategorized as fish, and one in which the process of diffusion is miscategorized as a "causal process" instead of an "emergent process." The first case is easy to repair because students already have a rich understanding, with many examples, of the category of *mammals*. Thus, when an instructor or text says that whales are a type of mammal instead of fish, the student can easily shift their concept into this existing category. However, students typically have a great deal of difficulty understanding diffusion. In fact, less than 2% of high school biology students understand it (Marek, Cowan, & Cavallo, 1986). Even when students are taught about the nature and behavior of molecules, concentration gradients, equilibrium, etc., they still describe the process of diffusion in causal terms, which prevents the understanding of diffusion on a deep level. Our claim (regarding this example, which will be explicated in more detail below) is that students lack a category of *emergent processes*, and thus cannot recategorize diffusion as this type of process. In other words, students cannot repair misconceptions if conceptual shift is not possible. This is what makes certain misconceptions more difficult to repair than others.

5. CONCEPTUAL SHIFT FROM CAUSALITY TO EMERGENCE: A CASE STUDY

In order to more clearly demonstrate the reasons why certain misconceptions are difficult, we will provide an in depth analysis of the diffusion example mentioned above. Note that diffusion is just one example of a large class of science concepts (e.g. electrical current, heat flow, natural selection) that are particularly troublesome for students at the middle- and high-school grades to learn with deep understanding. These concepts will be referred to as "complex, dynamic processes."

5.1. *Complex, Dynamic Processes*

For these concepts, the observed behavior at the perceptual, or macroscopic, level emerges from the behavior of actors/constituents at the molecular, or microscopic, level. In addition, behavior at the two levels is not isomorphic. By behavior, we refer to the actions and interactions of the actors, and the parameters that affect these actions and interactions. Because the "macro" level behavior *emerges from* the non-isomorphic "micro" level behavior, we say that these are "emergent processes."

This is contrast to causal processes, in which the macro and micro levels are isomorphic and behavior at the macro level *is caused by* behavior at the micro level. In general, these emergent process concepts are often misclassified as causal events or processes. This misclassification occurs in part because students lack a category for emergent processes in the first place. This lack also makes the repair of such misconceptions very difficult.

5.2. *Diffusion: Behavior at the Macro (Perceptual) Level*

Suppose we pour a dollop of white cream into a cup of dark brown coffee. As the cream "diffuses" throughout the coffee, it presents the appearance of white cream slowly merging or mixing with the brown coffee. Over time, the cream seems to spread out so that the white and brown liquids are indistinguishable. Thus, at this perceptual level, the behavior consists of 1) actors such as the cream and coffee, 2) actions such as the flow-like blending of the two liquids, 3) parameters that affect the action or rate of flow (e.g. concentration of cream, state of the equilibrium, medium or aperture of flow, etc.). Most textbooks are quite capable of describing the nature of such actors, their actions, and the parameters (including formulas) that govern these concepts.

How can we characterize behavior at the macro level? Our claim is that the characteristics of behavior at the perceptual level are compatible with the features of a causal event or process. There are five such features:

1. *Distinct actions* taken by the different actors – the cream seems to be moving in one direction (towards the coffee), while the coffee appears not to be moving in any specific direction
2. *Sequential actions* – the "flow" of the cream is "from an area of high concentration to low concentration"
3. *Dependent actions* – the flow pattern (such as initiation, duration, direction) seems to be constrained by factors such as initial concentration differences
4. *Termination* – the flow seems to cease after equilibrium is reached, when the coffee and cream are blended

5. *Goal-directed actions, or intentionality* – its as if the cream molecules need or want to move into the area of less concentration

We posit that these five features (also listed in the left-hand column of Table 1), that one can impose or infer from observation of the macro level, constitute the features of a *causal process* category.

5.3. *Diffusion: Behavior at the Micro (Molecular) Level*

At this level, the behavior consists of 1) the individual objects or actors such as molecules[2], 2) the actors' actions (molecules move in all directions randomly), 3) their interactions (collisions between molecules), and 4) parameters that affect the actions and interactions of molecules (molecular size and mass, which affects speed of motion). Note that the behavior at the micro level is distinct from the behavior at the macro level; they are isomorphic.

5.4. *How the Two Levels are Related*

Although it may be difficult for students to untangle the presence of two levels, and the associated behaviors, it is not uncommon for many objects and events to have dual levels with distinct behaviors. For example, students are accustomed to knowing that human skin is made of cells, and that the properties of skin are different from the properties of individual cells. What students don't understand is how the perceptual, macroscopic level behaviors and the molecular, microscopic level behaviors are connected. In diffusion, the question is: how does the flow-like behavior of the macro level *emerge* from the collision behavior of individual molecules?

In order to understand emergence, students must attend not to the *actions* (and attributes) of the micro level actors as a *class* (i.e. how molecules move, their sizes, etc.), but to the *collective interactions of all the molecules*. This means that they must focus on the sum of all interactions of the individual molecules across time. For example, right after the cream is poured into the coffee, both "cream molecules" and "coffee molecules" are bouncing around and colliding with each other. Some of the cream molecules, by chance, might bounce into empty spaces near coffee molecules. Similarly, coffee molecules might bounce into spaces between the cream molecules. Molecules can also move randomly into spaces between molecules of their same type. Perceptually, because there is much less cream than coffee, it appears that the cream is flowing throughout the coffee.

The characteristics of the collective interactions that give rise to the macro level phenomenon are diametrically opposite of those characterizing processes in a *causal process* category. This suggests that emergent process and causal processes are ontologically distinct. In terms of diffusions, we see:

---

[2] *For simplicity's sake, we will talk about "cream molecules" and "coffee molecules", although this obviously incorrect. Both coffee and cream are composed of a number of different substances and molecules, and water is also present.*

1. *Uniform interactions* – all actors interact in the same manner (with random motion and collisions). Coffee and cream molecules do not behave in distinct ways.
2. *Simultaneous interactions* – the actions and interactions are all occurring at the same time, and are not sequential. Both coffee and cream molecules are moving randomly and colliding at the same time.
3. *Independent interactions* – whether or not two molecules collide is independent of whether others collide. In other words, the interactions occurring at one time point do not depend on prior interactions. If a molecule of cream moves into an area occupied by coffee molecules, a later collision could send the cream molecule back towards other cream molecules or towards other coffee molecules.
4. *Continuous interactions* – molecular motion and collisions are occurring at all times, and do not stop. When equilibrium is reached, molecules continue to bounce around, although the cream and coffee appear to have stopped mixing.
5. *Local and decentralized interactions* – the actions of the actors are not directed towards any goal. The coffee and cream molecules don't *have* to mix, or achieve a balance of concentrations, they simply move around and collide randomly.

These features are presented on the right hand column of Table 1 (see also Chi, 1997). We argue that such characteristics capture the features of an *emergent process* category.

Table 1. Features characterizing causal and emergent categories

Actions of a causal category	Interactions of an emergent category
1. Distinct	1. Uniform
2. Sequential	2. Simultaneous
3. Dependent	3. Independent
4. Terminates	4. Continuous
5. Global, goal-directed	5. Local, decentralized

5.5. *Misunderstanding*

Our claim is that students miscategorize emergent processes as causal processes. From this perspective, we offer two reasons why understanding diffusion (and other complex, dynamic processes) is so difficult.

First, the behavior at the macro level, as we have described, is consistent with a causal explanation of diffusion. The molecules of coffee and cream seem to move in different ways, seem to have a goal or purpose, the process of mixing seems to end with equilibrium, and so on. Thus, when asked to explain diffusion, students' causal explanations are correct at the perceptual level. For example, if students were asked, "What caused the cream to spread in the coffee?" they can respond by saying "The difference in concentration or density of cream and coffee makes it spread." Because the students can readily answer such questions, they are not aware that their understanding is flawed. From an educator's point of view, explanations at this level cannot reveal underlying misconceptions.

When this same question is asked at the micro level, however, students give the same basic answer, simply substituting the terms "cream molecules" and "coffee molecules" for "cream" and "coffee," respectively. Thus, they could say, "The cream molecules want to go to the less crowded area of the coffee," which implies both intentionality and unidirectionality. What these students are doing is treating the micro and macro levels as isomorphic, which is consistent with causal processes. These misconceptions are revealed only when students must give an explanation at the micro level[3].

Although students may be told that their explanations are incorrect, the main difficulty in repairing these misconceptions lies in the fact that students do not possess an *emergent process* category. Therefore, they cannot reassign the concept of *diffusion* to its proper category, and the misconception is maintained because they continue to inherit the features of an inappropriate category. To substantiate this "missing category" claim, we turn to preliminary data collected on another complex, dynamic process, "natural selection".

In Ferrari and Chi (1998), we examined explanations given by college students (Study 1) in response to questions about natural selection in evolution. The explanations in each case were coded not only for correctness, but also (and more importantly) whether they appealed to causal or emergent features, as listed earlier. For example, the following explanation was coded as evidence of the "sequential actions" feature in natural selection: "*First*, many trees will die, *and* only a few new trees will adapt to the new climate, and *finally*, a whole new species may evolve." The use of terms like "first" and "finally" clearly indicate a view of natural selection as a sequential process, consistent with a causal view.

Figure 3 shows that students used many more causal attributes than emergent ones. Specifically, 63% of the identifiable features were causal ones and only 8% were emergent. Thus, these results support the argument that students lack a well-defined category for emergent processes, which prevents the recategorization and repair of such misconceptions.

---

[3] *The simplified, correct explanation is that all of the molecules bounce around. At first, the coffee molecules will collide mainly with other coffee molecules, and cream molecules will collide with other cream molecules. At the boundaries between the coffee and the initial dollop of cream, some cream molecules will collide with coffee molecules and vice versa. Over time, such random collisions will result in some cream molecules occupying spaces where coffee molecules were, and vice versa. Thus, the molecules will mix.*

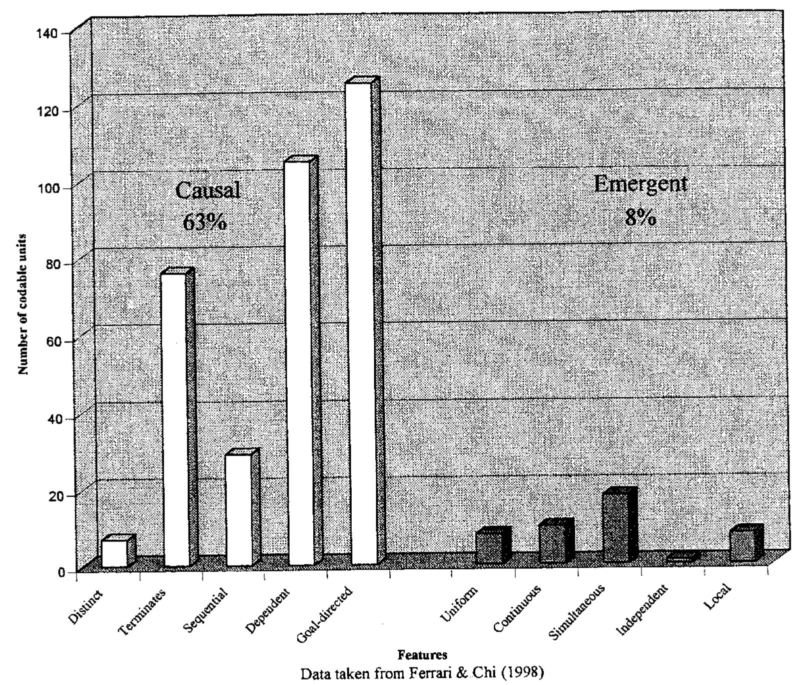


Figure 3. Number of causal and emergent features in explanation of evolution (out of 545 codable units)

6. CONCLUSIONS

In this discussion of conceptual change, we have sought to meet two primary goals. Our first goal was to answer the question of what exactly constitutes conceptual change. Does conceptual change include the accumulation of new knowledge and the revision of mental models? Does conceptual change involve shifts in perspective during problem-solving? Is conceptual change analogous to theory change? Our second goal was to explain why some prior conceptions strongly resist repair through instruction. Do these special cases of naïve knowledge involve concepts that are incommensurate with the correct concepts? Is conceptual change just a very difficult process? As part of addressing these questions, we also examined several different views of naïve knowledge that exist in the literature and how these speak to the issues of process and difficulty in conceptual change.

6.1. *Miscategorization*

We have defined misconceptions as miscategorizations of concepts across ontological categories. In other words, misconceptions are based on the assignment of a given concept, like *whales* or *diffusion*, to an incorrect category. This view helped to resolve the circularity problem that arose when misconceptions are defined in terms of "incommensurable" theories. Are theories incommensurate because their participating concepts are incompatible, or are concepts incommensurate because they are embedded in incompatible theories? By defining incommensurability as "ontological distinctiveness," we were able to circumvent this problem and offer an easy test of incommensurability, the predicate test.

One question arose about defining these incommensurable categories. Is there a point at which categories are either "incommensurate" or "commensurate," or is this a continuous variable? In other words, is incommensurability a matter of degree? We have no way of answering this question at this point in time. However, future work could address this question by systematically testing (through predicate tests) a number of concepts in different ontologies and examining the distribution of predicates that demarcate boundaries.

6.2. *What is Conceptual Change? Why and When Is It Difficult?*

In our answer to these central questions, we have argued that conceptual change is the process of shifting concepts across ontological boundaries. This reassignment process is believed to be simple and straightforward, analogous to linking or associating a concept with a different category. Other types of reconceptualization, like perspective shifts, and accommodation, are better described as "conceptual reorganization". Such reorganization involves hierarchical conceptual shifts or incremental changes, but not ontological shifts.

But if conceptual change is a simple process, then why are some naive conceptions, referred to as misconceptions, so difficult to fix? We answer this second question by arguing that when conceptual change is difficult, it is often because students lack awareness of their misunderstanding, or they lack an alternative category to shift concepts into. It is this second obstacle that presents the greatest difficulty to repairing certain misconceptions. For example, there is a class of complex, dynamic processes/concepts (i.e. diffusion, natural selection, heat flow) that few students seem able to understand deeply. We have suggested that these students misclassify these processes as "causal" when they are actually "emergent" processes. Furthermore, students seem to lack this *emergent process* category, which precludes the repair of this misconception through conceptual change.

This raises one final issue. How can we provide students with this *emergent process* category that they are missing, but need in order to understand so many scientific topics? Would it be sufficient to teach students the five features of emergent processes, and to contrast these with causal processes? Or do students require hands-on demonstrations or simulated environments? This is an open question which will be a focus for much of our future research.

ACKNOWLEDGMENTS

The authors are grateful for support of this research from the Spencer Foundation.

REFERENCES

Carey, S. (1991). Knowledge acquisition: Enrichment or conceptual change? In S. Carey & R. Gelman (Eds.), *The epigenesis of mind* (pp. 257-291). Hillsdale, NJ: Lawrence Erlbaum Associates

Carey, S. (1985). *Conceptual change in childhood.* Cambridge, Mass, MIT Press.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. Giere (Ed.), *Cognitive models of science: Minnesota Studies in the Philosophy of Science*, (pp. 129-186). University of Minnesota Press: Minneapolis, MN.

Chi, M. T. H. (1997). Creativity: Shifting across ontological categories flexibly. In T.B. Ward, S.M. Smith, R.A. Finke & J . Vaid (Eds.), *Creative thought: An investigation of conceptual structures and processes.* (pp. 209-234). Washington, DC: American Psychological Association.

Chi, M. T. H. (2000a). Cognitive understanding levels. In: Encyclopedia of Psychology, Vol. 2, Kazdin, A.E. (Ed.). Pp 172-175, Oxford University Press.

Chi, M. T. H. (2000b). Self-explaining: The dual processes of generating inferences and repairing mental models. In R. Glaser (Ed.), *Advances in Instructional Psychology.* Mahwah, NJ: Lawrence Erlbaum Associates.

Chi, M. T. H., de Leeuw, N., Chiu, M. H., & LaVancher, C. (1994). Eliciting self-explanation improves understanding. *Cognitive Science, 18*, 439-477.

Chi, M. T. H., Siler, S. A., Jeong, H., Yamauchi, T., & Hausmann, R. G. (In press). Learning from human tutoring. *Cognitive Science.*

De Leeuw, N. (1993). Students' beliefs about the circulatory system: Are misconceptions universal? In *Proceedings of the Fifteenth Annual Conference of the Cognitive Science Society* (pp. 389-393). Hillsdale, NJ: Lawrence Erlbaum Associates.

De Leeuw, N., & Chi, M. T. H. (In preparation). Self-explanation, comprehension, and conceptual change. Chapter to appear in G.M. Sinatra and P.R. Pintrich (Eds.) *Intentional Conceptual Change.* Hillsdale, NJ: Lawrence Erlbaum Associates.

diSessa (1993). Toward an epistemology of physics. *Cognition and Instruction,* 10, 101-104.

Ferrari, M., & Chi, M. T. H. (1998). The nature of naive explanations of natural selection. *International Journal of Science Education, 20*, 1231-1256.

Gelman, S. A. (1988). The development of induction within natural kind and artifact categories. *Cognitive Psychology, 20*, 65-95.

Gunstone, R.R., Champagne, A. B. , & Klopfer, L. E. (1981). Instruction for Understanding: A case study. *Australian Science Teachers Journal, 27*, 27-32.

Hempel, C. (1966). Laws and their role in scientific explanation. *Philosophy of Natural Science*, Chapter 5, Englewood Cliffs, NJ: Prentice Hall.

Hewson, P. W. (1981). A conceptual change approach to learning science. *European Journal of Science Education, 3*, 383-396.

Jeong, H. (1998). *Knowledge co-construction during collaborative learning.* Unpublished Ph.D. thesis, University of Pittsburgh.

Keil, F. (1979). *Semantic and conceptual development: An ontological perspective.* Cambridge, MA: Harvard University Press.

Marek, E. A., Cowan, C. C., & Cavallo, A. M. L. (1986). Students' misconceptions about diffusion: How can they be eliminated? *The American Biology Teacher, 567*, 74-77.

McCloskey, M. (1983) Naive theories of motion. In D. Gentner & A.L. Stevens (Eds.), *Mental Models* (pp. 299-324). Hillsdale, NJ: Lawrence Erlbaum Associates.

Osborne, R. J. & Wittrock, M. C. (1983). Learning science: A generative process. *Science Education, 67*, 489-508.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*, 211-27.

Slotta, J. D., Chi, M. T. H, & Joram, E. (1995). Assessing students' misclassifications of physics concepts: An ontological basis for conceptual change. *Cognition and Instruction, 13*, 373-400.

Sommers, F. (1971). Structural ontology. *Philosophia, 1*, 21-42.

Thagard, P. (1990). Concepts and conceptual change. *Syntheses, 82*, 255-274.

Thagard, P. (1996). The concept of disease: Structure and change. *Communication and Cognition, 29*, 445-478.

Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. *European Journal of Science Education, 1*, 205-21.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*, 535-585.

Wiser, M., & Carey, S. (1983). When heat and temperature were one. In D. Gentner & A. Stevens (Eds.), *Mental models* (pp. 267-297). Hillsdale, NJ: Lawrence Erlbaum Associates.