Pergamon

Learning and Instruction, Vol. 4, pp. 27–43, 1994
Copyright © 1994 Elsevier Science Ltd
Printed in Great Britain. All rights reserved
0959–4752/94 $26.00

FROM THINGS TO PROCESSES: A THEORY OF CONCEPTUAL CHANGE FOR LEARNING SCIENCE CONCEPTS

MICHELENE T. H. CHI, JAMES D. SLOTTA and NICHOLAS de LEEUW

University of Pittsburgh, U.S.A.

Abstract

Conceptual change occurs when a concept is reassigned from one category to another. The theory of conceptual change in this article explains why some kinds of conceptual change, or category shifts, are more difficult than others. The theory assumes that entities in the world belong to different ontological categories, such as MATTER (things) and PROCESSES. Many scientific concepts, for example light, belong in a subcategory of PROCESSES, which we call constraint-based interactions. However, students' initial conceptions of these concepts are categorized as MATTER. The ontological status of the initial and scientific conceptions determines the difficulty of learning. If the two conceptions are ontologically compatible (e.g., both are MATTER), conceptual change is easy. If the two conceptions are ontologically distinct, learning is difficult. Evidence for these two cases is presented from studies of learning about the human circulatory system and about key physics concepts, such as heat and light.

Introduction

This article entertains a theoretical notion that explains how conceptual change determines the difficulty or ease of learning concepts, such as those in science. The theory also services to unify the discrepant findings concerning conceptual change reported in the literature where conceptual change itself is largely ill-defined.

Conceptual change is broadly defined as learning that changes some existing conception. This presupposes that one already has some notion of what a particular to-be-learned concept is. Within this framework, a concept's category membership would be its most crucial aspect. Therefore, the simple working definition adopted here is that the meaning of a concept is determined by the category to which the concept is assigned. Conceptual change occurs when the category, to which the concept is assigned,

---

Address for correspondence: M. T. H. Chi, 821 Learning Research and Development Center, 3939 O'Hara St, University of Pittsburgh, Pittsburgh, PA 15260, U.S.A.

changes. For instance, re-assigning the concept of a whale from the category of "fish" to the category of "mammal," changes the fundamental *essence* or ontology of the concept "whale." The critical issue then becomes: what kind of reassignment of a concept's category constitutes "conceptual change," since the term seems to refer to a specific kind of change. Why some conceptions are difficult to change and others are not is the key issue to be addressed here. Finally, the term "conceptual change" unfortunately can refer to both the processes of change as well as the resulting change (i.e., the new category to which a concept is assigned). An effort will be made to specify which meaning is being referred to.

The article opens with a discussion of the proposed theory of conceptual change which is grounded in three suppositions. This theoretical definition predicts certain observable patterns in the existing data that will then be reviewed, particularly in the science learning literature. Finally, a discussion of how conceptual change can be assessed is presented along with a brief summary and conclusion.

A Theory of Conceptual Change

The theory of conceptual change proposed in this article relies on three suppositions: an epistemological one concerning the nature of entities in the world; a metaphysical one concerning the nature of certain science concepts; and a psychological one concerning students' naive conceptions. The conjunction of these three suppositions produces the Incompatibility Hypothesis, which explains why some concepts are particularly hard to learn.

An Epistemological Assumption Defining the Criterion of "Different"

The first supposition states that entities in the world may be viewed as belonging to different ontological categories. Three primary ontological categories (henceforth referred to as "trees," and signified by capital letters) are depicted in Figure 1: MATTER (or THINGS), PROCESSES and MENTAL STATES. There is a hierarchy of subcategories embedded within each of these major trees (i.e., PROCESSES can be divided into Events, Procedures, or Constraint-Based Interactions; MATTER can be divided into Natural Kinds and Artifacts). These are shown in Figure 1 with members of an ontological category appearing in parentheses and ontological attributes appearing in quotes. As we are not philosophers nor epistemologists, we are not particularly committed to the exact hierarchy shown in Figure 1; other hierarchical organizations are possible. For example, Keil (1979), following Sommers (1963), divides Objects (analogous to our MATTER category) into Solids and Aggregates, as opposed to our division of Matter into Natural Kinds and Artifacts. However, we *are* committed to the existence of major ontological trees, whereas Keil (1979), for instance, has omitted completely the tree of PROCESSES, which is prominent in the theoretical and experimental work presented here. More than three trees may exist (e.g., MENTAL STATES may be differentiated into two or more trees), but because this paper focuses predominantly on the trees of THINGS and PROCESSES, less concern will be concentrated on the existence of other trees and the accuracy of the hierarchical categories. The main concern will focus on the mere existence of major ontological trees, since re-assigning a concept from its initial tree onto another tree is the crux of our notion of conceptual change.

Categories within a given tree *differ* ontologically from any category on another tree, because they do not share any ontological attributes. For example, any category of MATTER, such as Living Things or Solids, is ontologically *different* from any category of PROCESSES, such as Naturally Occurring Events. An ontological attribute, as distinct from either defining attributes or characteristic features, is a property that an entity *may potentially* possess as a consequence of belonging to that ontological category; whereas defining attributes are those an entity *must have*, and a characteristic feature is one that an entity *most frequently* has. For example a coffee carafe, which is an artifact in the MATTER category, must have a spout (a defining attribute). It is often made of glass, though not necessarily (a characteristic feature), but it can potentially be broken (an ontological attribute). Thus, an ontological attribute is qualitatively different (and probably orthogonal) to either characteristic features or defining attributes. Objects in the MATTER category (such as sand, paint, or human being) have such ontological attributes as "being containable," "storable," "having volume" and "mass," "being colored," and so forth. PROCESSES reflect their own distinct set of attributes, such as "occurring over time," "resulting in," and so forth. These attributes are shown in quotes in Figure 1.

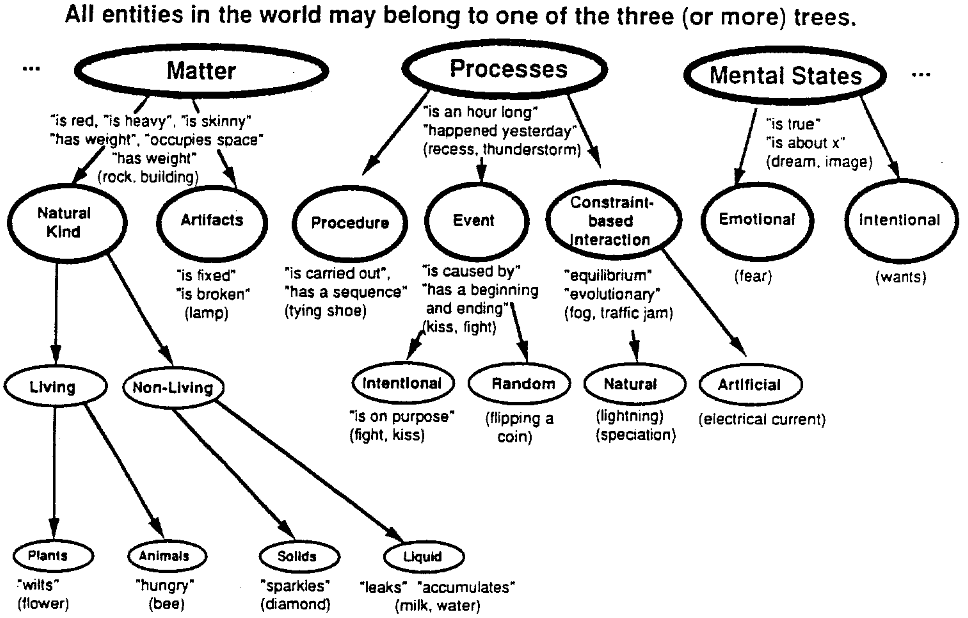
All entities in the world may belong to one of the three (or more) trees.

Figure 1. An epistemological supposition of the nature of our conceptions about the entities in the world. One possible categorization scheme. The three primary categories of MATTER, PROCESSES, and MENTAL STATES are ontologically distinct, and other subcategories on each tree, which are separated horizontally, may be as well.

People's conception of the entities in the world should correspond to such ontological distinctions. The psychological reality of the distinctness of ontological categories can be tested by predicating an ontological attribute onto a category member, and asking people to judge whether such a proposition is sensible or anomalous. In such a task, people are asked whether sentences such as "A canary is an hour-long" make sense. People typically respond that the sentence above is nonsensical (referred to as a category mistake), whereas "A canary is blue" might be judged wrong, but sensible. The former sentence is anomalous, because a canary is modified by a predicate (hour-long) that describes an attribute (time duration) from an ontologically distinct category (in this case, Events). The latter sentence "A canary is blue" is merely false due to an incorrect attribute. The anomalous sentence, however, is more than false, since it cannot be made sensible even if it is negated: Saying that "A canary is not an hour-long" is equally anomalous. Keil (1979) discusses other related tasks, such as co-predication, which can also be used to capture the psychological reality of ontological attributes.

Because philosophers primarily discuss categories within a given tree, the same criterion of non-overlapping attributes can be used to determine whether two categories within the same tree are ontologically distinct or not. Sommers (1963), for example, determined that two categories are not ontologically distinct if an ontological attribute exists that can "span" or be applied to members of the two categories. For example, in Figure 1, "hungry" can be applied to the category of Animals and all its subcategories, such as Humans. Therefore, Animals and Humans are not ontologically distinct. Using such a definition, when an attribute of one category cannot span members of another category, then the two categories are ontologically distinct, and will be referred to here as "parallel" categories (meaning any horizontally separate branches or categories such as Natural Kinds and Artifacts, that are both embedded within the same tree, in this case MATTER, and are ontologically distinct). For example, an attribute from one category, such as "is broken" (an attribute of the Artifact category), cannot be used sensibly to modify an entity from a parallel category such as a dog (a member of the Natural Kind category). There is psychological evidence to suggest that parallel categories within the same tree are ontologically distinct, because even young children (age 5 years) seem to honor these distinctions, such as the difference between Artifacts and Natural Kinds (Gelman, 1988). Keil (1989) for instance, has also shown that young children are unable to accept transformations of an object which crosses ontological boundaries of parallel categories. When asked if a scientist could ever perform sufficient operations on a toy bird to make it into a real bird, even young children thought it would not be possible.

Thus, both philosophers and psychologists would consider two parallel categories on the same tree (e.g., Natural Kinds and Artifacts) as ontologically distinct even though there may exist higher order ontological attributes that span them both, such as "is brown" and "can be contained" for objects such as a dog and a knife. The difference, however, between ontological trees and parallel ontological categories within a tree, is that the ontological attributes of trees are mutually exclusive. There is no higher order ontological attributes that can span entities on two different trees. However, when parallel categories are subsumed under the same tree, there do exist attributes that can be used to modify both of them, such a "is brown," or "can be contained" for objects dog and knife, even though the sensibility test and others that Keil has used, show them to be ontologically distinct. The special status of trees is consistent with the findings of Gerard and Mandler (1983). That is, although they found disparity between their data from those of Keil in the positioning of the predicates and terms within the Physical Entities tree (MATTER tree), there was no question that their data revealed a clear distinction between objects (MATTER) and non-objects (which they refer to as Events and Abstract Ideas). Thus, Gerard and Mandler (1983) surmised that "events and abstract ideas may not fit into a hierarchical mold, or else they may belong to a separate hierarchy" (p. 119). Hence, the three major ontological trees depicted here already have some empirical support for their existence. Interestingly, the primary category of PROCESSES has never been suggested, although the subcategory of Events has been. Hence, the kind of assessment techniques used in the literature do not discriminate between ontological distinction at the level of trees versus ontological distinction at the level of parallel categories within trees.

In sum, ontological distinction underlies our notion of conceptual change: Conceptual change occurs when a concept has to be re-assigned to an ontologically distinct category (*across trees*). This definition specifies clearly what a distinct ontological category is, by means of the non-overlapping ontological attributes. Whether a change across parallel categories *within* a major ontological tree constitutes conceptual change of a lesser degree is not clear at this time. It so happens that learning science concepts requires conceptual change across trees, this is why they are so difficult (more about this point later). A more modest claim is that the earlier in the trees of Figure 1 that the learner's conception branches from the scientist's conception, the greater the degree of conceptual change involved in bringing them together.

A Metaphysical Assumption about the Nature of Scientific Concepts

Many scientific concepts belong to an ontological category which we currently refer to as Constraint-Based Interaction, a subcategory of PROCESSES. Constraint-Based Interactions are determined by a known or knowable set of constraints. While this definition is quite abstract and perhaps only an approximation of the true definition, it is hoped that the meaning will become more clear by using some examples and attributes to illustrate this category. Take the concept of electrical current as an example member of this Constraint-Based Interaction category: Current exists only when electrically charged particles are moving, usually because of an electric field. A field fills all space, but an electrical current exists only when a charged particle is introduced into the field. Hence, an electrical current is neither MATTER nor properties of MATTER, but a PROCESS that is fundamentally constraint-based and has no causal agents. The same applies to the concept of heat, force, and light, which are all entities whose veridical (metaphysical) conception belongs in the Constraint-based Interaction category.

Some of the attributes of this Constraint-Based Interaction category may be characterized more clearly by contrasting them with attributes of Events, another PROCESS category. A Constraint-Based Interaction has no obvious beginning and end, but an Event does. For instance, in the Event of a baseball game, certain things happen in the beginning of the game and other things happen at the end of the game. A Constraint-Based Interaction, such as an electrical current, does not have this dynamic quality. That is, no aspect of a Constraint-Based Interaction can be pointed to as the beginning, and no specifiable aspect can be pointed to as nearing the end of the Process. There is basically no change with time or location, because the process is uniform and simultaneous everywhere. Because of this, one can predict the end of an Event, but one could not necessarily predict the end of an Constraint-Based Interaction. That is, one could state that an Event is about three-quarters through, based on information from the Event itself. A Constraint-Based Interaction provides no information about its time-course, because it has no time course. Thus several attributes of this category are proposed: no beginning or end, no progression, acausal, uniform in magnitude, simultaneous, static, on-going, and so forth. These attributes may in fact be correlated. Other terms which describe this quality of Constraint-Based Interaction are "steady state" and "equilibrium."

Confusion may arise, because Constraint-Based Interactions involve components of other ontological categories, especially MATTER. Returning to the example of electrical current, the MATTER components include moving particles, wires, batteries, and so on. But the involvement of these components does not imply that electrical current belongs in the same category with them: It remains neither a substance, nor a property of one of the component substances. It is simply a process which involves these substances. Similarly, there are Events associated with the initiation of a current (e.g., closing a circuit) but these do not make the current itself an event in the same sense. The current remains a process that is influenced by or is a component of Events that have beginnings and ends, but there is no intrinsic time course to the Process itself.

This characterization applies to science concepts outside the physical sciences as well. For example, within the topic of evolution, there are Constraint-Based Interactions crucial to a complete understanding. Like electricity, evolution includes Constraint-Based processes such as mutation, reproductive behavior, genetic equilibrium, and more. Thus, concepts of the Constraint-Based Interaction category are not confined within disciplinary boundaries, although it may be the case that there are more of them in some disciplines (such as the physical sciences) than others (such as biological sciences).

A Psychological Assumption About the Nature of Misconceptions

The psychological supposition concerns the ontological status assigned by students to certain science concepts. In physical science domains, students' "alternative," "naive," "initial," or "mis" conceptions of concepts such as heat, light, electrical current, and forces are such that they are categorized as a kind of MATTER, or else are endowed with properties of material substances. For example, students often think of force as a kind of impetus imparted to a body or as an intensive property that a body possesses (similar to velocity). They believe that this impetus or "oomph" can be used up. Such misconceptions typically show up in students' attempts to understand Newton's laws of force, resulting in the familiar assumption that when there is no force, there is no movement (because of the absence of impetus). Similarly, students often believe gravity to be "in the earth" rather than a constraint-based relationship between the earth and other objects. These misconceptions actually show up most readily in the context of explaining everyday phenomena in the physical world. The prevalence and homogeneity of such substance-based misconceptions across several physical science concepts are reviewed in Reiner, Chi and Resnick (1988) and Reiner, Slotta, Chi and Resnick (submitted).

Although it is easy to illustrate these substance-based misconceptions for physical science concepts, such misconceptions are not restricted by disciplinary boundaries such as physical versus biological science. In junior high school textbooks, discussion of the human circulatory system consists almost entirely of conceptions which belong to the MATTER category, because the topics covered pertain strictly to physical connections between the blood vessels and the heart, lungs and other organs, as well as the direction and paths of blood flows. However, if one were to discuss the same topic in a medical textbook in which deeper analyses and system-wide constraints such as pressure and volume are to be considered, then concepts belonging to the Constraint-Based Interaction category will often come into play. In fact, the most common misconception about the circulatory system held by medical students, is that "no pressure implies no flow" (Kaufman, Patel, & Magder, 1992). This is synonymous with the "no force implies no motion" misconception identified among physics students (Chi & VanLehn, 1991). So it appears that misconceptions that cross ontological boundaries can occur in various scientific disciplines, and at various levels of analyses.

Although misconceptions about physical science concepts have been the primary focus of these analyses thus far (to show that they are MATTER-based), a preliminary consideration of some naive misconceptions about biological concepts shows that some of them may be MENTAL STATES-based. That is, attributions are given to biological phenomena in terms of the Intentional States. For example, Carey's (1985) characterization of young children's explanation for how animals grow is that "the animals want to." Children thus interpret basic biological phenomena in terms of the desires and wants (the Emotional States) of the animals, rather than their physiological requirements. In our own data, we find that in the topic of the human circulatory system, students like to describe the working of valves as intentional rather than acausal. Likewise, students often attribute evolutionary processes to the intention of the evolving organism. This is a very prominent misconception of evolution: that an organism perceives the adversity of the environment, and says to itself, "I better grow long fangs to survive. Maybe I will have kids with long fangs . . .," when in fact all mutations are random, and only the "fittest" ones happen to survive. In any case, it becomes clear that misconceptions about certain biological and physical science concepts arise because students have initially placed them in a category to which they do not belong. This is in light of the metaphysical supposition about the nature of science concepts.

The Incompatibility Hypothesis

In formulating the three suppositions of the proposed theory, some insight and clarification has emerged pertaining to: (a) the nature of entities in the world, in particular, the existence of a PROCESS category; (b) the nature of certain science concepts as Constraint-Based Interactions; and (c) the nature of misconceptions about certain science concepts as MATTER-based. Additional refinement of these suppositions should in principle be left to the philosophers of science, to the physical and biological scientists, and to science educators, respectively. As cognitive scientists, the primary concern is in explaining *learning* or *failures of learning*, as the case may be, in science learning.

Many obvious reasons have been entertained for explaining why science concepts are difficult to learn: they are often represented by mathematical expressions; they are often abstract; they often use technical jargon that overlap with everyday usage (such as the concept of weight or heat), and so forth. We believe, however, that these are not the key reasons for why certain science concepts are hard to learn. The conjunction of the three aforementioned suppositions frame a theoretical account of why students have difficulty *learning* certain scientific concepts. This difficulty stems from the existence of a *mismatch* or *incompatibility* between the categorical representation that students bring to an instructional context, and the ontological category to which the science concept truly belongs. That is, students' naive conceptions represent a concept such as "forces" as a kind of substance that an object possesses and consumes. Thus, in students' minds, "forces" are entities that belong to the MATTER category, when in fact forces are a kind of Constraint-Based Interaction between two objects (a PROCESS). When a student's initial representation of the concept is incompatible with the concept's veridical ontological status, then learning the concept requires *conceptual change*, meaning that the concept's categorical membership has to be re-assigned *across trees*. In order to assimilate new information about the concept of force, a student must store this new information under the Constraint-Based Interaction category. But instead, because a student's prior conception about force is stored under the MATTER tree, new instruction will ultimately be assimilated into the MATTER tree as well. Thus, students can never achieve complete understanding of the concept unless they undergo a conceptual change, thereby assimilating the to-be-learned concept into a different ontological tree.

To return to the electricity example, consider what happens when a student persists in assimilating new information about electrical current into the ontological class of MATTER (in the case when electrical current is analogized as flowing water, as it is in most introductory textbooks). If students assimilated new information about electrical current into the "liquid" subcategory (see Figure 1, lower left), then the concept might also inherit properties such as "has volume," "occupies space" and other ontological attributes of the MATTER category. This explains why misconceptions about electrical current often include statements such as "it can be stored in the battery" or "it can be used up." Pfundt and Duit (1989) list over 1500 studies that capture misconceptions of this and related natures. This inheritance of ontological attributes may also explain the context-dependency of students' misconceptions of a particular concept. According to the proposed theory, the variability can be explained by the specific ontological attribute of the MATTER category that a student happens to attribute to his/her conception of any given PROCESS concept. Chi and Slotta's commentary (1993) of diSessa's notion of "knowledge in pieces" addresses these issues.

There are several implications of the Incompatibility Hypothesis that also contribute to the difficulty of learning incompatible concepts. (Henceforth, concepts whose true ontological status mismatches the student's naive conceptions will be referred to as *incompatible concepts*.) One implication is that many science concepts, as mentioned earlier, embody both MATTER as well as PROCESS entities, so that a learner must alternate between these two conceptual categories in trying to understand them. A second implication is that the Constraint-Based Interaction category is very difficult to define, and so must be difficult to explain and to teach. Certainly, this category of knowledge is never made explicit in physics textbooks; in reviewing several physics texts, the word "process" was not even listed in the appendix. Finally, the natural preference to conceptualize many concepts as MATTER-based may be due to familiarity with such concepts, and the consequential well-developedness of the MATTER category. The proposed theory predicts that the incompatibility of concepts, and problems associated with that incompatibility, determines the difficulty of learning many science concepts, in addition to many obvious factors such as abstractness, mathematics, and so forth. In sum, under the Incompatibility Hypothesis, it is the ontological status of a student's initial conception of such concepts which renders them difficult to learn, since acquiring the true conception requires a shift in ontological status (radical conceptual change).

Predictions of the Theory

By the same token, the Incompatibility Hypothesis would predict that concepts for which the naive conceptions and the scientific conceptions are compatible should be relatively easy and straightforward to learn. This is in fact true in both individual cases and cross sectional data. Take, for example, the biological concept of *animal*. Children's misconceptions about the concept *animal* stem from representing it as a variant on the concept of *human* (Carey, 1985). But this misconception does not involve an incompatibility of ontological classes, because in an adult (or the correct scientific) conception, *human* belongs to the more superordinate *animal* ontological category. Therefore, children acquire a fairly sophisticated understanding of the concept of *animal* by age 10 years, as Carey's (1985) data, and more recently, Massey, Freyd, and Roth's (1992) data have shown. In contrast, incompatible concepts are often not acquired even after college-level instruction (McCloskey, Caramazza, & Green, 1980).

This general prediction about the ease of learning compatible concepts and the difficulty of learning incompatible concepts was also confirmed when Chi (1992) examined the misconception literature (taken from a large body of published results). In fact, a diametrically opposite *pattern* emerges for either compatible or incompatible concepts. When the to-be-learned concepts are incompatible with initial conceptions, then the naive conceptions tended to be:

(a) "robust," meaning that students hold onto their initial beliefs firmly, so that they are difficult to overcome by instruction, confrontation, or any other mode of challenge;
(b) "consistent" over time and situations, meaning that the same misconception is displayed by the same student over different times and across different contexts;
(c) "persistent" across different ages and schooling levels, such that college students, high school and elementary school children all maintain more-or-less the same sort of misconception (i.e., there is no developmental trend);
(d) "homogeneous" among different students (i.e., different students in either the same or different studies display similar misconceptions);
(e) "recapitulated" across historical periods (i.e., the medieval scientists and contemporary naive students tend to hold the same misconceptions); and

(f) "systematic" in the sense of whether the misconceptions conform to a coherent "theory" or whether they are fragmented (this distinction will not be entertained here, and is being pursued in the commentary by Chi and Slotta, (1993).

On the other hand, when one examines misconceptions about scientific concepts for which the naive and the scientific representations are compatible, then the opposing pattern occurs: misconceptions are not robust (can be removed), not consistent, not persistent, not homogeneous, and not recapitulated. Below, the available evidence relevant for each component of the opposing pattern is described. Because much of the evidence for the opposing pattern is gathered in our own laboratory, a brief outline of the design of the study and the kind of measures taken is presented.

The study consisted of tracking learning of a 102-sentence passage about the human circulatory system by eighth grade students who have never had a complete unit about this topic before. (Details of the methodology appear in Chi, de Leeuw, Chiu, & LaVancher, in press.) Prior to the studying phase, students were pre-tested with a variety of topic-related terms (that are introduced and defined in the passage), a set of questions pertaining to historical misconceptions (derived from reading history of science papers on Harvey's discovery), and a set of questions targeted at the content of the passage (we refer to these as text-based questions). Students studied the passage by reading each sentence one at a time. They were then asked to "explain" each sentence as they read it. These self-explanation protocols provided data to observe and track the students' on-line understanding. Below, evidence is presented concerning each component of the *pattern* outlined above.

Robustness

For simple compatible biological concepts, there is some preliminary evidence to show that instead of holding on to persistent misconceptions, students often appeal to a lack of knowledge (Lawson, 1988). In our own data concerning the circulatory system, pre-test results show that students often state "I don't know" when asked to explain certain terminologies or to make predictions. Catherall (1981), in trying to uncover children's beliefs about the function of the heart, the paths and methods of blood circulation, and so forth, also found that over 60% of the second graders had "no idea" what the function of blood was. Hence, unlike physical science concepts, many children will state that they do not know rather than hold onto some robust misconception.

Another way to assess robustness is to look at the ease of removing the misconceptions. In our work, a set of stable beliefs were first identified — those that were mentioned more than once (to be defined in the next paragraph). The point to note here is that the great majority of this smaller set of more stable beliefs were removed by instruction (namely, after reading the 102-sentence passage). Of 31 stable false beliefs captured across 12 students, 26 were contradicted either directly or indirectly by the passage. Of these 26, at least 19 were definitely removed, or 73% (de Leeuw, 1993). This high proportion of successful removal suggests that these misconceptions are not robust.

Consistency

The issue of consistency in a single student's conceptions in topics outside of physics has received little attention. Thus, there is little existing evidence to support or refute the notion that students display consistent responses in different contexts for those domains in which the naive and scientific conceptions are ontologically compatible.

In looking at the issue of consistency in our study of students learning about the circulatory system, it was found that while students had many false beliefs, few of these were consistent over time and context. Context in this case is defined by the different sentences within the passage (which can be different triggering cues for the same misconception), or different tasks, either during pre-test, studying the text, or the post-test. In one section of the pre-test, for example, where students had to define a set of terms, it was found that students exhibited on average 16 false beliefs. Yet, fewer than three of these, on average, were mentioned again throughout multiple hours of testing, sentence-explaining, question-answering, and so forth.

While both we and Arnaudin and Mintzes (1985) did find some misconceived belief trends across students (e.g., attributing additional functions to the heart), these represent only a loose consistency. Even though the false beliefs of a significant minority of students may share similar elements, they are not the same beliefs. In our study, only five false beliefs were articulated by more than two students out of the 14, even including the less stable beliefs mentioned only once.

Persistency

There is evidence that students's beliefs about compatible science concepts do improve with age and schooling. Again using the circulatory system as an example, there is evidence in Gellert's (1962) data, and in Arnaudin and Mintzes' (1985) work, that there is a developmental progression in the acquisition of these concepts. For example, at a young age (second grade level), children have knowledge of the properties of the heart (such as its size, shape, and location). By sixth grade, each major component of the circulatory system appears to be linked with a greater number of structural properties. There is also a greater ability to identify the function of components (Catherall, 1981). There are certainly a great deal of data in related domains, such as the concept of *animal*, that show improvement with age (Carey, 1985).

Homogeneity

While one would expect incompatible concepts to give rise to similar misconceptions among different students due to a similar underlying ontological commitment, we would expect more variability in the false beliefs about compatible concepts, because there would be a range of information or inferences that could give rise to student's beliefs. Data about the circulatory system are consistent with this expectation. Arnaudin and Mintzes (1985) collapsed students beliefs into categories, but still found four or more categories of responses for most of the questions they asked. In most cases, there was no dominant response that more than half the students ascribed to. Catherall (1981) also found a variety of responses to his questions about the circulatory system, each accounting for a minority of students. As mentioned in the section on consistency, our own study also found little homogeneity in false beliefs about the circulatory system. Most false beliefs were expressed by only a single subject, out of 14. Differences in the level of agreement in our work and in previous work are probably due to a different grain-size of categories.

Recapitulation

If modern students hold beliefs that are related to historical theories of ontologically compatible topics, one would expect them to refer to those beliefs when questioned about historical beliefs and theories. In our study of the human circulatory system, no evidence was found that they do. The historical misconception set of questions in the study were designed to assess whether contemporary students recapitulated the misconceptions of medieval scientists, as has been found in physics. Students correctly answered most (55%) of these questions in the pre-test, showing that at worst, they shared a minority of historical beliefs. But the wrong answers in this section may also have been due to other false beliefs and to wrong guesses, as in other sections of the pre-test. There are three pieces of evidence to suggest that recapitulation of historical ideas did not account for many of the wrong answers, even in the historical misconception questions. First, students scored better on the misconception questions than on other sections, suggesting that they were less likely to hold historical misconceptions than "random" false beliefs. Second, only a minority (30%) of the false beliefs mentioned more than once were at all related to historical misconceptions. Finally, ranking the students according to the number of false beliefs that they held was not predictive of their pre-test scores (even on the historical misconception questions). Unlike the case in physics, then, their false beliefs did not interfere in important ways with their correct knowledge, and their confusion in general was not related to that of an earlier era.

Even if a subset of the wrong answers in the historical misconceptions questions were due to beliefs echoing historical theories, they did not resist removal, as in physics. In the post-test, students' scores in this section improved to 83%, indicating that whatever the source or sources of their incorrect answers was in the pre-test, they were corrected by instruction.

The Opposing Pattern

In sum, we take these opposing patterns of results for what we surmise to be compatible and incompatible concepts as consistent with a theory in which a clear segregation is made in the requirement for conceptual change. That is, if a concept's ontology is incompatible with a student's initial representation, then one pattern of result would hold. If a concept's ontology is compatible, then the opposing pattern would hold, more-or-less. This distinction can explain some of the dilemmas that show up in the literature. For example, the Incompatibility Hypothesis explains why Carey (1985) had difficulty reconciling her data with her theory of conceptual change. Because her data dealt with the concept of *animal*, her data basically show that children's knowledge of this concept improves from age 5 to 10 years from an accumulation of knowledge, analogous to the development of expertise, although her theory predicts a more abrupt conceptual change.

Hence, the Incompatibility Hypothesis proposes that some science concepts require no major conceptual change for deep understanding. These would be concepts for which the students' naive conceptions and the scientific conceptions share the same ontological class. Examples include learning to differentiate between mammals and fish; learning about the circulatory system at a simplified level; learning about the concept of plants and animals, and so forth. For these concepts, learning is more straightforward, and initial naive conceptions are more readily corrected. In fact, new evidence in support of this claim is emerging, such as the 92% success rate at removing prior conceptions of why seasons change and how mountains form (Muthukrishna, Carnine, Grossen, & Miller, 1993). There exists another set of concepts that are particularly hard to learn, because there is an incompatibility between the students' initial representation of the concept and the scientific conception. This does not address an additional theoretical question of why scientific concepts of a certain nature (those characterized by Constraint-Based Interactions) are particularly hard to learn: that is, do people have particular difficulty representing these Constraint-Based process-oriented concepts? Do people have a predisposition to think concretely (dealing with MATTER) or intentionally (MENTAL STATE)? These additional questions have not yet been dealt with.

Predicate Use

As mentioned earlier, the kind of tests used in the literature do not discriminate between ontological distinction at the level of trees vs ontological distinction at the level of parallel categories within trees. Slotta, Chi and Joram (submitted) have designed a technique for assessing when conceptual change has taken place at the tree level, by the kind of predicates students use to explain phenomena and situations. The following experiment illustrates this technique.

Physics novices were presented with relatively unfamiliar "physics concept problems" involving three physics concepts (light, heat, and electrical current). They were asked to reason about the situation in the problem in order to make a prediction as to its outcome and generate explanations for each prediction. (Here, we focus only on the explanation data.) These "physics concept problems" were then paired with isomorphic "material substance problems," whose situations were designed so that they would be as close as possible to MATTER-based conceptions of the corresponding physics concept problem. For example, one of the physics concept problems concerning electricity required subjects to predict the result of closing a switch in a parallel circuit containing several light bulbs at increasing physical distance from the battery. The material substance isomorph for this problem was a situation requiring subjects to predict the result of turning on a water faucet which supplied a series of water sprinklers extending away from the faucet along a hose. In both cases, the outcome concerns which light bulb (or sprinkler) would illuminate (or spray water) first, the one nearest the battery (or faucet), the one farthest, or all at the same time.

Table 1
Taxonomies used for Coding and Analysis of MATTER-based and *Constraint-based* or PROCESS-based Conceptions of physics topics.

Predicate	*Example/Equivalents*
Block	blocks, keeps, bounces off, hits, stops, . . .
Contain	holds in, stores, contains, keeps in, . . .
Move (as translatory motion)	moves, goes, leaves, comes, flows (through), . . .
Rest	stops, stays, rests, sits, . . .
Consume	uses up, gets used up, gets burned up, burns out, drains, . . .
Absorb	absorbs, soaks up, takes in, . . .
Quantity	some, all, most, more, less, none of, lots, little bit, . . .
Color Add	adds like colored paints, red and blue make purple, just like with paints, . . .
Accumulate	fills up, builds up, adds on, accumulates, keeps building, . . .
Supply	supplies, gives off, provides, comes from, comes out of
Equivalent Amounts	the same amount to all of the bulbs, energy from the battery would be spread out equally, . . .

Predicate	*Equivalents/Examples*
Propagation and Transfer Process	net flow of electrons, propagates through (the cup), transfer from one to another, . . .
Process of Excitation	a lot of phonon nodes to excite, need a lot of energy to excite them, . . .
Interaction Process	the interaction of the electric and magnetic fields, the light energy is absorbed and transformed, . . .
Uniform System Process	there's a field present throughout the wire, all see the same potential, . . .
Simultaneous System Process	they all see (the potential) at the same time, these are in parallel, there's an electric field throughout the wire, . . .

On the basis of our theory, a taxonomy of predicates were derived by enumerating the various ontological attributes of MATTER and Constraint-Based Interactions. The members of this taxonomy, in predicate form, together with their verbal equivalents (verbal words or phrases which were articulated by the subjects) are shown in Table 1. Explanations were transcribed and coded according to these predicates. If these predicates were observed in a subject's explanations, then they were taken as direct evidence that the subject maintained a MATTER-based or PROCESS-based conception, respectively.

The two parallel solid lines in Figure 2 show that novices used predominately Matter-based predicates (the upper solid line), whether they were explaining situations involving physics concept or material substance problems. Experts (the dotted lines), on the other hand, distinctly reserved the MATTER-based predicates primarily for the material substance problems, and used the appropriate Process-based predicates to reason about the physics concept problems. Moreover, novices and experts both used the Matter-based predicates to the same degree for material substance problems, whereas the experts, not surprisingly, surpassed the novices in their use of the Process-based predicates to explain the outcomes of the physics concept problems.

These results support the notion that novices are predisposed to categorize physics concepts as MATTER-based, in the sense that they use the MATTER-based predicates to the same degree in the physics concept and material substance problems. Experts, on the other hand, agreed perfectly with novices in their explanations of the material substance problems (as measured by their Matter-based predicate use), but apparently maintained Constraint-Based Interaction conceptions of the physics concept (heat, light, and electrical current). This experiment has provided direct evidence for our theory in the following sense:

(1) naive conceptions of physics concepts are MATTER-based, which suggest that a shift in ontology is necessary in order for novices to achieve conceptual understanding of physics concepts;
(2) novices do not make use of the veridical Process-predicates of these concepts, presumably because they either do not have such a subcategory in their ontology, or else they have the physics concepts stored within the Matter ontology; and
(3) experts clearly maintain a distinct ontological category for the physics concepts, which appears consistent with the proposed Constraint-Based Interaction ontology.

Although evidence of conceptual change has not been provided here *per se*, our theory-driven method of assessment is leading to a more rigorous way of operationalizing and assessing what is meant by conceptual change, and when and under what conditions it can successfully be captured. Such a method can clearly be extended to measure conceptual change in a longitudinal study.

We would also like to point out that these data provide the evidence to suggest that experts certainly acquire strong radical restructuring in the sense that they use predicates from the Constraint-Based Interaction category. Thus, we reject in principle Carey's (1985) view that acquisition of expertise represents a weak form of restructuring, but agree with Carey that our previous exposition of restructuring (in terms of an accumulation of more nodes and links to create new patterns of structures, see Chi, Hutchinson, & Robin, 1989) does represent only a form of weak restructuring. However, the Chi *et al.* (1989) exposition is consistent with our current view, only because we

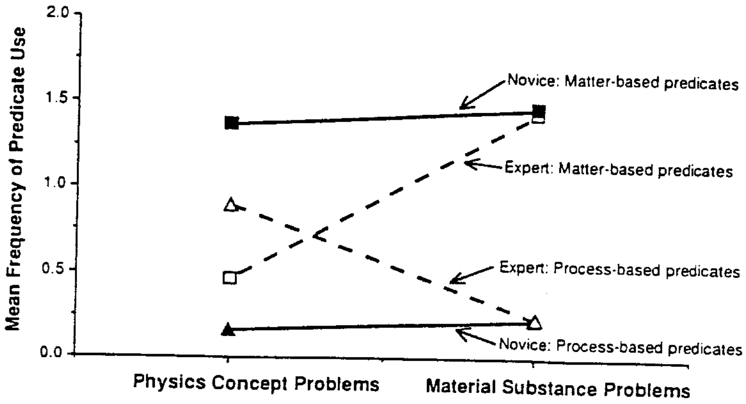

Figure 2. Use of MATTER-based and PROCESS-based predicates by 10 novices (solid lines) and four experts (dotted lines) for physics concept and material substance problems.

were discussing the acquisition of ontologically compatible concepts — the learning of dinosaur concepts.

Summary and Discussion

This article has presented a theory of conceptual change, based on three suppositions: an epistemological one about the nature of ontological categories, a metaphysical one about the nature of certain science concepts, and a psychological one based on the nature of people's naive conceptions. The conjunction of these three suppositions formulates the Incompatibility Hypothesis about learning, which asserts that concepts for which the veridical ontological status and the students' conception are incompatible will be more difficult to learn, than those concepts whose ontological status between the vertical and the naive conceptions are compatible. The extent to which these theoretical predictions for compatible and incompatible concepts are consistent with the data in the literature at large, as well as our own data, were explored in terms of a pattern of results on a number of dimensions. Based on our theory, an operational definition of conceptual change, which can be used to assess conceptual change, was generated. An example of its preliminary use is provided.

Basically, we view conceptual change (a change in the explanatory framework from one ontology to another) as necessary for any incompatible concepts (that is, concepts for which the ontological status of the veridical and the naive conceptions do not match). Such a definition provides a lens to scrutinize and make sense of a great deal of data in the literature (see Chi, 1992, for some discussion). Most distinctly, it provides coherence for a large body of contradictory results showing either the incremental learning trends for some concepts, and stubborn resistance to learning of other concepts. Moreover, it serves an important instructional function of allowing us to tease apart the conditions under which instruction should precede by explanations of the alternative framework, and instructions which can proceed in a cumulative way. For example, in the mathematics domain, fractions may be difficult to learn because they are ontologically distinct from integers; so that it may be important to point out these ontological distinctions before proceeding with details of their properties. Finally, our theory allows for the understanding of scientific revolutions that we might be witnessing right in front of our eyes, such as the shift from a matter-based conception of knowledge to a process-based conception of knowledge (see the first issue of the 1993 *Cognitive Science* journal).

Acknowledgements — Preparation of this article was supported by a grant from the A. F. Mellon Foundation. The opinions expressed do not necessarily reflect the position of the sponsoring agency, and no official endorsement should be inferred.

References

Arnaudin, M. W., & Mintzes, J. J. (1986). The cardiovascular system: Children's conceptions and misconceptions. *Science and Children*, **23**, 48.

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

Catherall, R. W. (1981). *Children's beliefs about the human circulatory system*. Unpublished master's thesis. University of British Columbia.

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. 129–160). Minneapolis, MN: University of Minnesota Press.

Chi, M. T. H., Leeuw, N. de, Chiu, M. H., & LaVancher, C. (Submitted). Eliciting self-explanations improves understanding. *Cognitive Science*.

Chi, M. T. H., Hutchinson, J., & Robin, A. F. (1989). How inferences about novel domain-related concepts can be constrained by structured knowledge. *Merrill-Palmer Quarterly*, **35**, 27–62.

Chi, M. T. H., & Slotta, J. (1993). The ontological coherence of intuitive physics: Commentary on diSessa's "Toward an epistemology of physics". *Cognition and Instruction* **10**, 249–260.

Chi, M. T. H., & VanLehn, K. A. (1991). The content of physics self-explanations. *Journal of the Learning Sciences*, **1**, 69–105.

Gellert, E. (1962). Children's conceptions of the content and function of the human body. *Genetic Psychology Monographs*, **65**, 293–405.

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

Gerard, A. B., & Mandler, J. M. (1983). Ontological knowledge and sentence anomaly. *Journal of Verbal Learning and Verbal Behaviour*, **22**, 105–120.

Kaufman, D. R., Patel, V., & Magder, S. A. (1992, April). *Conceptual understanding of circulatory physiology*. Paper presented at the annual meeting of the American Educational Research Association, San Francisco, CA.

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

Keil, F. (1989) *Concepts, kinds, and cognitive development*. Cambridge: MIT Press.

Lawson, A. E. (1988). The acquisition of biological knowledge during childhood: Cognitive conflict or tabula rasa? *Journal of Research in Science Teaching*, **25**, 185–199.

Leeuw, N. de (1993). Students' beliefs about the circulatory system: Are misconceptions universal? In *Proceedings of the 15th Annual Conference of the Cognitive Science Society* (pp. 389–393). Hillsdale, NJ: Erlbaum.

Massey, C., Freyd, P., & Roth, Z. (April 1992). *Conceptual change in 5th and 6th graders understanding of biological classification*. Poster session presented at the annual meeting of the American Educational Research Association, San Francisco, CA.

McCloskey, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. *Science*, **210**, 1139–1141.

Muthukrishna, N., Carnine, D., Grossen, B., & Miller, S. (1993). Children's alternative frameworks: Should they be directly addressed in science instruction? *Journal of Research in Science Teaching*, **30**, 233–248.

Pfundt, H., & Duit, R. (1988). *Bibliography: Students' alternative frameworks and science education* (2nd ed.). Kiel, Germany: Institute for Science Education.

Reiner, M., Chi, M. T. H., & Resnick, L. B. (1988). Naive materialistic belief: An underlying epistemological commitment. *Proceedings of the Tenth Annual Conference of the Cognitive Science Society* (pp. 544–551). Hillsdale, NJ: Erlbaum.

Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (Submitted) *An underlying materialistic commitment in naive thought. Cognition and Instruction.*

Slotta, J. D., Chi, M. T. H., & Joram, E. (Submitted). *The structure of conceptual knowledge: Preliminary findings in support of ontologically distinct categories. Cognition and Instruction.*

Sommers, F. (1963). Types of ontology. *Philosophical Review*, **72**, 327–363.