In R. Giere (Ed.) (1992) Cognitive Models of Science: Minnesota studies in the Philosophy of Science. (pp. 129-186). Minneapolis, MN: University of Minnesota Press.

Michelene T. H. Chi

Conceptual Change within and across Ontological Categories: Examples from Learning and Discovery in Science

1. Introduction

The simple working definition adopted in this essay for conceptual change is that it refers primarily to the notion of how a concept can change its meaning. Since a difference in meaning is difficult to define, one can think of it as a change in its categorical status: That is, changing the category to which the concept is assigned, since all concepts belong to a category. To assume that all concepts belong to a category is quite standard: For instance, A. R. White (1975) also assumed that a concept signifies a way of classifying something. Thus, this essay is not concerned with concept acquisition per se, but rather with how a concept can take on new meaning as a form of learning. This also presupposes that one already has some notion of what a particular concept is.

The term "conceptual change" is misleading in that it can refer either to the outcome of the change (or the resulting category to which a concept is assigned), or to the processes that achieve such changes. The literature on conceptual change is often ambiguous about this distinction. "Conceptual change" is used here to mean one of these ways and should be clear from the context; otherwise it is explicitly clarified.

The thesis to be put forth in this essay is that it may be important to discriminate between conceptual change that occurs within an ontological category and one that necessitates a change between ontological categories. The former I shall simply call conceptual change or conceptual change within an ontological category, and the latter *radical conceptual change* or conceptual change across ontological categories. Making such a discrimination may be critical for a better understanding of learning and development, as well as many other related phenomena, such as the occurrence of scientific discoveries.

1.1. The Nature of Ontological Categories

The nature of ontological knowledge has been investigated in the psychological literature primarily by Keil (1979). Ontology divides our knowledge into categories that are conceptually distinct in a way that is somewhat difficult to define, although the distinction can be easily captured. Consistent with theories provided by Sommers (1971) and Keil (1979), I propose that there exist a few major categories in the world that are ontologically distinct physically, and should be perceived by adults as ontologically distinct psychologically. Figure 1 shows three basic ontological categories: matter (or material substances), events, and abstractions. (There may be others as well.)

The intrinsic reality of ontological categories can be determined in two ways, as shown in the list below. First, a distinct set of physical laws or constraints governs the behavior and ontological attributes of each ontological category. For example, objects in the matter category must have a certain set of constraints that dictate their behavior and the kind of properties they can have. Matter (such as sand, paint, or human beings) has ontological attributes such as being containable and storable, having volume and mass, having color, and so forth. In contrast, events such as war do not have these ontological attributes and obey a different set of constraints. (An ontological attribute is defined by Sommers [1971] as a property that an entity has the potential to have, such as being colored, even though it does not have it. War or pain, for instance, does not have the ontological attribute of "being red," whereas squirrels can have such an ontological attribute even though squirrels are commonly not red.) Thus, events are governed by an alternative, distinct set of physical laws, such as varying with time, occurring over time, being unstorable, having a beginning and an end, and so on.

Corresponding Ways to Capture the Reality of Ontological Categories

Intrinsic Reality

1. A distinct set of constraints govern the behavior and properties of entities in each ontological category.
2. No physical operations (such as surgery, movement) can transform entities in one ontological category to entities in another ontological category.

Psychological Reality

1. A distinct set of predicates modify concepts in one ontological category versus another, based on sensibility judgment task.

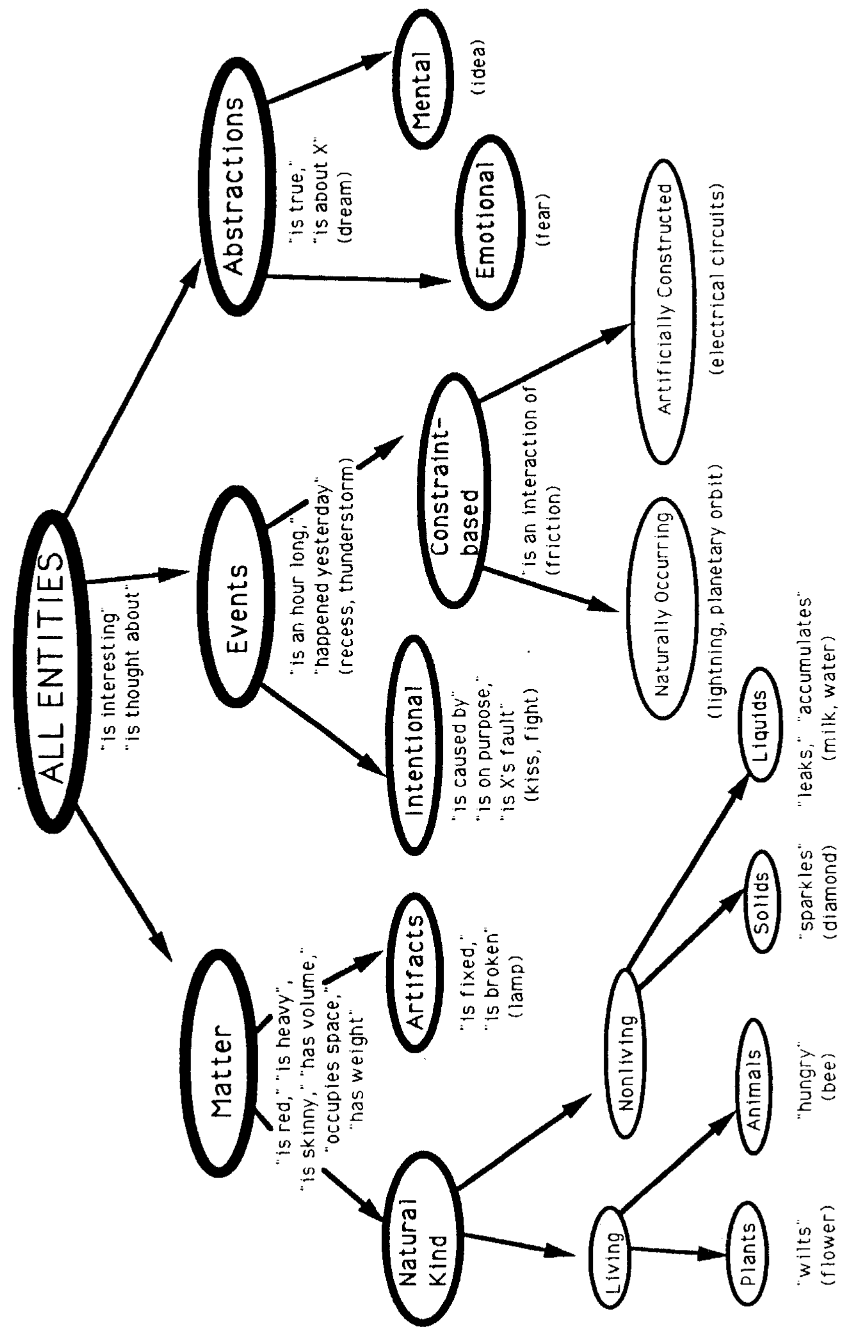

Figure 1. An idealized ontology.

2. No psychological mechanism (such as deletion or addition of features, analogy, generalization, specialization) can transform a concept in one ontological category to a concept in another ontological category.

A second way to capture the reality of ontological categories is to show that entities in distinct ontological categories cannot be transformed physically from one category to another. No physical operations (such as surgical operations, movement) can transform entities in one ontological category to entities in another. For example, "men" can participate in a "race" by moving and running (a physical operation), but "moving men" have not been transformed into a race: The men still preserve the identity of men.

Ontological categories can be determined empirically to be psychologically real and distinct if they are modified by distinct sets of predicates. A linguistic test commonly used by philosophers — the sensibility of the predicated term — can determine whether two categories are ontologically distinct or not. As illustrated in Figure 1, each of the major categories (matter, events, and abstractions) generates a "tree" of subcategories. A predicate (indicated in quotes) that modifies one concept will sensibly modify all other concepts below it on the same (branch of a) tree (commonly known as "dominate"), even if the modification is false. Thus, a bee has the potential to be "heavy" even though it is false, whereas a bee cannot be "an hour long." Conversely, an event can be "an hour long" but not "skinny." The point is that predicates on the same tree can modify concepts below it sensibly even if it is false, because the truth or falsity of the sentence can be checked. However, when predicates from a different branch of the same tree or different trees are used to modify concepts on another branch or another tree, then the sentence does not make sense. For instance, it makes no sense to say "The thunderstorm is broken." Such statements are called category mistakes. "The thunderstorm is broken" is not merely a falsehood, for otherwise "The thunderstorm is unbroken" would be true. "The thunderstorm is broken" is a category mistake because "broken" is a predicate used to modify physical objects made of material substances, whereas thunderstorm is a type of event, thus belonging to the other ontological category. The psychological reality of some of the ontological categories depicted in Figure 1 has been tested by Gelman (1988) and Keil (1979; 1989). Besides the sensibility judgment task, Keil (1989) has also used a physical transformation task such as surgical operations to show that even young children will honor the distinction between natural kinds and artifacts.

In general, categories are ontologically distinct if one is not a superordinate of the other. Thus, branches on the same tree can presumably form distinct ontological categories as well, as in the case of the distinction of natural kind from artifacts. For purposes of discussion, the three major ontological categories in Figure 1 will be referred to as the "trees," and "branches" that do not occupy a subordinate-superordinate role may be considered the basic ontological categories.

Three caveats are necessary. First, Figure 1 can be a hierarchy reflecting intrinsically real ontology (in which the term "entities" will henceforth be used to refer to the category members). By intrinsically real, I mean an idealization based on certain scientific disciplinary standards. There can be another tree that corresponds to a psychological ontology (in which the category members will be referred to as "concepts"). The idealized and the psychologically represented ontological trees should be isomorphic, even though they may not be. (In fact, the thesis presented here addresses precisely the problem that arises for learning when there is a mismatch between the intrinsic and the psychological ontology.) There is no literature or psychological evidence about this isomorphism (or lack of it).

A second caveat is that the distinction between basic and major ontological categories is made here for the sake of discussion. Whether or not there is a greater physical and/or psychological distance among major ontological categories than among the basic ones within a tree is not known. This is an empirically tractable question though. A third caveat is that the argument put forth here assumes an intrinsic and a psychological distinction among the trees (or major ontological categories) only. The extent to which the branches are ontologically distinct (e.g., Are fish and mammals ontologically distinct? What about plants and animals?) remains an epistemological and psychological issue that is not to be addressed here. For instance, the criteria described in the above list can also apply to the distinction between classes and collections (Markman 1979). To what extent classes and collections are ontologically distinct needs to be explored.

1.2. Assertions of the Theory

The theory proposed in this essay makes two assertions. First, that conceptual change within ontological categories requires a different set of processes than conceptual change across ontological categories. In fact, the kind of learning processes that can foster conceptual change within an ontological category is inappropriate initially for achieving conceptual change across ontological categories. Moreover, it may be inappropriate to think of conceptual change across ontological categories as a change at all. It may be more proper to think of this kind of radical change as the development or acquisition of new conceptions, with the initial conceptions remaining more or less intact.

Figure 2 depicts the two types of conceptual change schematically. For conceptual change within a tree (depicted by the two trees *a* and *b* in the left column of Figure 2), the concepts themselves do not change their basic meaning; thus, the shapes of the nodes in Figure 2*a* and 2*b* are preserved as the original tree evolves. What can change is the location of the nodes in the context of the tree: The concepts have migrated. Such migration can result from the concepts having acquired more attributes, or certain attributes may become more or less salient, and so forth. Examples of migration will be presented in the latter half of this essay. Thus, another good way to characterize nonradical conceptual change is reorganization of the tree, or perhaps even restructuring (although the term *restructuring* tends to imply radical conceptual change, so I will refrain from using that term).

For radical conceptual change (depicted by the tree *c* in the second row of Figure 2), the nodes themselves change meaning (thus represented by different shapes in Figure 2*c* from the original tree). And there is actually no isomorphic mapping between the nodes of the two trees, even though there may be superficial correspondences. For example, Black's concept of heat (which was differentiated from temperature in the eighteenth century) corresponds only superficially to the Experimenters' undifferentiated concept of heat (more analogous to hotness). This is what philosophers refer to as incommensurability of concepts. Thus, it is proposed here that radical conceptual change refers to an *outcome* of change in which a concept's original assignment to a category has shifted to a new assignment. One might conceive of a concept as initially belonging to the original tree, and subsequently after radical conceptual change it then belongs to the tree depicted in Figure 2*c*. The question that has been puzzling researchers is what mechanism moves a concept from one tree to another totally distinct tree. To preview a bit, the thesis to be put forth in this essay is that it may be inaccurate to think of conceptual change as a *movement* or *evolution* of a concept from one tree to another in a gradual or abrupt manner, as in the case of conceptual change within a tree. Rather, such concepts on distinct trees may be better developed independently, so that there is really no *shifting* per se, although the resulting outcome represents a *shift*. Thus, new conceptions on an ontologically distinct tree can be developed *gradually*, and yet the final outcome of the development (the shift) may appear to occur *abruptly*. This separation of outcome and process, I think, explicates the confusion in the literature about the abruptness or gradualness of conceptual change.

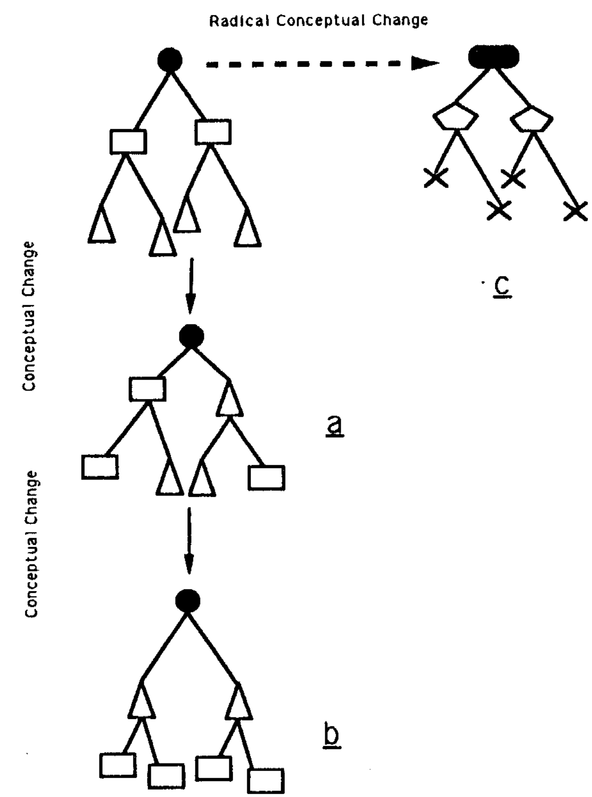

Figure 2. A schematic depiction of radical and nonradical conceptual change.

This view has two important implications. First, a concept may continue to remain on the original tree, even though its corresponding counterpart has developed on the new tree; and second, this view obviates the need to search for a mechanism that accounts for such a transition. Thus, this radical shifting (or lack of it) is depicted in Figure 2 by dotted lines.

Radical conceptual change (the outcome) must be more complicated than simply reassigning a concept to another category. Simple reassignment can occur on many occasions, such as when we are told that whales are mammals even though we initially thought that they were fish. This particular reassignment may be easy for adults to make for two reasons. The first possible explanation is that perhaps mammals and fish do not constitute distinct ontological categories for adults. That is, we know that mammals and fish are both kinds of animals; therefore our initial conception that whales are fish is merely false, and not a category mistake (Keil 1979). Category mistakes occur when we attribute a concept with a property that belongs to another ontological category. Thus the ease of reassigning whales to the class of mammals can take place precisely because no ontological boundary has to be crossed. An equally viable alternative explanation is that mammals and fish are distinct basic ontological categories, and the ease of reassigning whales to mammals is due to the fact that as adults, we are quite familiar with both the fish and mammals categories, so that we can easily attribute whales with all the characteristic and defining properties of mammals; and furthermore, we can verify that whales indeed do possess some of these properties.

By our definition, then, radical conceptual change requires that a concept be reassigned from one ontological category to another. If this definition prevails for radical conceptual change, then it is obvious that it must occur infrequently. So, for instance, we find it difficult to change our belief that an entity that belongs to one ontological category (such as a human being) can be changed to an entity in another ontological category (such as a spiritual being). Furthermore, a prerequisite for crossing such an ontological barrier is to have some understanding and knowledge of the target category to which the concept is to be changed. Our first assertion, then, is that different sets of processes are necessary for conceptual change within and across ontological categories. The exact nature of these processes will be elaborated later.

The second assertion is that learning certain science topics or domains, such as physics, requires conceptual change across ontological categories, and this is what causes difficulty. This is because the scientific meaning of physical science concepts belongs to a different ontological category than naive intuitive meaning. Some basic physical science concepts (those that are learned in an introductory physics course) are conceived by naive students as belonging to the ontological category of material substance, whereas scientists conceive of them as entities belonging to the ontological category of "constraint-based events" (a term I shall use to refer to entities such as current, see Figure 1 again).[1] Therefore, for physics entities, there is a mismatch between their intrinsic properties and how they are perceived psychologically. Students treat them as belonging to the same ontological category as other material substances, whereas in reality they are physically distinct. Thus, students perceive physics concepts to belong to the same ontological category as material substance, so that they use the behavior and properties of matter to interpret the behavior and properties of constraint-based events. This means that in learning physics, students need to differentiate their intuitive ontology of these concepts from their physics ontology.

The argument put forth in this essay, regarding the implication of a mismatch in the intrinsically real and the psychologically represented ontological categories for learning and discovering of science concepts, constitutes a preliminary sketch of a theory that implicates the psychological effect of ontological categories for learning and development. Although there is hardly any work in the literature about the psychological reality of ontological categories, my assertions are supported by the following three sets of general evidence. First, abundant data show that it has been extremely difficult to capture learning and understanding of basic physics in the laboratory or in the classroom, and similarly, it had been historically extremely difficult to discover the correct Newtonian views. This difficulty is consistent with the claim that such learning, understanding, and discovery require a radical conceptual change in students' and scientists' perception of individual physics entities from a type of substance to a type of constraint-based event. That is, to achieve radical conceptual change in this case is to learn to differentiate the two ontological categories, and not to borrow predicates and properties of the material substance category to interpret events in the alternative category. Second, there is an explicit similarity in the conceptions of physical science concepts by naive students and medieval scientists, and I interpret this correspondence to arise from both groups of people having adopted a material substance view. Third, the processes of discovery by medieval scientists and the processes of learning by naive students must be similar because they both require this radical conceptual shift. Details of this evidence will be presented later.

These assertions also have the following two implications: First, conceptual change across ontological categories is relatively difficult, not because the cognitive mechanism producing the change is complex and not well understood (as is often proposed for understanding transition, restructuring, and so forth), but because no cognitive processes (such as discrimination, differentiation, generalization, etc.) can *change* the meaning of a concept from one kind of a thing to another. For instance, adding or deleting features to the concept of "men" in a semantic network will not change "men" into the concept "war." "Men" can be a component of the concept "war," but the concept "men" will remain intact as an isolatable concept. Thus, the concept of "men" has not changed. More importantly, the concept "men" is embedded in a semantic network of human beings, as a kind of animal, which is then a kind of living thing, and so on. The concept "war" cannot possibly inherit these properties of "living things," so therefore the concept "war" cannot be modified from the concept "men" by an acquisition mechanism that we are familiar with. Instead, a new concept "war" can be built that consists of "men" as a necessary feature. Second, in order to have an ontological change as an outcome, we may have to first learn about the new category, before we can assign a concept from an original category to it. This suggests that the difficulty of radical conceptual change is not in the process of change itself (the process of reassignment), but the difficulty lies in two independent processes: (1) the new category of knowledge must first be learned and understood or induced; and (2) one often has to induce the realization (i.e., problem finding) that a concept does not belong to the category that the person had originally assigned it. For example, we may never realize that force is not a kind of impetus embodied in a moving object. To realize it on our own is clearly a nontrivial induction, comparable to a scientific discovery.

2. Conceptual Change across Ontological Categories

As mentioned earlier, radical conceptual change occurs infrequently in our everyday context. It is not often the case in our daily experiences that we have to change our conception of a physical object from being of one kind to another. Furthermore, to move a concept from one subtree to another appears counterintuitive, because it violates its physical meaning in terms of what kind of a thing it is. For example, even four-year-olds acknowledge that living things are fundamentally different from artifacts. Two pieces of evidence attest to this acknowledgment. First, four-year-olds never attribute artifacts with any animal or human properties (Carey 1985; Chi 1988). Keil's work (1989) shows that even at age five, children will agree that certain physical transformations are meaningful and others not, and the distinction is drawn between ontological categories such as natural kinds and artifacts. For example, they will agree that a skunk can be transformed to a raccoon with the appropriate operations, such as shaving off its fur, replacing the black fur with brown fur, replacing the tail with another, and so on. However, five-year-olds will not accept a transformation as possible that crosses boundaries of basic ontological categories, such as transforming a toy dog to a real dog. Thus, Keil's data provide evidence that even preschoolers will implicitly honor the boundaries between conceptual structures of "different" kinds. The following two sections discuss the extent to which physical science concepts belong to an ontologically distinct category from naive conceptions, and the processes of radical conceptual change.

2.1. Learning Science Concepts

One of the major occasions for needing radical conceptual change is in the learning of science concepts. This essay will argue that what creates difficulties for students in learning certain science domains is that the learning requires a fundamental change in the category to which one's initial conception of science concepts belongs. That is, naive conceptions about physics concepts belong to a different ontological category than scientific conceptions.

Understanding the nature of naive (or mis-) conceptions is a relatively recent inquiry. In the last decade or so, science educators have finally forgone Piaget's notion of viewing the learner as bringing to the task only logical-mathematical knowledge, and instead, have begun to investigate "the substance of the actual beliefs and concepts held by children" (Erickson 1979, p. 221). Thus, it has been recognized by science educators only within the last decade that students come to the classroom with naive conceptions or preconceptions of science concepts (as opposed to no conceptions), and these preconceptions are usually incorrect from the scientific point of view; thus they are referred to as *misconceptions*. A large number of studies (totaling more than fifteen hundred; see the bibliography of research on misconceptions in Pfundt and Duit 1988) in the past decade were devoted to analyzing children's and naive college students' ideas about forces, motion, light, heat, simple electrical circuits, and so forth (see Driver and Easley [1978] for a review). These misconceptions are very robust, and are very easily documented. For instance, the typical notion of force and motion is that force is an entity that can be possessed, transferred, and dissipated, such that there need to be agents for the causes and control of motion, as well as agents for the supply of force (Law and Ki 1981). Thus, force is a kind of impetuslike substance, and it is a property of material objects. This recognition was first brought to the attention of cognitive scientists by the publications of McCloskey and colleagues (McCloskey, Caramazza, and Green 1980).

What kind of conceptual change does learning science concepts require? Although the consensus among science educators is that a radical restructuring type of conceptual change is required, analogous to accommodation (Osborne and Wittrock 1983), no direct attempts have been made to explicate exactly what kind of changes are needed, and what mechanisms might produce such changes. Many instructional and laboratory attempts at producing changes have resulted in failures. The basic issues have then evolved into identifying whether or not students' naive beliefs are theorylike, and what kind of changes are required to modify the naive theory to a scientific theory.

The reason that learning science concepts is difficult and instruction has failed, according to the present theory, is because students treat scientific concepts as belonging to the same ontological category as matter. Therefore, in interpreting instruction about science concepts, they borrow ontological attributes of material substance to explain and predict behavior of scientific concepts. This assumption is supported by an extensive survey of the science education literature, in which Reiner, Chi, and Resnick (1988) and Reiner et al. (in preparation) have suggested that the fundamental conception that underlies most of the students' conception of physical science concepts is to treat them as a kind of substance. This conclusion was based on a survey of the literature examining students' misconceptions across four different concepts: A consistent pattern was found among students of all ages, in that they attribute heat, light, current, and forces with properties of substances.

Overall, four characteristics emerge from the data we have surveyed in the literature. First, there is an impressive amount of consensus among findings of different researchers on the same concept, even though the consensus is often implicit (for example, several researchers have suggested that students' naive conceptions of heat are substance-based: Albert 1978; Erickson 1979; 1980; Tiberghien 1980; Rogan 1988; Wiser 1987). Second, there is also an implicit consensus among the findings of different researchers on the different concepts. That is, we have argued that the evidence strongly suggests that all four concepts that we surveyed — heat, light, forces, current — are treated as substance-based entities (Reiner, Chi, and Resnick 1988). Third, there appears to be no obvious developmental improvement across age, nor instructional-based improvement across educational levels, suggesting that greater learning or experience with the concepts themselves do not seem adequate to promote conceptual change. In fact, McCloskey's study that identified the existence of these misconceptions was conducted with Johns Hopkins undergraduates who had completed a course in mechanics. And finally, students' naive conceptions are similar to medieval scientists' conceptions, inviting the inference that the medieval scientists' conceptions were substance-based as well. (This point will be developed further below.)

The conclusion I make is simply that the very nature of the general robustness of the results in terms of the consistency (1) across studies, (2) across concepts, (3) across ages, (4) across educational levels, and (5) across historical periods, suggests that substance is the ontological category to which students assign these physical science concepts. Thus, in order for students to really understand what forces, light, heat, and current are, they need to change their conception that these entities are

substances, and conceive of them as a kind of constraint-based event (including fields), thereby requiring a change in ontology. That is, for a lack of better terms, let us consider these physics entities, such as fields, as a type of constraint-based event: They exist only as defined by relational constraints among several entities, and their existence depends on the values or status of these other variables. For example, current exists only when charges move in an electric field between two points. A field is what fills the space around a mass, an electrical charge, or a magnet, but it can be experienced only by another mass, electric charge, or magnet that is introduced into this region. Hence, fields are neither substances nor properties of substances. Viewed this way, it becomes apparent that learning science concepts in the classroom requires radical conceptual change, in which students' initial conception of certain entities as a kind of substance has to undergo a reassignment into the constraint-based event category. This kind of reassignment cannot be achieved through any kind of acquisition mechanism, such as deletion or addition, discrimination or generalization, since such operations cannot simply transform a substance-based type of entity to a constraint-based event entity (as illustrated earlier with the concepts of "men" and "race"). One of the most compelling pieces of evidence is provided by Law and Ki. They asked high school students to write down a set of Prolog rules to describe the trajectories and forces of an object's motion. When the students are confronted with motion and trajectories that violate their rules' predictions, they then modify their rules by adding, deleting, refining, or generalizing them — mechanisms that are well-defined and implemented in computational theories of learning. However, such local patching did not change the fundamental meaning of their concept of forces, thus supporting our conjecture that radical conceptual change cannot be achieved by *revising* existing conceptions with common acquisition processes.

2.2. Processes of Radical Conceptual Change

The assertion to be proposed below about the cognitive processes responsible for conceptual change across ontological categories (i.e., in learning physics) is isomorphic to those of the physical processes in that no cognitive processes can directly transform a concept from one ontological category to another. This means that the processes of learning that cognitive psychologists currently understand — addition, deletion, discrimination, generalization, concatenation, chunking, analogizing — cannot actually transform a concept originally stored as belonging to one ontological category to another. Instead, conceptual change that requires crossing ontological boundaries must take place via a three-step procedure, as shown in the list below. The sequencing of the first two steps depends on whether the conceptual change is achieved by induction or by instruction. In any case, one of the three steps (Step 1 in the list below) is that the students must induce or be told that physics entities belong to a different ontological category. We surmise that this knowledge is induced in the context of the current mode of physics instruction, and it should probably be told instead (to be elaborated in the end of this essay). To have students find out themselves would be comparable to the processes of discovery, thus too difficult for students to undertake. In any case, a necessary step in radical conceptual change is to know about the properties and behavior of events, and in particular about this specific constraint-based kind of event.

Processes of Radical Conceptual Change

1. Learn the new ontological category's properties via acquisition processes;
2. Learn the meaning of individual concepts within this ontological category via acquisition processes;
3. Reassign a concept to this new ontological category (there are three possible sets of processes to achieve this reassignment):
   a. actively abandon the concept's original meaning and replace it with the new meaning;
   b. allow both meanings to coexist and access both meanings depending on context;
   c. replace automatically via coherence and strength of new meaning.

A second step (Step 2 in the list) in the ontological shift is to learn the individual physics concepts (such as heat, current) in a slow and laborious manner, proceeding in much the same way as traditional instruction. The learning process for this second phase occurs by the common acquisition processes that we already understand, such as deletion, addition, discrimination, generalization, and so on. However, the accretion and assimilation should be done in the context of the properties of the overarching constraint-based ontological category, rather than in the context of naive substance-based conceptions.

After such learning has taken place, in which the acquisition is embedded in the context of this event-ontological category, then the final stage (Step 3 in the above list) is for the students to "reassign" these entities (displacement view) or "identify" these entities with the event category (coexisting view). This reassignment procedure can take place in three ways. An explicit way (3a of the above list) is for the student to actively abandon the concept's original meaning and replace it with the new meaning, assuming that the person now has dual meanings associated with a concept. This explicit way is the most commonly conceived of way, such as by historians when they discuss scientific revolutions, and implicitly by many psychologists. For a simple example, it means we have to consciously think of whales as a kind of mammal rather than as fish. A better example would be for students to no longer think of forces as a kind of impetus that can be emitted by objects, but as a kind of attraction between two objects. A second way (3b) that a reassignment can take place is for the two assignments to co-occur simultaneously. That is, a concept simply takes on two meanings or gets assigned to two different categories, and one does not replace the other. The two meanings are accessed under different circumstances. This coexisting view is probably what actually happens. Evidence shows that even physicists will occasionally revert back and use naive notions to make predictions of everyday events (McDermott 1984). The third way (3c) that a reassignment can take place is for it to happen automatically, without conscious effort, by the mere fact that the concept's new meaning is perhaps more coherent and robust, since this new category of knowledge is usually learned via instruction, whereas a concept's original meaning is usually induced from the environment in everyday context, in a haphazard fashion. Thagard's (1989) computational model of theory selection can be viewed as a mechanism to account for this kind of reassignment. All three reassignment procedures can take place. No empirical evidence exists to discriminate among them.

The totality of all the processes outlined in the above list constitutes "the processes of radical conceptual change." Notice that acquisition processes (such as deletion, addition, generalization, and so on) are embedded in the subprocesses of the total processes of radical conceptual change. The point is that radical conceptual change requires the learning of Steps 1 and 2 in the above list (either from induction or from being told). Acquisition processes are responsible for the learning at these stages.

To recapitulate, radical conceptual change (or a shift) has taken place after the processes of Steps 1, 2, and 3 have occurred. Traditional physics instruction focused primarily on Step 2. We surmise that students who have successfully learned physics have induced Step 1, and executed Step 3. Instruction may have to focus on teaching Step 1 and explaining Step 3.

2.3. Discovering Science Concepts

In the previous section, the argument put forth is that *learning* physical science concepts requires the student to undergo the processes of radical conceptual change as depicted in the list in the previous section. In this section, I explore the possibility that radical conceptual change is the critical factor that underlies scientific revolutions, scientific discoveries, as well as scientific thinking by lay adults and by children.

At the level of discussion that occurs in the literature, there is no question that there exists a superficial similarity in the processes of scientific revolutions and individual scientist's discoveries, as well as children's scientific reasoning. Revolutions, discoveries, and reasoning usually proceed in a broad five-step procedure, as shown in the accompanying list.

Five-step Procedure Leading to Scientific Discovery, Revolutions, or Thinking

1. a set of anomalies exists (or an unexplained phenomenon is encountered, or an impasse is reached);
2. their abundance reaches a crisis state (or the individual is overwhelmed by the conflicts or confrontations so that he/she realizes that there is a problem, sometimes referred to as the state of problem finding);
3. a new hypothesis is made or induced (i.e., abduction);
4. experiments are designed to test the new hypothesis, and a new theory is formulated on the basis of the results of the experiments;
5. the new theory is accepted (old theory is abandoned, overthrown, or replaced).

This five-step procedure varies only slightly depending on whether one is discussing a scientific revolution, an individual's discovery, or scientific thinking. In a revolution, there are some extraneous processes between Steps 4 and 5, such as the individual scientist has to convince a community of scientists to accept the new theory and abandon the old. Below, the argument presented proposes that a critical stage of discovery that has been overlooked may lie in a preceding step, one not depicted in the above list. This step is the stage at which a radical conceptual change is made, which then leads to the recognition that an anomaly presents a problem (Steps 1–2). But in order to recognize that a situation is anomalous, the scientist must undergo radical conceptual change prior to such recognition, assuming that the nature of medieval and naive conceptions are both substance-based. Such an assumption provides a reasonable interpretation to the somewhat confusing findings in the literature showing that sometimes anomalies are responsible for discoveries and other times not. (This will be elaborated below.) Unfortunately, the majority of the existing research on scientific discoveries does not focus on this preceding step of the discovery processes.

2.3.1. A Framework for Defining Scientific Revolution, Theory Change, and Conceptual Shift

Historians and philosophers of science have been discussing scientific revolutions for decades, as a form of change that comes about from processes that are beyond an incremental, piecemeal process (T. S. Kuhn 1970). They involve changes more extensive than at the level of individual theories; rather, such changes or revolutions involve the research traditions under which specific theories are constructed.

T. S. Kuhn (1970), Lakatos (1970), and Laudan (1977) all discuss theory change at the level of paradigms, or research programmes, or research traditions (these terms will be used interchangeably): that is, what constitutes a paradigm shift, or changes in world views. Paradigm shifts may be conceived of as analogous to crossing ontological boundaries. Perhaps a visual depiction of it will make this discussion clearer. In Figure 3, I have depicted the paradigms (X and Y) as the large circles, each encompassing individual theories (A, B, ... or E, F). Each theory within a paradigm includes a set of concepts ($a_1, a_2, \dots b_1, b_2, \dots$), and these concepts are shared by the different theories (A and B) in the same paradigm. Basically, a paradigm (corresponding to an ontological category) contains a small set of overarching, core assumptions ($X_1, X_2, \dots$): assumptions about the kind of basic entities in the world, how these entities interact, and the proper methods to use for constructing and testing theories about these entities (Laudan 1977). All scientists working within the framework of a given paradigm adopt this implicit set of assumptions. For instance, "evolutionary theory" really refers to a family of doctrines in which the fundamental assumption is that organic species have common lines of descent. All variants of evolutionary theories would implicitly make that assumption. Atomic theories refer to a large set of theories all of which are predicated on the assumption that matter is discontinuous. Likewise connectionist theories in psychology would assume that mental processes occur in parallel, as opposed to serially (Schneider 1987).

Thus, two research paradigms (X and Y) differ if they differ in their ontology and methodology, meaning that (1) their core concepts (a_1,

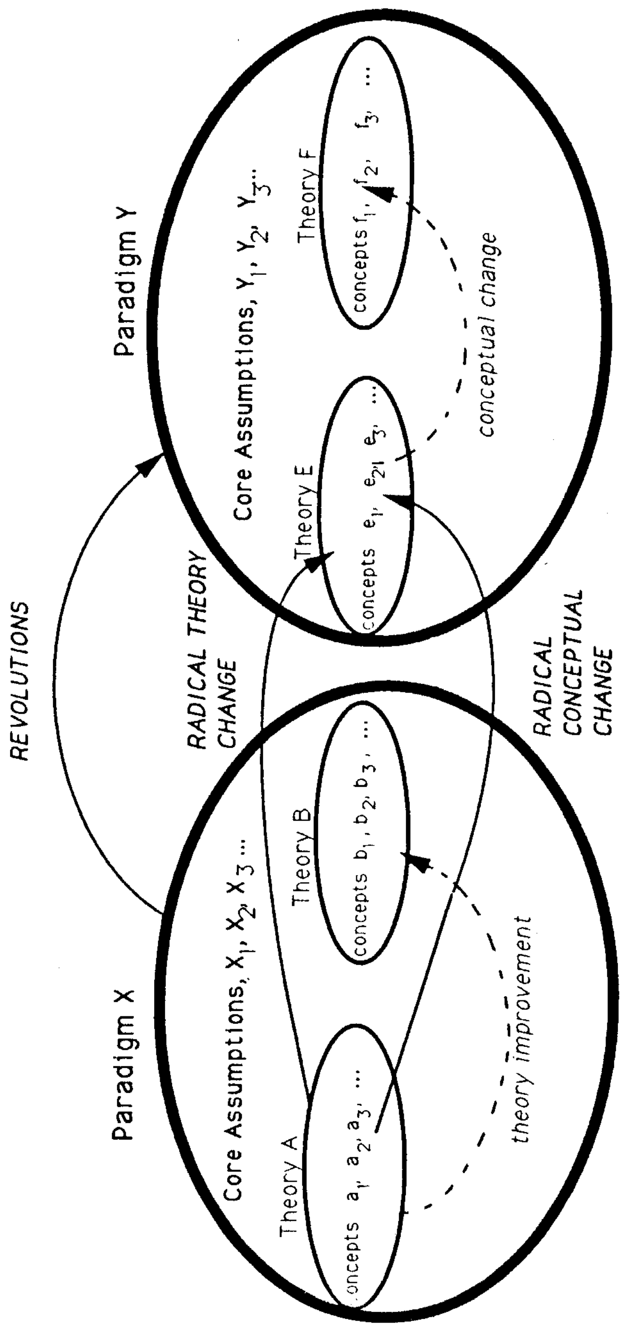

Figure 3. A schematic depiction of paradigm changes, theory changes, and conceptual changes.

$a_2, \ldots e_1, e_2, \ldots$) are ontologically different, (2) their explanations (based on those core concepts) must be different, and (3) the methodology by which the research is conducted is different. The idea is that because two paradigms are radically (or ontologically) different, it takes a revolution to overthrow one and replace it by another. By implication, the theories constructed from different paradigms (e.g., Theories A and E) would be radically different as well.

Different theories within a paradigm (A and B, or E and F), however, are not radically (or ontologically) different. They are merely modifications of one another, and they presumably assume the same set of concepts and scrutinize the same set of problems that are considered to be legitimate or admissible problems to be solved within the paradigm. Theory change within the same paradigm, on the other hand, is considered to be incremental, in the way normal science usually proceeds. Furthermore, scientists working within the same paradigm use the same set of methodologies or instruments to do their sciences. (All radical changes in Figure 3 are represented by solid arcs, and nonradical changes are represented by dotted arcs.)

Hence, in discussing paradigm shifts, historians and philosophers of science discuss the shifts predominantly at two levels: either at the level of the paradigm, such that the shift is referred to as a revolution, or at the level of individual theories embedded in *different* paradigms, referred to here as *"radical" theory change*, to be consistent with the terminology of radical conceptual change.

The proposal here is that one might want to interpret the occurrence and processes of paradigm and radical theory change to be predicated upon the existence of an underlying ontological conceptual shift. Thus, even though historians and philosophers of science discuss paradigm shift at the global level of revolutions, so that they have to worry about additional sociological and political processes involved in achieving the revolutions, this does not preclude the possibility that the impetus for such a revolution is the occurrence of an underlying radical conceptual change and a change in the explanations and principles based on these concepts. Of course, one often cannot discuss radical change at one level without simultaneously considering changes at other levels. So, for instance, although Nersessian's work (1989) discusses the historical shift at the level of a theory (from an impetus theory to a Newtonian inertial theory), because she is selecting theories that are embedded in different paradigms (thus radical theory change by definition), she is really addressing both the issues of paradigm change and radical conceptual change at the same time. However, because paradigm change is more global, we may gain greater understanding of paradigm shift if we first understand the radical conceptual change on which it is based, but the converse may not be true. Therefore, it seems critical that we understand conceptual change first.

To determine whether two theories *within* the same paradigm have undergone some significant change, two different sorts of analysis are probably required: one analysis considers the predictability and robustness of a theory in terms of how much evidence it can explain and how reliable the explanations are; the second analysis requires a determination of the structure and coherence of a theory. This is the sort of evaluation that all trained scientists are quite equipped to do. Thus, the issues that have to be considered for determining whether one theory is significantly better than another theory within a paradigm (let us call it *theory improvement*) are quite different from the issue of radical theory change (or how two theories from ontologically different paradigms differ). For theory improvement within a paradigm, one need not consider whether the two theories adopt the same concepts and/or the same methods. This is assumed. Instead, other considerations are needed, such as the criteria to be used for determining whether one theory is better than another. Thus, theory improvement is analogous to conceptual change within an ontological category, to be elaborated in the second half of this essay.

2.3.2. The Processes of Scientific Discovery, Reasoning, and Revolution

As stated earlier, by identifying the five-step procedure (see the list in sec. 2.3) as being responsible for scientific discovery, scientific reasoning, and scientific revolution, philosophers, psychologists, and developmentalists are not necessarily illuminating the dilemma that remains about how revolutions and discoveries occur. For example, this five-step process is often used to describe a child's adoption of a new theory. Karmiloff-Smith and Inhelder's data (1975) are a classic example, illustrating a discovery that is akin to the five-step process. Karmiloff-Smith and Inhelder observed what implicit theories children use to balance various beams whose center of gravity has been surreptitiously prearranged. Children began balancing by implicitly using the "theory" that the center of gravity necessarily coincides with the geometric center of the object. (Note that a more appropriate term to use here in describing their work might be "strategy" rather than "theory.") However, because the beams had been "fixed," Karmiloff-Smith and Inhelder were able to see when and how children would modify their original geometric-center theory. Children began by refusing to change their strategy of balancing the beam in its geometric center even though the feedback

contradicted their predictions. Thus, the feedback may be considered to be a confrontation of anomalies. However, after numerous counterexamples, children eventually developed the new theory, and abandoned their original geometric-center theory. Note that Karmiloff-Smith and Inhelder's use of the term "theory change" is not the same as the use defined in this essay. (Such diverse uses of the terms add considerable confusion to the literature.) In any case, because comparisons of scientific thinking and scientific discovery are often made at this global level, "the metaphor of the lay adult — or the child — as an intuitive scientist has gained wide acceptance in the last decade" (D. Kuhn 1989), and probably inappropriately so.

At this global level, the only key difference between scientific revolutions and individual scientist's and/or a child's discovery is that in the case of the individual, a scientist or a child has to convince only him/herself, whereas in the revolution case, the scientist has to convince a community of scientists, as well as the community at large. Besides the fact that such global mapping between historical analyses and individual analyses is too vague to be of any use, two questions remain unanswered with respect to the first two steps of the list in section 2.3. First, empirically, there are myriads of counterevidence showing that anomalies do not always foster discovery or conceptual shift for an individual. That is, Steps 1 and 2 (of the list in sec. 2.3) are not adequate to produce Steps 3 and 4. This is particularly clear in empirical results using a training-type of paradigm. It is also evident in Piaget's data and their replications. Instead, anomalies are often rejected or assimilated, or ad hoc explanations are provided to account for them. Anomalies are often rejected because they have not been recognized as such: that is, they are often rejected by theorists as inconsequential evidence. There is abundant evidence in both the developmental literature as well as in cases of scientific discoveries of such failed recognition. For example, the following sequence of events has been identified as having led to Lavoisier's discovery of oxygen (taken from T. S. Kuhn's account [1970, pp. 53–56]):

1. In 1772, Lavoisier was convinced both that something was amiss with the phlogiston theory, and was already anticipating that burning bodies absorbed some part of the atmosphere;
2. In 1774, Priestley had succeeded in collecting the gas released by heated red oxide of mercury and identified it as nitrous oxide;
3. In 1775, Priestley further identified it as common air but with less than its usual amounts of phlogiston;

4. In 1775, Lavoisier thought that the gas obtained by Priestley was air itself except perhaps it was more pure;
5. In 1777, Lavoisier finally concluded that the gas was one of the two main constituents of the atmosphere.

Note that the conclusion that Lavoisier came to was never reached by Priestley, and in fact, oxygen was isolated much earlier by Scheele, in the early 1770s. Hence, what led one scientist to the proper recognition and not others? Similarly, what led Faraday to recognize that the brief "sensible effect" of his galvanometer occurring when he connected the ring to the battery was a critical observation (Tweney 1985)? Or what enabled Alexander Fleming to notice that the mold that killed the bacteria that he was trying to grow on sterile agar plates was important? The point is that the knowledge embodied by some scientists is represented in a way to prime them to recognize that a given phenomenon is an important anomaly — a common finding in the perception literature; otherwise anomalies are rejected.

There are also many examples of assimilation. That is, anomalies are often not treated as an unusual event, but instead are assimilated into the existing knowledge and explained away by it. Vosniadou and Brewer (1989) have some great examples of assimilation. In their study of young children's conception of the earth's shape, Vosniadou and Brewer found that children assimilate the new correct information that the experimenter provided in numerous interesting ways. For example, if children think of the earth as square, and you tell them that it is round, they will then think that it is round like a pancake, rather than round like a sphere. If further instructed with the fact that the earth is round like a sphere, children then reconcile their conception of a flat earth with the information that the earth is a sphere by imagining a disklike flat surface inside or on top of the sphere, and people residing on that disk. These are clear examples of assimilation in that new information is incorporated into an existing knowledge structure. (Although young children do not remove their misconception about the shape of the earth that people stand on, this example of robustness illustrates a different cause of resistance than the factor of ontological change [see Chi, Chiu, and de Leeuw 1990].)

In those instances when new pieces of information cannot be assimilated, they become anomalies that can often then be explained away by ad hoc explanations. Abundant evidence of ad hoc explanations can be seen in the science education literature.

Besides the fact that anomalies can be rejected or assimilated or explained away, there is no reason why an individual or a scientist cannot

simultaneously operate under two theories, such that the anomalies can be explained in the context of one theory but not the other, as Laudan (1977) has also proposed. Therefore, there is no clear conclusion to be drawn about when and how anomalies can take the role of triggering a paradigm shift or conceptual change, unless we first understand the nature of the person's (or scientist's or child's) knowledge representation. This view is shared by Lakatos (1970), who has also claimed that paradigm shifts are not necessarily brought about by the accumulation of anomalies.

The second problem with such a global analysis of similarity in the five-step process of discovery, reasoning, and revolution is that the mechanism for what triggers discovery in both the historical and the individual cases is still not clear. It has been extremely difficult to capture the triggering event. For example, it may be nearly impossible to study the mechanism of discovery through historical analysis. Although the approach of diary analysis might be promising, the diary entries are often spaced too far apart to capture the processes of radical conceptual change. And numerous uncontrolled factors may play roles that are impossible to reconstruct historically.

Further, it has been equally difficult to capture the actual process of discovery in psychological laboratory studies. Most of the time, no overt observations can be made for inferring the internal mechanism (for example, in Karmiloff-Smith and Inhelder's data, the actual processes of shift could not be ascertained). At other times, the kind of evidence that has been captured for the presence of "invention" or "discovery" of a new strategy (which, as stated above, is not *akin* to discovering an ontologically new theory) is nothing more than a longer pause before a new strategy is adopted, or longer latencies. Siegler and Jenkins (1989), for instance, showed that the trial during which young children shift from using a simple counting strategy (the sum strategy) in which they add up two single-digit numbers (let us say $5 + 3$) by counting each hand (1,2,3,4,5; 1,2,3) then counting both hands together to get the sum (1,2,3,4,5,6,7,8), to a more sophisticated min strategy (in which they assert rather than count the quantity of one hand — 5, then increment the amount of the other hand, 6,7,8) was preceded by a trial with a very long latency, on the order of twenty seconds. It is not exactly clear what occurs during those twenty seconds of the preceding trial. Was the child testing the new strategy? In other words, perhaps the child simply adopted the min strategy, and double checked that it was accurate, thus requiring the extra twenty seconds. This length of time is consistent with this interpretation. However, the crucial question is: What made the child think of adopting this new strategy in the first place? Likewise, in traditional verbal learning tasks (Postman and Jarrett 1952), subjects were either informed or uninformed about the principle underlying the paired associations. However, uninformed subjects' performance improved dramatically on and after the trial at which they could state the principle. There is no direct evidence to reveal exactly what triggered the ability to finally state the principle, other than a noticeable improvement for a few trials preceding the first trial at which the principle was stated. An interpretation similar to the one I proposed for the Siegler and Jenkins result can be offered here as well, namely that in the trials preceding the principle-stating trial, subjects could have incidentally made the correct response, and took notice of the rule governing the response. When they are certain that the rule applies for a few trials, they then finally announced it. So, the trial at which they announced it simply reflects the point at which their confidence about the rule that they have induced has reached a critical level. What triggered the induction is still not captured.

Thus, it may actually be next to impossible to capture the very moment of transition, either during strategy shift or during some process of discovery. The best one can hope for is to model computationally the mechanism that might be taking place, and see whether the mechanism proposed actually predicts the timing and location during which "discovery" or "strategy shift" actually occurs. This is precisely what has been done by VanLehn (1991). (Note that a caveat is necessary: To repeat, the aforementioned strategy-shift literature is not entirely analogous to radical conceptual change, which may not occur in an instantaneous way, as the processes of the list in section 2.2 indicate. These works are cited here to illustrate a methodological difficulty.)

An alternative research approach is to worry less about the actual mechanism that may be responsible for the discovery or strategy shift, but rather, be more concerned about the structure of the mental representation at the time that such a discovery was made, so that the occurrence of an event that matched the representation could trigger the process of recognition, and thereby the subsequent processes of discovery. In other words, perhaps the fruitful questions that should be asked are those pertaining to Steps 1 and 2 of the discovery processes: how anomalies are seen as such, and how they reach crisis proportion, rather than Steps 3 and 4, in which one is concerned primarily with the process of formulating the final hypothesis. "Discoveries" are made only when the scientist's knowledge is represented in such a way that a specific recognition of the problem can be appropriately made. This is the same rationale I have given to the early problem-solving work, in which we focused on the initial representation that experts and novices bring

into the problem-solving situation, rather than focusing directly on the processes of problem solving as a search through a set of permissible states, thereby ignoring the role of the representation as it dictates the space from which the experts and novices search (Chi, Feltovich, and Glaser 1981). Thus, here, I propose the same line of analyses: unless we can clearly lay out what the scientist's initial representation is, we will not be able to fully uncover the mystery of the discovery process itself.

Because the nature of a scientist's representation in the process of discovery has not played a significant role in the research agenda of cognitive, developmental, and computational scientists, they have naturally focused their attention on the five different stages of this discovery process as depicted in the list in section 2.3. The majority of the research has focused on the processes of Steps 3–5 of the list (D. Kuhn 1989; Klahr and Dunbar 1988). Langley et al.'s work (1987), for example, addressed the problem of discovering laws given a set of empirical observations. For instance, BACON.5 can look for a linear relation among a set of variables by using a standard linear-regression technique. If the variables and their values fit a monotonically increasing relation, then the ratio between the two terms is found, if the signs of the values of the two terms are the same. If a monotonically decreasing trend occurs, then a product is defined, and so on. BACON.5's discovery is restricted to finding an appropriate fit of a mathematical expression to the empirical values that correspond to a prespecified set of variables. This process corresponds to the formulation of a new theory or principle (in the form of a mathematical expression) on the basis of experimental results (Step 4 of the list in sec. 2.3).

Much computational work is emerging concerning the other processes of discovery as well, such as the mechanism leading to the formulation of new hypotheses (Step 3 of the list in sec. 2.3, Darden and Rada 1988), and with designing experiments (Step 4, Falkenhainer and Rajamoney 1988; Dietterich and Buchanan 1983; Rajamoney 1988). Neither of these works focuses on the preceding stages of discovery — namely, the conditions of the knowledge representation that triggered "problem finding" or "recognizing a phenomenon as an anomaly," which is clearly viewed here as the most critical part of the discovery processes. In artistic productions, Getzels and Csikszentmihalyi (1976) also believe that problem finding is the most creative aspect.

In sum, in this section, I have argued that identifying what anomalies led to scientific discoveries, and/or inducing regularities in empirical data, and/or formulating the right hypotheses to test, may not be the loci of scientific discovery. Instead, scientific discoveries may be predicated upon the occurrence of radical conceptual change, which occurs prior to the five-step process. Radical conceptual change may have already occurred prior to the (1) recognition that a phenomenon is anomalous, (2) induction of regularities that exist in the empirical observations, and (3) formulation of hypotheses to test. Since these processes may occur after radical conceptual change has taken place, research efforts focused on these processes may not lead to an understanding of what triggered the processes of discovery, beginning with a recognition of anomalies.

2.3.3. Scientific Thinking

Because of the interest in the processes of discovery, there is a large body of literature concerning scientific thinking in the lay person. The idea behind this research is that the reason few discoveries are made (in either the everyday context or in scientific fields) may perhaps be due to the fact that children and the lay adults do not reason in a scientific way. Reasoning in a scientific way refers essentially to the methods that are used by scientists or what has been referred to as "the scientific method" (corresponding basically to the five-step procedure of the list in sec. 2.3). Hence, this line of research explores in what ways children and the lay adults are more naive in the way they reason: Is it because they do not weight all the available evidence? Is it because they cannot formulate all the hypotheses exhaustively? Is it because they do not search in a dual space? Is it because they do not engage in analogical reasoning? (See Klahr and Dunbar 1988; D. Kuhn, Amsel, and O'Loughlin 1988.) In short, most of the research in cognitive science, developmental psychology, and artificial intelligence concentrates on Steps 2–5 of the scientific method. Although the developmental findings offer interesting results, naturally showing that younger children are less efficient at scientific thinking than older children or adults (for example, younger children consider and/or generate fewer alternative hypotheses than older children), it is difficult to conclude from such results that younger children think less scientifically than older children or adults. An equally viable interpretation is that the form of reasoning most scientists can and do engage in is available to novices and perhaps children as well, but they merely lack the appropriate content knowledge to reason with. For example, Chi, Hutchinson, and Robin (1989) have shown that both experts (in the domain of dinosaurs) and novice children (of equal ability and age, about five to seven years old) are competent at using analogical comparisons to reason about novel dinosaurs (analogical reasoning is considered to be a significant part of the scientific method). The difference is that the expert children picked the exactly appropriate dinosaur family with which to incorporate and compare the novel dinosaur, whereas the novice children picked the closest animal family to

make their analogical comparisons. The outcome of course is that the expert children made all the correct inferences about a novel dinosaur, whereas the novice children made many incorrect inferences, since they based their analogies on an inappropriate source. Likewise, Schauble et al. (1991) looked at poor and good solvers' predictions of the outcome of a simple circuit, and found that the solvers' understanding of the circuit does exhibit the use of analogy. Both the good and the poor solvers show the same frequency of analogy use. The success, then, seems to depend on picking the right analogy, one that shows deep understanding of both the analogy and the target domain. Thus, the crucial matter is not whether you are or are not able to use analogies (part of a scientific method), but whether your knowledge base allows you to pick the appropriate analogy and reason from it.

Although it is probably true that people who have not made discoveries, or children who use more naive methods or mental models to solve a problem, are more likely to be less systematic and use less sophisticated strategies, this may be an outcome, rather than a cause, of their poor performance. Thus, the conjecture proposed here is that the ability to recognize a problem (Steps 1–2) is the crucial process that determines how successfully one can subsequently formulate a good hypothesis, and perform an experiment, and so forth. This would suggest that being *told* what the problem is may not be as effective, since the knowledge structures required to be able to "recognize" the problem are not necessarily available to the scientist who is simply told the problem.

Conversely, even though the literature is full of evidence depicting the lay person's and the child's fallacious reasoning, it has also been shown that scientists can reason fallaciously as well. For example, it is not uncommon for scientists to show confirmation biases: that is, testing hypotheses that can confirm their beliefs rather than disconfirm them (Faust 1984; Greenwald et al. 1986). Thus, although research on scientific thinking may uncover interesting differences between the way children and adults reason, or between the lay adults and scientists, my interpretation of such differences is that they are the outcome, and not necessarily the cause, of scientific discoveries. That is, a person tends to think systematically, and/or generate hypotheses exhaustively, and/or use analogical reasoning appropriately, only if he/she has a well-organized representation of the problem space that he/she is working with. Therefore, analyzing the reasoning strategies per se will not tell us what representation the reasoner is acting on, and whether it is the representation that dictated the pattern of the reasoning processes.

In sum, the argument put forth in this section asserts that in order for scientific discoveries to occur, a scientist or an individual must first be able to recognize that there is a problem. This recognition in turn requires that the person's knowledge be represented in such a way as to permit such a recognition. This implies that some form of radical conceptual change (in the case of discovering in the physical sciences) has probably taken place so that the knowledge representation is primed for such recognition. Thus, radical conceptual change may underlie the entire (five-step) discovery process, rather than an efficient use of "the scientific method," for the kind of ontological changes discussed here.

2.4. Similarity between Medieval Theories and Naive Conceptions: What Constitutes a "Theory"?

There are basically two ways in which similarity between medieval beliefs and naive beliefs have been drawn. One of the ways is to point to similarity in the actual beliefs or in the underlying assumptions. Using the actual-belief approach, Nersessian and Resnick (1989), for example, pointed out three categories of beliefs that constrained both the medieval as well as the contemporary views about motion, and these are: (1) all motion requires a causal explanation; (2) motion is caused by a mover or "force"; and (3) continuing motion is sustained by impetus or "force." Similarly, using the underlying-assumption approach, McCloskey proposed that students' naive intuitions resemble the assumptions made by the medieval scientists. For instance, the naive notions about motion are like the impetus theory discussed by Buridan in the fourteenth century in that both the naive notions and the impetus theory use the following two assumptions:

1. that an object set in motion acquires an internal force, and this internal force (impetus) keeps the object in motion;
2. that a moving object's impetus gradually dissipates (either spontaneously or as a result of external influences) so that the object gradually slows down and comes to a stop.

Wiser (1987) also uses this kind of argument to make claims about the similarity between naive conceptions of heat and those held by medieval scientists holding the source-recipient model.

A second way to point to the similarity between intuitive beliefs and medieval beliefs is to appeal to the notion that they are both theorylike. Thus, science educators are concerned with the issue of whether naive theories or conceptions conform to the notion of a "theory." The problem is how to define what a theory is, and how one can tell whether one has a theory or not. This is a problem that philosophers have tackled extensively (e.g., see Suppe 1977). Science educators and cognitive scientists implicitly assume the definition of a theory to be one that applies

to a scientific theory. Thus, in order to decide whether naive students' conceptions or beliefs are theorylike, many researchers point to the similarity between the students' thinking and that of medieval scientists, in a global sort of way. Besides drawing upon parallels between the contemporary students' views and the historical views in a global way (as illustrated in the foregoing paragraph), these researchers assume that naive students' beliefs are theorylike in the scientific or nomological sense of a theory, one in which the laws play a significant role in scientific explanation (Hempel 1966). Viennot (1979), for example, even tried to fit mathematical formulas to students' beliefs, thus raising the status of their beliefs to quantifiable laws. Viennot goes so far as to describe the students' conception in terms of mathematical equations, such as $F = \beta v$, and referred to these expressible pseudolinear relations as intuitive "laws." Clement (1982) also thought of students' conceptions as zeroth-order models that can be modified in order to achieve "greater precision and generality" (p. 15). A less principle-related way of claiming that students' naive conceptions are theorylike is to point to the general characteristics of their conceptions, which are (1) consistent or not capricious, and (2) robust and resistant to change.

It is easy to understand how the notions of a theory are borrowed from the scientific notion of a theory, since we are preoccupied with learning science domains, and all science domains are defined and bounded by their theories. Scientific theories tend to satisfy the classical positivists' view of a theory, in the sense that it explains a wide set of phenomena, is coherent (in the sense that there are no internal contradictions), and is often deductively closed. However, implicitly adopting the scientific definition of a theory may be the wrong assumption for determining the psychological nature of a "theory"; in other words, determining whether a body of knowledge from which one can generate explanations constitutes a "theory" or not is equivalent to determining what underlies a coherent theoretical structure for naive explanations. That is, does the knowledge from which naive explanations are generated have a coherent internal structure? Assessing the psychological coherence of such a knowledge structure should determine whether naive explanations are "theorylike." Furthermore, whether a set of naive explanations is theorylike cannot be determined by a single criterion, such as whether or not it is analogous to medieval conceptions. At the very minimum, one should determine whether naive explanations are theorylike on the basis of at least four criteria: consistency across studies, across concepts, across ages and/or schooling, and across historical periods. But preferably, one should develop methods to assess directly the structure and coherence of the knowledge base that generated naive explanations on an individual basis.

There is the alternative, contrasting view that the initial conceptions the student holds are not a theory at all in either the scientific sense or any sense of a theory, but merely an "untidy, unscientific collection of meanings" that are socially acquired and personally constructed (Solomon 1983, p. 5). In order to know that a set of meanings is not coherent, one must determine first what coherence is: Solomon basically meant it designated being consistent and logical, and perhaps also noncontradictory. Because students often seem unbaffled by contradictions in their explanations, Solomon therefore concluded that their world views are incoherent. (As noted earlier, ignoring contradictions need not imply that students' theories are or are not coherent.) DiSessa (1988) likewise holds the view that students' naive conceptions are not theorylike, but instead are disjointed, piecemeal, and fragmented. These pieces of knowledge are derived from phenomenological experiences, such as "overcoming" and "dying away" (to correspond to dissipating forces). Students' explanations are composed of a series of these phenomenological primitives, joined together to explain a particular event.

The reason that both of these theoretical views (a theorylike view and a non-theorylike view) are viable is because the empirical evidence seems to support both. Most of the time, students' explanations are robust, consistent over time, and sometimes consistent across different situations that tap the same concepts. But at other times, students' explanations seem ad hoc, and students seem to be able to accept and produce contradictory explanations, or ignore them. There are two ways to resolve such discrepancies. On the one hand, one could dismiss any discrepancy between the two views by saying that DiSessa's nontheory view, in principle, could be correct, and yet it need not necessarily be viewed as a refutation of McCloskey's and others' claim that naive explanations are theorylike. Instead, one could think of DiSessa's analysis as a reduction of the components of a theory into fundamental primitives. Such reductions need not be viewed as supplanting the claim that the naive beliefs are theorylike (Haugeland 1978). Reductions can be viewed as independent of the issue of whether or not the set of beliefs constitutes a coherent theory. On the other hand, the discrepancy might be resolvable if we adopt a uniform definition of a "theory." For instance, a theory might be a set of coherent primitives, so that the question then becomes: Are the phenomenological primitives coherent in some way?

There is no question that there exists a superficial similarity between contemporary students' beliefs and medieval theories, independent of

the issue of whether or not they are theorylike. However, the similarity is not at all surprising if one considers the origins of these naive conceptions. This is the occasion in which historical analogy is useful: for it may suggest what the origins of the misconceptions are, such as whether they are perceptually based on the external world, as in the case of physics concepts, or whether they are based on internalized knowledge, as in the case of some biological concepts. They must have arisen from our and the medieval scientists' daily experiential encounters with the physical world, with "objects in a friction-full world" (Clement 1982; Nersessian 1989). Such experiences began at birth, and Spelke (1990) has some fascinating data showing that even six-month-old infants are sensitive to the fact that solid objects such as a ball cannot pass through another solid object, such as a shelf. Nersessian (1989) goes on to point out, correctly, that such parallels are only weak ones, or exist only at a global level, because there are clearly fundamental differences between naive students and medieval scientists that are trivial to point out: the strongest argument against taking a strict parallel view is that in contrast to the conceptions of naive adults or children, medieval conceptions were "developed in response to problems with Aristotelian physics and metaphysics as well." Furthermore, these "historically naive conceptions are products of centuries of reasoning about problems of motion" (pp. 4–5). Twentieth-century students are not plagued by these metaphysical and epistemological problems. Brewer and Samarapungavan (in press) point out many additional differences between scientists and naive students. Nevertheless, there remains a consistent but weak similarity between the naive reasoning of the twentieth-century students and the reasoning of the medieval scientists. Although such similarity no doubt arose, "in part, from intuitions based on... interaction with the natural environment — with how things appear to move when dropped or thrown" (Nersessian 1989), the assumption of this essay would predict that such similarity must have arisen from the underlying assignment of these physical science concepts into the material substance category by both the medieval scientists and the naive students. That is, from their daily experiences, both the naive students and the medieval scientists have formed a substance schema that they use to judge, interpret, predict, and understand physical phenomena. Thus the coherence observed in naive explanations arises from the structure of the underlying substance schema.

I am not proposing that a general case can be made regarding all scientific concepts; that is, that all scientific revolutions are based on an ontological conceptual shift, and that naive conceptions are similar to the medieval ones because they are both based on the same underlying ontological belief. For instance, in biology, Harvey's discovery of the circulatory system, although hailed as a major breakthrough for modern scientific medicine, comparable in significance with the work of Galileo in physics (McKenzie 1960; Pagel 1951), may have characteristics to indicate that this discovery may not have required radical conceptual change of the kind that physical science concepts undergo. To support this point, we can use the four criterion characteristics cited above to see whether students' learning about the circulatory system has the same characteristics as are required for learning physical science concepts. Based on a survey of the scant literature available: (1) there basically appears to be no consistency across naive students' misconceptions about the circulatory system (Arnaudin and Mintzes 1986; Gellert 1962); (2) there was little consistency across different ages; (3) there was little consistency across schooling (in fact, there are usually developmental improvements in what students can understand about the circulatory system; see, for example, Gellert's data [1962]); and most importantly, (4) there seems to be no similarity at all between students' naive conceptions and the medieval misconceptions, as those held by Servetus, Columbus, and others (see progress report by Chi et al. 1989). Thus, I take these characteristics of the evidence to suggest that conceptual change across ontological categories is necessary for certain physical science concepts, whereas in some other types of scientific discipline, drawing on the topic of the circulatory system in particular, conceptual change does not require an ontological shift. In fact, the difficulty students have in learning about the human circulatory system may have nothing to do with the historical barriers that prevented the scientific discoveries from taking place. (The reasons why students may have difficulty learning about systems are spelled out in Chi 1990, and are independent of the issue of radical conceptual change.) Such differences in the nature of the underlying conceptual change among different scientific disciplines (or even different topics within any given discipline) have direct implications for learning and instruction.

The interpretation offered here can make sense out of seemingly discrepant data. Osborne and Wittrock (1983) noted that the proportion of children who held an ancient Greek view of mechanics *increased* from age thirteen to fifteen, whereas the proportion of children who considered a worm and a spider not to be animals *decreased* significantly from age five to eleven. Such discrepant findings can be easily interpreted in the current framework, in which misconceptions about mechanics can increase with age because an ontological shift did not occur with development, whereas misconceptions about animals can decrease because no ontological shift is needed to remove these sorts of misconceptions — they are based on learning that occurs with schooling and development. Examples of this sort are numerous.

In sum, this section addresses the issue that has plagued the research in science education — whether or not naive explanations conform to a theory. Note that the issue of theorylikeness is really quite independent of the issue of theory change. Theorylikeness represents a digression that has been misleading the research agenda, because it does not shed any more light on what constitutes theory change.

2.5. Evidence of Radical Conceptual Change

Now that we have some sense of what radical conceptual change is, is there any empirical evidence of success at eliciting it? There are numerous attempts that failed, especially in the educational literature. I am aware of only two attempts that claim to be somewhat successful, and these two will be discussed to see whether radical conceptual change has been successfully induced, elicited, or instructed. Since radical conceptual change is necessary primarily in physical science concepts, the examples will be taken from that domain (Ranney 1988; Joshua and Dupin 1987).

Ranney's dissertation data (Ranney 1988) attempted to generate evidence to determine the extent to which empirical and analogical feedback can produce coherence-enhancing reorganization among naive beliefs about kinematics and dynamics. Table 1 shows the five tasks Ranney used and the sequence of testing and feedback employed. Task 1 asks students to predict by drawing the trajectories of pendulum bobs that have been released from different points during a swing. Task 2 asks for the trajectories of heavy objects being dropped or thrown. Some of the problems in Tasks 1 and 2 are isomorphic. Task 3 asks students to match each pendulum release problem in Task 1 with a dropping/throwing problem in Task 2. That is, students are asked for a similarity judgment. Task 4 is a near-transfer task, consisting of problems involving a trapeze and a wrecking ball, rather than a pendulum bob. Task 5 is a far-transfer task in which the problems ask for trajectories of projectiles released in the absence of gravity. Table 1 shows a simplified version of Ranney's design: students are given pretests in all the tasks, feedback on Tasks 1 and 3, prediction on Task 2, posttests on Tasks 2, 4, and 5, and delayed posttests on all five tasks. The main result shows that from pretest to delayed posttest, there are significant improvements in all tasks except Task 5, the far-transfer problems.

Table 1. Ranney's Tasks and Sequence of Testing and Feedback

	Task 1 Pendulum	*Task 2* Dropping	*Task 3* Similarity	*Task 4* Near transfer	*Task 5* Far transfer
Pretest	X	X	X	X	X
Feedback	X		X		
Repredict		X			
Posttest		X		X	X
Delayed	X	X	X	X	X

This pattern of results is not surprising given that students were given feedback in both the pendulum release trajectories as well as the matching task (of pendulum release and dropping/throwing problems). Feedback in Task 3 on the similarity between problems of Tasks 1 and 2 allows the students to see the similarity in these types of problems without deep understanding. Therefore, they cannot make accurate predictions for the far-transfer problems. Although Ranney (1988) also reported evidence of greater consistency among the responses from pretest to posttest, such as more symmetrical predictions of leftward and rightward swings of the pendulum release problems, such increased consistency does not imply that students have gained greater understanding of the underlying kinematic knowledge. Such symmetrical responses can be gleaned from the symmetrical feedback. In sum, although there is no question that students' responses after feedback did become more consistent and coherent, this does not imply deeper understanding even though deeper understanding usually does lead to consistent and coherent responses. Ranney himself concluded that "deep conceptual changes, i.e., from impetus to inertia, were rare" (p. 6).

Joshua and Dupin (1987) attempted to demonstrate conceptual change in the context of understanding. That is, they attempted to teach understanding of electric current by analogizing it to a moving train. Naive students think of electric current as some kind of flowing fluid (instead of moving charges); thus they cannot understand how this fluid (the current) can be both conserved while it circulates (i.e., the intensity of the current is the same in the circuit), and yet wear out in the battery (i.e., providing the energy). An analogy of a train circulating on a closed loop track is provided. The analogy is made up of cars only (without locomotion) rigidly linked. In a station, workers permanently push on the cars going past in front of them and influence the train speed. Obstacles also exist

in the track that influence train speed (corresponding to resistance). The men pushing the train correspond to the battery, the muscular fatigue of men corresponds to the wearing out of the battery, and the car flow-rate corresponds to the current intensity, which should be the same at each point on the track because the cars are rigidly connected.

The claim is that this analogy enabled the students to understand that the current is the same everywhere (just as the car speed is the same everywhere on the track), and the battery can wear out just as the men can get tired from pushing. It is easy to see how students can learn some specific facts from this analogy without generalized understanding. What the students may have understood is the mapping from the local inferences that they can naturally draw about men and muscles, to the electric circuit. For example, they can draw the inference that if men continuously push on the train, then they will get tired, so that by analogy a battery must also wear out after persistent use. Likewise, the students can also draw and map the inference that if cars are rigidly attached, they must travel at the same speed; therefore, if electric charge is comparable to a rigidly attached train, then charge too will have the same intensity (speed of the train) throughout the whole circuit. They thus are asked, in a sense, to take the inferences they can naturally draw (tired men, same speed of train) and apply them directly to the circuit. However, it is not clear what can be gained from such limited and fragmented understanding. No relationship necessarily exists between the concepts of men and train, on the one hand, and the concepts of battery and current, on the other hand. For example, students will not understand that what *caused* current to flow is the potential difference that is provided by the voltage source (the battery), such that when the charge stops flowing, both ends of the electric conductor reach a common potential. There is not a comparable concept in the train-men analogy. Another way to put it is to ask what causes the current to cease flowing. There is a precise, predictable point at which current ceases: when there is no longer a potential difference. Thus, it is the difference in potential between two end points, rather than a single source (the men pushing), that causes current to flow. Thus, although this study claimed to have demonstrated conceptual change, I believe that only very localized mapping of inferences was made.

In sum, neither of the two studies achieved deep conceptual change of the kind discussed in this essay. This is because deep or radical conceptual change is not something that can be achieved easily through one or two sessions of instruction, feedback, or analogical illustrations.

2.6. Fostering Radical Conceptual Change in the Context of Instruction

Assuming that students' naive intuitions are different in kind from the scientific view (that is, the naive concepts are assigned to a different ontological category than the scientific concepts), what instructional strategy can be offered to revise this intuitive belief? Erickson (1980) summarizes a few standard procedures: (1) provide the students with a lot of experience with the concept (such as heat), (2) discuss and clarify these experiences, (3) create anomalous situations in which the outcome of the situation is counterintuitive to their initial ideas, and (4) restructure their initial ideas through group discussion and teacher intervention in which the inconsistency between accurate interpretation and students' ideas is pointed out. Suggestions 1 and 2 are the aims of traditional classroom instruction, and they presumably have failed to foster understanding of physical science concepts. Suggestion 3 is problematic in numerous ways that I have already cited. But to recapitulate, it has been found repeatedly that counterposing the students' intuitive ideas with the scientific theory does not lead to radical conceptual change: the preinstructional intuitive ideas may remain, although sometimes hidden or covered up with new words, or the new and old ideas coexist (Driver and Easley 1978). These instructions use a number of different tactics, such as providing counterexamples and conflicting evidence (Driver 1973). Again, the use of conflicting evidence is supposed to provoke a state of "cognitive conflict" or "mental disequilibrium" in the case of instructing children, so that the child may restructure (Posner et al. 1982). (The term "restructure" here is borrowed from Posner et al., and I use it in a generic sense. But in this case, it does refer to radical conceptual change.) However, because cognitive conflict does not yield new understanding, it is taken as evidence in favor of Piaget's notion that learning certain science concepts depends on preexisting logical operations.

The only novel suggestion is the fourth one, namely, that restructuring may be achieved via group and paired discussion. One of the ideas of group or paired problem solving is that it gives students an opportunity to be aware of their preconceptions and encourages them to compare and confront their ideas with the scientific ones. Such confrontations presumably would force them to explain the empirical observations. Thus many people are employing this approach (e.g., Minstrell 1988). But it is not entirely clear what aspects of these activities can produce cognitive changes, nor why such self-realized conflicts are more potent in producing change than those confrontations presented by the teacher, which we already have said are useless. From these group problem solving events, we also cannot know what each of the individual student's initial intuitive ideas are; therefore we cannot possibly know how malleable the individual student's ideas are to change. Although group or pair discussion has certain appeal as an instructional approach (Chi and Bjork, in press), it is not clear how group or pair discussion can promote radical conceptual change per se. Moreover, there is equally convincing negative evidence showing that group discussion in a class is not particularly productive at inducing conceptual change of the radical kind (Joshua and Dupin 1987).

Finally, there are other approaches to instructional interventions beside group discussion. The majority of these use novel technological advances, such as computerized microworlds, in which the concepts can be presented using visual displays (Roschelle 1986), so that they become more concrete (Champagne and Klopfer 1982; Wiser 1987; White and Fredricksen 1986). The overall success of these new approaches has not been systematically evaluated. However, I am skeptical about the tacit assumption underlying these approaches, which is that constraint-based events can be better understood by using concrete substance-based models in the instructional materials.

Any proposed instruction for learning physical science concepts must obey two constraints: First is that human processors understand new information by assimilating it with existing information; and second, that learning physical science concepts requires changing the ontology of the concepts. What kind of instruction can be proposed that fits these two constraints? There are two possible approaches. The first is the revision approach: that is, the attempt to modify a student's initial or naive conception. There are several ways to achieve this. The most obvious and direct way is to force revision by presenting other features and properties of the physics concept by building upon student's naive concepts (through adding, deleting, etc). We had already discussed why this would not make sense, because the naive concepts hang on a different ontological tree than the physics concepts, so that the naive concepts naturally inherit properties from their superordinate categories that would not be correct for the scientific meanings of the concepts. A second revision approach is to present conflicts. Again, we had discussed the discrepant role of conflicts. Conflicts between the student's predictions of a physical phenomenon and a scientific one can lead only to frustration and not to conceptual change (as discussed earlier in the context of the Law and Ki results), because the student cannot possibly *understand* the scientific prediction. Such understanding is the bottleneck to learning the new concept because we are constantly trying to understand this new ontology of concepts by using our substance-based schema. A third and more creative application of the revision approach, proposed by Clement (1982), is to *bridge* the new concepts to the existing concepts. Bridging is a slightly different notion than revising. Bridging means that you find a situation in which the student's naive understanding is consistent with the scientific one, and then build your instruction around this naive but correct understanding. Clement (1982), for example, picked a universally believed idea that is correct (such as that a hand does push up on a rock that the hand is holding) as an anchor from which to bridge an understanding of the idea of normal force, such as that a table would also be pushing on a rock, even though a table is inflexible. The progressive analogies that the student is taught (from the hand, to a spring, to a table) seem to work (that is, students now do believe that a table pushes up on a rock). But it is difficult to see what kind of understanding the students have gained about forces by accepting isolated facts that tables and other hard surfaces apply forces, since they never did understand why a hand pushes up on a rock in the first place. To understand *why* a table or a hand pushes up on a rock is equivalent to understanding the nature of forces.

Besides the revision approach, an alternative approach proposed here is the three-step procedure, corresponding to the processes of radical conceptual change outlined in the list in section 2.2. These processes include merely teaching the new concept and its domain independently (Step 2 of the list in sec. 2.2), much as the way traditional instruction has proceeded, but in addition, to add to such instruction of the specific content domain by emphasizing the ontology of this whole category of concepts (Step 1 of the list in sec. 2.2). So, for instance, such instruction would underscore the ontological attributes of constraint-based events (as opposed to matter) such as being dynamic, time-based, not concrete, often not visible, and so forth, and that many physical science concepts fall into this category. Teaching (or pointing out) such broad-based category knowledge would allow the students to build the bridge that links new domain information about physics concepts with the appropriate ontological tree. This means that the new knowledge can be built or assimilated in the context of the appropriate ontological tree, so that the concepts would not mistakenly inherit properties of the substance category. Thus, the bridge for assimilation is not with existing misconceptions, but with knowledge about the general characteristics of such an ontological category. That is, students could be given instruction first on the nature of this category of constraint-based events, so that additional learning about the concepts within this category can then be assimilated. As Feynman (1963) said, "One has to have the imagination to think of something that has never been seen before, never been heard of before." This instructional approach implicitly implies that students' naive views could be kept intact, since they are quite adequate for predicting everyday phenomena, and an independent knowledge structure should be developed for these new "never been heard of before" concepts.

The notion of having two independent knowledge structures operating — one naive and one formal — seems to have some support. There is evidence to suggest that people who have expert knowledge in physical science domains do seem to maintain two independent knowledge systems about physical science concepts (as if they have two separate microworlds). That is, experts often do fall back and use their naive intuitive notions to make simple predictions about their everyday physical events. This suggests that the naive notions have not been replaced by the scientific theories, but they in fact coexist with the scientific concepts. However, the naive notions are often not accessed, probably because the scientists or experts know that they are inappropriate. However, when scientists are caught off-guard, such as when they are requested to make predictions in an everyday context, or when they are not given time to reflect, they do resort to using their naive notions (Viennot 1979).

There are some informal observations that such an alternative instructional approach is viable. An analogy to the distinction between matter and events may be extensive and intensive quantities — the former is substance-based and the latter is not. Such a distinction between extensive and intensive quantities occurs throughout numerous physics concepts, such as the distinction between heat and temperature, charge and potential, momentum and velocity. A number of instructional approaches in Germany have attempted to introduce the distinction between extensive and intensive quantities, and then have used it to teach the physics concepts. Informal observation by S. Kesidou (personal communication, April 26, 1991) on ten students instructed this way showed that they seemed to have more correct and deeper understanding than students taught in the traditional way.

3. Conceptual Change within an Ontological Category

Conceptual change within an ontological category is by no means mundane. It is often quite difficult to achieve. But the difficulty resides in a number of factors, such as a lack of knowledge, or the complexity of the memory search processes, or the need for extended practice, and so forth, as opposed to a difficulty required by a reassignment across ontological categories. The critical distinction between conceptual change across versus within ontological categories is that concepts in the *within* case can migrate up and down a given tree, but not across the branches, since the branches can represent distinct ontological categories. So, for instance, "plants" and "animals" can merge to form a new superordinate category, "living things," but "plants" cannot become a part of "animals." There are various types of conceptual change within an ontological category. Five will be discussed.

3.1. Revision of Part-Whole Relations

The first type captures a kind of conceptual change in which a concept changes the level it occupies within the tree: Therefore, the concept's part-whole relationship relative to other concepts in the same tree has changed. Let me illustrate with a widely studied topic in developmental psychology. A commonly investigated subject in the developmental literature concerning conceptual change has to do with the concept of "living things." To illustrate the problem, I have depicted a young child's (usually intended to mean preschoolers) conception of "living" and "nonliving" things, based mostly on an interpretation of Carey's results (as shown in her 1985 book in Table 3.1, pp. 80–81). Shown in the top half of Figure 4 is a generic depiction of a young child's concept of "living," which has at least two separate categories, "animals" and "people" (whether "plants" exist as a separate category at this age is not completely clear from the data, so I have depicted that category in broken lines). Actually, a more accurate way to depict this is to say that "animals" and "people" are clearly distinct categories for the child's representation, both probably subsumed under the abstract category "living."

Although it is not clear what kinds of attributes are associated with the "living" node at this age, it is clear that there does exist an implicit contrasting category of "nonliving" things, corresponding to artifacts. Evidence for the existence of the "nonliving" category will be presented below. (However, because of the tenuous existence of the "nonliving" category, I have depicted it in a broken-lined oval also.) Aside from the issue of conceptual change, this literature also is concerned with questions such as whether or not children can make inductions based on category membership, and whether or not children exhibit false semantic mapping between the term *not alive* and the concept *dead*. We will not be dealing with these side issues explicitly.

To justify my depiction of a young child's representation, three sets of converging evidence will now be presented to support it. First, not only do young children exclude people from their category of animals (as when they are asked to pick out all the animals from a pile of pictures that include people), but furthermore, they do not project people

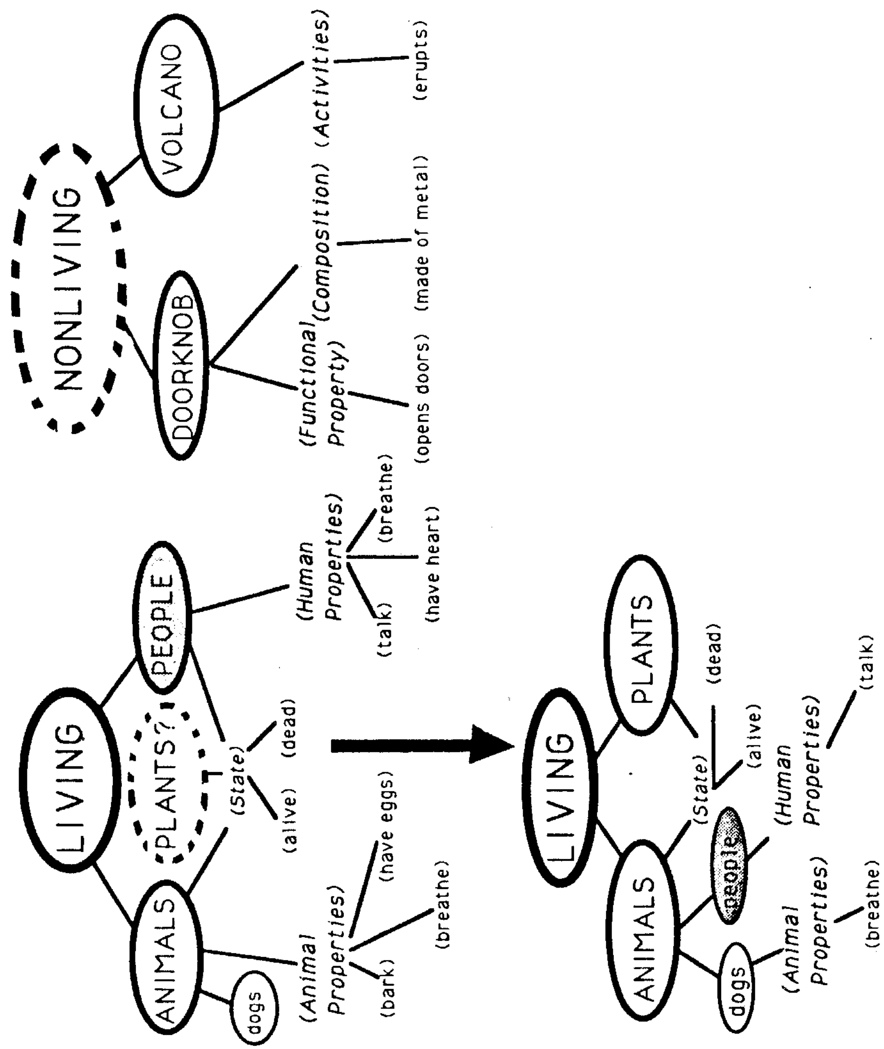

Figure 4. A generic representation of a four-year-old's knowledge of living and nonliving things.

attributes (such as eating and breathing) to other animals (such as hammerhead and stinkoo, which they know are different kinds of animals, when they are asked to pick all the animals out, Carey 1985). Second, although the categories of "living things" and "nonliving things" are never explicitly mentioned, it is obvious that they exist in a young child's representation and may be distinct categories, because properties of living things are *never* attributed to nonliving things such as a volcano or a cloud (Carey 1985; Chi 1988). For example, young children would never agree that "a doorknob breathes" (Chi 1988). Finally, Carey's data are convincing in favoring the interpretation that responses to attribution questions such as "Does a stinkoo breathe (or sleep, get hurt, have a heart, eat)?" are generated by comparing a specific animal in question to its likeness to people, since children know that these probed attributes are attributes of people. Taken together, these pieces of evidence suggest that it is safe to depict "people" as a separate subcategory of "living things," occupying an equivalent level as the subcategory "animals" within the hierarchy.

So far, the top half of Figure 4 simply shows a static and generic representation of a four-year-old's representation of "living" and "nonliving." What changes with development? Presumably, "people" eventually becomes a subset of "animals," and "plants" may gain equal status with "animals" as another kind of "living things." Thus, conceptual change from an inaccurate to an accurate adult representation would involve the migration of the "people" category to a subcategory of "animals," thereby sharing equal status with other instances of "animals," such as "dogs" (shown in the bottom half of Figure 4). This kind of conceptual change, in which concepts either ascend or descend branches of a tree, will be noted as a *change within the same tree* or ontological category, and will be referred to as reorganization.

This example should not confuse two separate claims. On the one hand, one could of course argue that a child who differentiates the concept of "people" from "animals" is fundamentally different from the child who has these concepts coalesced. What I am proposing, basically, is a definition of "fundamentally different." My point is that this kind of conceptual change, although rather dramatic, may not be radical in the sense that no ontological categories were crossed. Thagard (1989) may be making a similar discrimination in a kind of change that he calls *branch jumping*. It makes no difference at what level of the tree the changes are made. The point is that the change is within the same ontological category, occurring in an ascending or descending order. It is not the case, for example, that "people" have become a kind of "plants," which presumably are distinct, "basic" ontological categories.

How might this kind of conceptual change come about? It is clear, from both intuition and Carey's data, that such changes can come about from the acquisition of biological knowledge. One can conceive of necessitating two kinds of acquisitions: First, children need to be told that "people are a kind of animal" so that they can begin to form links between "people" and "animal" categories. Second, they need to learn about many biological features of people as well as other animals, and notice that these features are shared. For instance, if they are instructed in or exposed to the knowledge that giraffes have live babies and suckle their young, and that people do the same, and other animals as well, then over time, the overlapping and correlational nature of these features will be noticed (or stored), and "people" will eventually be one kind of "animals." Thus, storing many new features will ultimately change the nature of the linkages among the concepts, as well as change the nature of their salience (as engendered by frequency of encounters, and so forth), so that a different pattern of linkages will emerge. (See Chi, Hutchinson, and Robin [1989] for more exhaustive explanations, and Chi [1985] for some suggestive evidence of such a developmental progression.)[2] The point is that simple acquisition processes such as encoding or storing factual information, discrimination, generalization, and so forth, can account for reorganization.

3.2. Formation of New Superordinate or Subordinate Categories

An obvious second kind of conceptual change within an ontological category is the formation of new superordinate categories (integrating or coalescing "plants" and "animals" into the "living things" category), or the differentiation of a category into two, such as differentiating "chairs" into "high chairs" and "rocking chairs," in which the categories do not have to be ontologically distinct. Rosch and Mervis (1977), for example, showed that three-year-old children can sort pictures only at the basic level, whereas by age four, they can correctly sort at the superordinate level. My assumption is that the formation of such superordinate categories clearly is learned by simple acquisition processes. This can be supported by the evidence collected using either expert and novice children (five- and six-year-olds who are knowledgeable about dinosaurs), or expert children asked to sort a more familiar and a less familiar set of dinosaurs (Chi and Koeske 1983; Chi, Hutchinson, and Robin 1989). That is, my colleagues and I have shown that children at the same age can sort either at a more basic level or at a more superordinate level, depending on the amount of knowledge they have about dinosaurs. Likewise, children will sort a subset of dinosaurs at a more basic level if they are less familiar with the subset, and sort them at a more superordinate level (on the basis of diet) if they are more familiar with another subset. These results, together, imply that with greater acquisition of knowledge, children learn to coalesce categories on the basis of some more abstract attribute, such as diet.

Again, several possible acquisition processes can explain this kind of conceptual reorganization, such as addition, deletion, generalization, and discrimination. Thus, this kind of formation of superordinate categories and differentiation of subordinate categories seems to be explainable by nonmysterious acquisition processes. Note, however, that differentiation of heat from temperature (Wiser and Carey 1983) requires conceptual change across ontological categories, and cannot be achieved by the processes discussed here.

3.3. Reclassification of Existing Categories

In the previous example of conceptual change, distinct categories (whether at the superordinate or subordinate levels) did not yet exist. And mechanisms of differentiation and integration (or possibly induction) produced the new categories. These new categories are usually produced from the results of acquiring additional features about the concepts. In the case here, categories already existed, and conceptual change in this case requires the formation of new categorical structure without necessarily involving the acquisition of new features. Thus, it is primarily a reorganization of an existing structure. The point is that migration of concepts within a tree can occur with or without the addition of new knowledge. Again, let me illustrate with a specific piece of suggestive evidence from the developmental literature (Chi 1985).

In this study, whose original concern addressed the role of a representation and its interaction with strategy usage, I showed that a five-year-old represented her classmates in an open-classroom type of setting in terms of a spatial layout of the room. (This is not uncommon among young children. See evidence provided by Bjorklund and Bjorklund 1985.) Thus, for concepts that children are very familiar with (classmates), they have their classmates coded hierarchically according to their seating arrangement in the room. In this case, there were four separate sections, with five to six children per section. The children in this case were a mixture of boys and girls, from first and second grades, racially mixed. This representation was assessed by asking the child to retrieve all the names of her classmates. The organization of this particular representation was determined by several converging pieces of evidence. First, retrieval order conformed to a seating arrangement in the sense that the same set of children from each seating section was recalled in a cluster. Second, the cluster or seating section boundaries were

further evidenced by long pauses in retrieval. Finally, the child could tell you that this is how she retrieved the names of her classmates.

This evidence shows, first of all, that this particular representation is quite robust. The robustness can be further confirmed by the finding that when the child was asked to retrieve in some other categorical way, such as "all the girls," "all the second graders," or "all the black classmates," the retrieval order obeyed the seating section boundaries. That is, in order to retrieve in a specified categorical way (such as "all the girls"), the child basically searched through each seating section, and named the girls. The reason one could conjecture that a search had occurred was because the retrieval proceeded at a much slower rate, but nevertheless, there was still the same pattern of differential retrieval rates: shorter pauses within a seating section, and longer pauses between sections. Although the study did not continue, there is no question in my mind that with extended practice, the child could eventually reorganize her initial robust representation, from one in which the classmates were organized by their seating section, to one in which they were organized by whatever categorical structure I specified, such as the "girls" versus the "boys" categories. (Actually, with repeated trials of retrieval in a prespecified way, a new representation may be constructed with the original one — by seating arrangement — remaining intact.) Thus, here is an example of a kind of reorganization that is possible to implement with practice, and it is not the radical kind, in the sense that each individual concept (each classmate) has not changed its meaning, but its status within the tree has changed (rather than belonging to the category of a seating section, it could, with practice, be stored in the category of "boy classmates" and "girl classmates"). Each concept has migrated within the same tree. This example is somewhat analogous to the jury decision work to be mentioned later (Hastie and Pennington 1991), namely that the evidence for the crime has not changed during jury deliberation, but the category to which the crime fits has changed.

The kind of learning mechanism that can account for this kind of migration is similar to the acquisition mechanism postulated earlier: namely, that continued re-formation of new categories according to some selected features can eventually be stored, so that they can be accessed later.

There are probably many other variants of the three types of conceptual change described above. Their similarity lies in the facts that, first, they can all be seen as migration of one sort or another within the same tree; and, second, straightforward acquisition processes can account for their changes, usually based on the similarity of shared features. The outcome of the behavioral manifestation after the conceptual change, however, can be rather dramatic, so that it is often difficult to believe that simple acquisition mechanisms have produced the changes, unless a computational model has been implemented to explicate the learning processes. However, many researchers do recognize this kind of change as more pedantic, so Carey has referred to it as *weak restructuring*, and Keil referred to it as *nonradical*. Further evidence for this kind of reorganization can be seen explicitly in Chi, Hutchinson, and Robin (1989).

3.4. Spreading Associations in Insight Problems

There are many other occasions when conceptual change is required, and it is often difficult to achieve. But this difficulty is of a different sort than the one imposed by radical conceptual change. The difficulty can result, for example, from a complicated search process. A good example is the issue of insight to the solution of puzzle problems. Insight refers to the phenomenon during which a sudden new way of looking at a situation or problem occurs. A classic example is Maier's (1970) two-string problem, in which the problem solver is presented with two strings hanging from a ceiling with a distance between them that is too far to reach one of the strings while holding on to the other. The goal is to tie the two strings together. Lying about is a set of apparently irrelevant objects, such as a hammer, and so forth. The solution is to tie the hammer to one of the strings and swing it like a pendulum weight, so that it can be caught while holding on to the other string.

The Gestalt psychologists saw restructuring primarily as a perceptual problem (although the Gestalt psychologists discuss many other kinds of problems as well; see Ohlsson 1984a for a review). Thus, somehow one is able to "see" an object from a different vantage point, either in what it looks like, or in its function. However, the solution to this type of insight problem clearly fits the definition proposed in this essay for conceptual change, namely that a concept (such as a hammer) has to change its categorization from a kind of tool to a kind of swinging object. How difficult such reconceptualization is depends, according to the view presented here, on how distinct the two categories are psychologically. Ohlsson (1984b), for example, presents a theory that uses the mechanism of memory retrieval as a basis for the reconceptualization. Thus, in order to see a hammer as a pendulum, one may spread activation to (and thus retrieve) related concepts, such as that a hammer is a kind of tool, and tools are kinds of artifacts, and a type of artifact is a clock, and a specific type of clock is a pendulum clock, and a part of a pendulum clock is the pendulum. Note that this activation process is equivalent to what has been referred to in this essay as traversing up and down a tree.

Thus, the idea is that this migration is within a given tree or ontological category. Thus, although the mechanism that accounts for the Gestalt type of reconceptualization is far from trivial, it seems to occur with far greater frequency than conceptual change of the radical kind. In Maier's two-string problem, for instance, typically around 30 percent of students were able to solve it correctly. The percentage of successful solution can increase to perhaps 80–90 percent, depending on the amount of hints given. This rate of success clearly far exceeds the frequency of scientific discovery, and also outnumbers the percentage of the student population who understand physics.

Even though the solution of Maier's two-string problem may be the within-a-tree kind, nevertheless, one can envision what may cause difficulty in such reconceptualization. The path relating hammer to pendulum is quite lengthy in terms of the number of links, and the links are probably not very strongly associated, given that such a path was probably never directly taught, nor activated previously. That is, at every junction where a node is associated with several links, the probability that the correct path is associated during the search is low. Thus it is unlikely that the right path will be found by spreading activation among various chains of weak links that are potentially unconstrained. One could potentially prime the activation by selectively suggesting or activating some of the intermediate links. For instance, suppose we remind the solver that certain clocks have pendulums that swing, a pendulum is usually made of a heavy object, and that swinging changes the location of an object. One would then predict, if such a theory is correct, that systematic reminding of this sort can enhance the probability of achieving "insight" or conceptual change of this kind.

Thus, Ohlsson's model basically conceived of restructuring as a kind of search in which the meaning or representation of a concept is changed so that an existing operator or rule can apply toward reaching a solution. Thus, in the hammer-pendulum case, the solver already has the rule of swinging a pendulum. In order for that rule to apply in the two-string problem, the solver had to reconceptualize the hammer as a pendulum. This would predict that the ease with which an "insight" problem is solved depends upon the degree to which the reconceptualization has to migrate, either across or within a tree. For instance, a simple example of reconceptualization may be to change the concept at hand in terms only of its subordinate-superordinate relation, in order for an operator to apply. An example that Ohlsson gave concerns the situation in which one wants to have peace and quiet, and a canary is making lots of noise. The situation can be represented as follows:

(Goal: PEACE AND QUIET)
(X IS A NOISE SOURCE)
(X IS A CANARY)

The operator that a person has that can solve this situation is SCHOO-AWAY. But the operator SCHOO-AWAY(X) has the following conditions for applicability:

(Goal: PEACE AND QUIET)
(X IS A NOISE SOURCE)
(X IS A BIRD)

Therefore, in order for the SCHOO-AWAY operator to apply, an inference has to be made, on the basis of world knowledge that a canary is a bird. Thus, in this example, the reconceptualization of the situation's concept, canary is a bird, is one of subordinate-superordinate relation. As discussed earlier, this kind of reconceptualization is not radical, since it does not require an ontological change. It is comparable to the kind of reconceptualization needed to comprehend the riddle "A man who lived in a small town married twenty different women of the same town. All are still living and he never divorced a single one of them. Yet, he broke no law. Can you explain?" Again, here, the reconceptualization needed is to spread activation from the node "man" to its subordinate node "clergyman." It seems less difficult than the reconceptualization of a hammer as a pendulum, in terms of the distance (number of links) one has to traverse within one's semantic memory representation. Perhaps due to the distance of search needed to transform a hammer into a pendulum (and, therefore, the low probability that this transformation will succeed), this kind of problem solution is usually credited as "insightful" or "creative." Hence, we may want to restrict the definition of "creativity" to this sort of conceptual change, one that is not necessarily between trees, but merely one that is unlikely to occur, due to the distance that activation has to traverse and spread from the original concept. Hayes (1989), for example, categorizes Galileo's invention of the science of physics along with telling a simple bedtime story as creative acts. Perhaps a distinction of the kind proposed here will separate out the creative acts of different magnitudes. Telling an interesting and unique bedtime story is analogous to the hammer-pendulum kind of creativity, and Galileo's invention would be consistent with the radical restructuring of the across-tree kind.

3.5. Direct Reassignment within Ontological Categories

Occasionally, as mentioned earlier, we may have to reassign a concept from one category to another directly, such as the example of whales

being mammals rather than fish. When we are required to make this kind of direct reassignment, we usually think either there is something about the concept that we do not know (in the case of whales, we may not know that they bear live young), or there is something about the category to which it actually belongs (mammals) that we are ignorant of. The next example illustrates this latter case.

Hastie and Pennington (1991) have some preliminary data that may be interpreted as representing conceptual change of this kind. Their work examines jury decision. In particular, I am interested in the case of the jury members changing their opinion during the course of deliberation. In order to understand what causes the jurors' change of opinion, Hastie and Pennington analyzed the contents of the discussion two minutes prior to an individual juror's announcement that he/she has changed his/her opinion about the proper verdict. From such an analysis, what was uncovered is the fact that the discussion preceding changes of opinion did not focus on "story-relevant" events concerning what had happened in the criminal circumstances, but rather, on the law, such as the definitions of the verdict categories and the appropriate procedures the jurors should apply in determining the appropriate classification of the event to the verdict category. Thus, I take this to be an example of conceptual change in which a given concept (in this case a criminal situation) is changed in terms of what category (of verdict) it belongs to. And in this particular example, the trigger of the change is elaborating and defining more clearly what the other category is. This suggests (and is consistent with our proposal about instruction, discussed earlier) that in order to have a conceptual change, adequate knowledge must be available first about the "other" category into which the concept is to be reclassified.

The extent to which this kind of reassignment is difficult depends on a different set of processes than those involved in the other kinds of nonradical conceptual change. In the example presented here, the evidence suggests that the difficulty resides in the processes involved in refining the definition or knowledge about the category to which the concept is being reassigned, or refining the knowledge about a concept (as in the whale-mammal case).

3.6. A Caveat

Nonradical conceptual change is not necessarily straightforward. One cannot simply input an attribute, for example, and hope that it will be encoded and attached at the appropriate place and modify the representation readily. The best example to illustrate this would be Vosniadou and Brewer's study of the encoding of an attribute of a concept that violates a child's existing knowledge of the concept's attributes. In this case, the child is told that the earth is round like a sphere rather than flat like a pancake, as the child initially believed. Although this kind of modification would not be considered radical conceptual change, the data show that children find it difficult nevertheless to accept the new feature, and furthermore they have a tendency to assimilate the information instead, such as thinking that the parts of the earth that people stand on are flat, residing inside the sphere. My only explanation of this resistance to change is that learning a new feature is not as straightforward as what the instruction entails. That is, although it seems easy enough for us simply to tell the children that the earth is round like a sphere, what we do not understand is the fact that any new piece of information presented to the child must be assimilated into the child's *coherent* knowledge structure, which means that the new piece of information has to propagate to other pieces of knowledge, and they all have to make sense. For instance, simply telling the child the earth is round like a sphere does not explain to the child how we can stand erect on a spherical surface. Thus, because a child may not understand the consequences of having a spherical earth — that people stand on its surface rather than its inside, and that the earth's surface is so massive that we do not notice its curvature — these associated pieces of information must also be taught before the child can understand the impact of the factual statement that the earth is round like a sphere. Thus, my point is that the instruction must be coherent as well, and cannot be delivered in a piecemeal fashion. The children's resistance to and difficulty in modifying their concept of the earth are tangential to the factor involved in radical conceptual change, because in this case, no distinct ontological categories have to be crossed in order to change their original conception from a flat earth to a spherically shaped earth. The barrier lies in other problems, such as the correctness and/or coherence of the child's initial mental model (see Chi 1990). In any case, all nonradical conceptual change processes are distinctly different from conceptual change that requires crossing ontological categories.

4. Conclusion

I have proposed that there are basically two kinds of conceptual change: one within an ontological category, and one across ontological categories. Conceptual change within an ontological category, although at times difficult, is not impossible. Insight problem solution, in which the solver can finally see a "hammer" as a "pendulum" in Maier's two-string problem, may be an example of a difficult case of conceptual change within an ontological category. Another example may be a child's ability to see a yellow flower as both a flower (a superset) as well as a yellow flower (a subset). To be able to view a specific item as belonging to two conceptual categories at the same time may be viewed as a kind of conceptual change that has to cross categories, but these categories are not ontologically distinct.

Conceptual change that requires crossing ontological categories is nearly impossible to accomplish, in both physical as well as psychological terms. There are no concrete operations that can transform a physical object, such as a cup, into an ontologically different entity, such as a dream. Likewise, there is no psychological learning mechanism that can modify a concept from one ontological category to another. No mechanism of addition, deletion, generalization, discrimination, specialization, proceduralization, and so forth can change the meaning of a concept from one ontological category to another, because any of these mechanisms applied at a local level can only modify a concept in a local way, which means that it will continue to inherit the properties of its superordinate category. Therefore, the implication is that instruction about a new ontological category must proceed by teaching this new ontological category of concepts independently of the old or existing conceptions. This would be the case for teaching physical science concepts; for example, physical science concepts belong to a distinct ontological category (constraint-based events), whereas naive conceptions of these physical science concepts consider them to be a kind of substance or material kind.

Drawing a distinction between these two kinds of conceptual change has important implications for learning and development. It can clarify a number of contradictory findings. Let me list several instances. Piaget and Inhelder (1974) attributed the formal operational child (or the adult) to have understanding of density, and yet few lay adults understand the concept of weight. One way to resolve this discrepancy is to say that density is an attribute of material kind, and is not an ontologically difficult concept to understand. (Density is mass per unit volume, whereas weight is gravitational force.) Weight, on the other hand, is a concept of the constraint-based kind, and should therefore be difficult even for adults to understand.

A second example is the discrepancy between the notions of whether students' and children's naive conceptions and misconceptions constitute a theory or not. Most of the work arguing for the "theory" view draws evidence from physics. These views, as I have said, may seem theorylike and consistent primarily because they are all based on applying the substance schema to generate the explanations. That is, their consistency derives from using this ontological category of knowledge. On the other hand, Lawson (1988) argues that children's naive views are not theorylike at all. He based his conclusion on interview data with children on various topics of biology. He noted that children most often provided a great deal of "I don't know" responses; their beliefs were not resistant to instruction or to being told; their ideas were not well articulated; and they often were not able to state the reasons for their beliefs. This scenario is in stark contrast with interviews about physical science concepts, as gathered in a large body of literature. Again, the discrepancy can be resolved by postulating that the acquisition of a majority of biological concepts does not require conceptual change that crosses ontological categories. In fact, based on such an assumption, I am currently carrying out work that shows that naive biology misconceptions about the human circulatory systems do not resemble medieval ones. Furthermore, misconceptions about biological concepts can be easily removed by instruction. And finally, biological misconceptions decrease with age and schooling (Chi, Chiu, and de Leeuw 1990). These factors, taken together, suggest that whether or not misconceptions are robust, consistent, and theorylike depends on whether an ontological shift is necessary in their removal.

Finally, by proposing two kinds of conceptual change, it is *not* implied that conceptual change within an ontological category is necessarily a simplistic process. Conceptual change is fairly difficult, and its outcome is fairly dramatic. However, conceptual change within an ontological category does occur with greater frequency than conceptual change across ontological categories, and the former may be more experimentally tractable than the latter as well. Thus, all the data in the science education literature basically constitute empirical evidence showing how difficult it is to achieve radical conceptual change. Furthermore, because it requires extensive learning about the new domain, radical conceptual change cannot be some minute event that one can capture in the laboratory during a few sessions of work. Rather, it can probably come about only after extensive learning about the new domain or ontology of concepts (such as during the process of acquiring expertise). Only after thousands of hours of learning these new conceptions could their mere abundance, coherence, and strength potentially appear to overtake the existing conceptions if one believes in the third type of reassignment process (see 3c of the list in sec. 2.2). Overtaking can be taken to mean merely that the new conceptions are accessed more frequently than the old conceptions, which may still exist and remain intact.

The distinction between the two types of conceptual change cautions against using examples from physical science to illustrate limitations in

learning and transfer. For example, J. S. Brown (1989) recently characterized classroom instruction as teaching abstract knowledge that is not particularly transferable, and used physics as an example. Due to its ontological property, I think physics is a unique example that should not be cited as a general case. Also, correctly so, we all tend to think of understanding as seeing (or assimilating) something as an instance of something else that we do understand (Schank 1986; Schon 1987). However, physical science concepts probably cannot be understood that way.

Notes

Preparation of this chapter was supported by the Mellon Foundation, as well as by an institutional grant from the Office of Educational Research and Improvement for the Center for Student Learning. The germ of the idea in this essay was presented at the 1987 meeting of the American Educational Research Association, Washington, D.C., as well as at a 1989 symposium of the Society for Research in Child Development. The opinions expressed do not necessarily reflect the position of the sponsoring agencies, and no official endorsement should be inferred. I would like to thank Susan Carey, Richard Duschl, Ronald Giere, Stellan Ohlsson, Michael Ranney, and Kurt VanLehn for their helpful comments during the preparation of this manuscript. I also benefited greatly from discussions with my students, Nicholas de Leeuw and James Slotta.

1. One could argue that these physical science entities are not constraint-based events. However one wishes to classify them, they are clearly not substances. Feynman (1963) referred to them as "something that has never been seen before, never been heard of before." Therefore, to indicate that they belong to a category other than substance, we will simply consider them to be constraint-based.

2. Notice that this would involve *widening* the attributes associated with the concept of "animals," so that people and other animals will share certain attributes, and stored with each animal and people category will be their individual features, as is possible with a traditional hierarchical semantic network model. Thus, in this sense, we use the term *widening* of the conceptual category to indicate the role of the set of generic features defining the category, and not in the sense of the number of category members, as is intended by Anglin (1977) and Carey (1985).

References

Albert, E. 1978. Development of the concept of heat in children. *Science Education* 62, no. 3:389–99.

Anderson, J. R. 1987. Skill acquisition: Compilation of weak-method problem solutions. *Psychological Review* 94:192–210.

Anglin, J. 1977. *Word, object and conceptual development.* New York: Norton.

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

Bjorklund, D. F., and B. R. Bjorklund. 1985. Organization versus item effects of an elaborated knowledge base on children's memory. *Developmental Psychology* 21:1120–31.

Brewer, W. F., and A. Samarapungavan. In press. Children's theories versus scientific theories: Difference in reasoning or differences in knowledge? In R. R. Hoffman and D. S.

Palermo, eds., *Cognition and the symbolic processes: Applied and ecological perspectives.* Vol. 3. Hillsdale, N.J.: Erlbaum.

Brown, J. S. 1989. Toward a new epidemiology for learning. In C. Frasson and J. Gauthiar, eds., *Intelligent tutoring systems at the crossroads of AI and education*, pp. 266–82. Norwood, N.J.: Ablex.

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

Champagne, A. B., and L. E. Klopfer. 1982. *Laws of motion: Study guide.* Pittsburgh: University of Pittsburgh, Learning Research and Development Center.

Chase, W. G., and H. A. Simon. 1973. The mind's eye in chess. In W. G. Chase, ed., *Visual information processing.* New York: Academic Press.

Chi, M. T. H. 1985. Interactive roles of knowledge and strategies in the development of organized sorting and recall. In S. Chipman, J. Segal, and R. Glaser, eds., *Thinking and learning skills: Current research and open questions.* Vol. 2, pp. 457–85. Hillsdale, N.J.: Erlbaum.

———. 1988. Children's lack of access and knowledge reorganization: An example from the concept of animism. In F. E. Weinert and M. Perlmutter, eds., *Memory development: Universal changes and individual differences*, pp. 169–94. Hillsdale, N.J.: Erlbaum.

———. 1989. Assimilating evidence: The key to revision? (Commentary on P. Thagard's paper entitled Explanatory Coherence). *Behavioral and Brain Sciences* 12:470–71.

———. 1990. The role of initial knowledge in science learning. Technical proposal from the Learning Research and Development Center, Center for Student Learning, University of Pittsburgh, pp. 72–82.

Chi, M. T. H., and R. Bjork. In press. Modelling expertise. In D. Druckman and R. Bjork, eds., *In the mind's eye: Understanding human performance.* Washington, D.C.: National Academy Press.

Chi, M. T. H., M. Chiu, and N. de Leeuw. 1990. *Learning in a non-physical science domain: the human circulatory system.* Office of Educational Research and Improvement Milestone Report. Pittsburgh: Learning Research and Development Center.

Chi, M. T. H., P. J. Feltovich, and R. Glaser. 1981. Categorization and representation of physics problems by experts and novices. *Cognitive Science* 5:121–52.

Chi, M. T. H., J. E. Hutchinson, and A. F. Robin. 1989. How inferences about novel domain-related concepts can be constrained by structured knowledge. *Merrill-Palmer Quarterly* 34:27–62.

Chi, M. T. H., and R. D. Koeske. 1983. Network representation of a child's dinosaur knowledge. *Developmental Psychology* 19:29–39.

Chi, M. T. H., et al. 1989. *Possible sources of misunderstanding about the circulatory system.* Office of Educational Research and Improvement Milestone Report. Pittsburgh: Learning Research and Development Center.

Clement, J. 1982. Students' preconceptions in introductory physics. *American Journal of Physics* 50:66–71.

Darden, L., and R. Rada. 1988. The role of experimentation in theory formation. In D. Helman, ed., *Analogical reasoning: Perspectives of artificial intelligence, cognitive science, and philosophy*, pp. 341–75. Boston: Kluwer Academic Publishers.

Dietterich, T. G., and B. G. Buchanan. 1983. The role of experimentation in theory formation. In *Proceedings of the 2nd international machine learning workshop*, Monticello, Ill.

DiSessa, A. A. 1988. Knowledge in pieces. In G. Forman and P. B. Pufall, eds., *Constructivism in the computer age*, pp. 49–70. Hillsdale, N.J.: Erlbaum.

Driver, R. 1973. The representation of conceptual frameworks in young adolescent science students. Ph.D. diss., University of Illinois.

Driver, R., and J. Easley. 1978. Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education* 5:61–84.

Erickson, G. L. 1979. Children's conceptions of heat and temperature. *Science Education* 63:221–30.

———. 1980. Children's viewpoints of heat: A second look. *Science Education* 64:323–36.

Falkenhainer, B., and S. Rajamoney. 1988. *The interdependencies of theory formation, revision, and experimentation.* Technical report no. UIUCDCS-R-88-1439. Urbana, Ill.: University of Illinois at Champaign-Urbana.

Faust, D. 1984. *The limits of scientific reasoning.* Minneapolis: University of Minnesota Press.

Feynman, 1963. *The Feynman lectures on physics.* Vol. 2. Reading, Mass.: Addison-Wesley.

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

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

Getzels, J., and M. Csikszentmihalyi. 1976. *The creative vision: A longitudinal study of problem finding in art.* New York: Wiley.

Greenwald, A., et al. 1986. Under what conditions does theory obstruct research progress? *Psychological Review* 93:216–29.

Hastie, R., and N. Pennington. 1991. Cognitive and social processes in decision making. In L. Resnick, J. Levine, and S. Teasley, eds., *Perspectives in socially shared cognition*, pp. 308–27. Washington, D.C.: American Psychological Association.

Haugeland, J. 1978. The nature and plausibility of cognitivism. *Behavioral and Brain Sciences* 2:215–60.

Hayes, J. R. 1989. *The complete problem solver.* Hillsdale, N.J.: Erlbaum.

Hempel, C. 1966. Laws and their role in scientific explanation. *Philosophy of Natural Science*, chap. 5. Englewood Cliffs, N.J.: Prentice Hall.

Joshua, S., and J. J. Dupin. 1987. Taking into account student conceptions in instructional strategy: An example in physics. *Cognition and Instruction* 4:117–35.

Karmiloff-Smith, A., and B. Inhelder. 1975. If you want to get ahead, get a theory. *Cognition* 3:195–212.

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

———. 1986. The acquisition of natural kind and artifact terms. In W. Demopoulos and A. Marrar, eds., *Language, learning, and concept acquisition*, pp. 133–53. Norwood, N.J.: Ablex.

———. 1989. *Concepts, kinds, and cognitive development.* Cambridge, Mass.: MIT Press.

Klahr, D., and K. Dunbar. 1988. Dual space search during scientific reasoning. *Cognitive Science* 12:1–48.

Kuhn, D. 1989. Children and adults as intuitive scientists. *Psychological Review* 96:674–89.

Kuhn, D., E. Amsel, and M. O'Loughlin. 1988. *The development of scientific thinking skills.* Orlando, Fla.: Academic Press.

Kuhn, T. S. 1970. *The structure of scientific revolutions.* Chicago: University of Chicago Press.

Lakatos, I. 1970. Falsification and the methodology of scientific research programmes. In I. Lakatos and A. Musgrave, eds., *Criticism and the growth of knowledge*, pp. 91–195. Cambridge: Cambridge University Press.

Langley, P. W., et al. 1987. *Scientific discovery: Computational explorations of the creative process.* Cambridge, Mass.: MIT Press.

Laudan, L. 1977. *Progress and its problems.* Berkeley: University of California Press.

Law, N., and W. W. Ki. 1981. A.I. programming environment as a knowledge elicitation and cognitive modelling tool. Paper presented at the Third International Conference on A.I. and Education.

Lawson, A. E. 1988. The acquisition of biological knowledge during childhood: Cognitive conflict or tabula rasa? *Journal of Research in Science Teaching* 25:185–99.

McCloskey, M., A. Caramazza, and B. Green. 1980. Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. *Science* 210:1139–41.

McDermott, L. C. 1984. Research on conceptual understanding in mechanics. *Physics Today* 37 (July): 24.

McKenzie, A. E. E. 1960. *The major achievements of science.* Vol. 1. Cambridge: Cambridge University Press.

Maier, N. R. F. 1970. *Problem solving and creativity in individuals and groups.* Belmont, Calif.: Brooks/Cole.

Markman, E. M. 1979. Classes and collections: Conceptual organizations and numerical abilities. *Cognitive Psychology* 11:395–411.

Minstrell, J. 1988. Teaching science for education. In L. B. Resnick and L. E. Klopfer, eds., *Toward the thinking curriculum: ASCD yearbook.* Alexandria, Va.: Association for Supervision and Curriculum Development; Hillsdale, N.J.: Erlbaum.

Nersessian, N. J. 1989. Conceptual change in science and in science education. *Synthese* 80:163–83.

Nersessian, N. J., and L. B. Resnick. 1989. Comparing historical and intuitive explanations of motion: Does "naive physics" have a structure? In *Proceedings of the eleventh annual conference of the cognitive science society,* Ann Arbor, Mich.

Newell, A., and H. A. Simon. 1972. *Human problem solving.* Englewood Cliffs, N.J.: Prentice-Hall.

Ohlsson, S. 1984a. Restructuring revisited. I: Summary and critique of the Gestalt theory of problem solving. *Scandinavian Journal of Psychology* 25:65–78.

———. 1984b. Restructuring revisited. II: An information processing theory of restructuring and insight. *Scandinavian Journal of Psychology* 25:117–29.

Osborne, R. J., and M. C. Wittrock. 1983. Learning science: A generative process. *Science Education* 67:489–508.

Pagel, W. 1951. William Harvey and the purpose of circulation. In *ISIS* 42, pt. 1, April. Reprinted in the Bobbs-Merrill Reprint Series in History of Science, HS-58. Washington, D.C.: Smithsonian Institution.

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

Piaget, J., and B. Inhelder. 1974. *The child's construction of quantities.* London: Routledge and Kegan Paul.

Posner, G. J., et al. 1982. Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education* 66:211–27.

Postman, L., and R. F. Jarrett. 1952. An experimental analysis of learning without awareness. *American Journal of Psychology* 65:244–55.

Rajamoney, S. A. 1988. Experimentation-based theory revision. In *Proceedings of the AAAI spring symposium on explanation-based learning.*

Ranney, M. 1987. Restructuring naive conceptions of motion. Ph.D. diss., University of Pittsburgh.

———. 1988. Contradictions and reorganizations among naive conceptions of ballistics. Paper presented at the annual meeting of the Psychonomic Society, Chicago, Ill.

Reiner, M., M. T. H. Chi, and L. Resnick. 1988. Naive materialistic belief: An underlying epistemological commitment. In *Proceedings of the tenth annual conference of the cognitive science society,* pp. 544–51. Hillsdale, N.J.: Erlbaum.

Reiner, M., et al. In preparation. Materialism: An underlying commitment.

Rogan, J. M. 1988. Development of a conceptual framework on heat. *Science Education* 72:103–13.

Rosch, E., and C. Mervis. 1977. Children's sorting: A reinterpretation based on the nature of abstraction in natural categories. In R. C. Smart and M. S. Smart, eds., *Readings in child development and relationships.* New York: Macmillan.

Roschelle, J. 1986. *The envisioning machine: Facilitating students' reconceptualization of motion.* Palo Alto, Calif.: Xerox Palo Alto Research Center.

Schank, R. C. 1986. *Explanation patterns: Understanding mechanically and creatively.* Hillsdale, N.J.: Erlbaum.

Schauble, L., et al. 1991. Causal models and processes of discovery. *Journal of the Learning Sciences* 1, no. 2:201–38.

Schneider, W. 1987. Connectionism: Is it a paradigm shift for psychology? *Behavior Research Methods, Instruments, and Computers* 19:73–83.

Schon, D. 1987. *Educating the reflective practitioner.* San Francisco: Jassey-Bass.

Siegler, R., and E. Jenkins. 1989. *How children discover new strategies.* Hillsdale, N.J.: Erlbaum.

Smith, C., S. Carey, and M. Wiser. 1985. On differentiation: A case study of the development of the concepts of size, weight, and density. *Cognition* 21:177–237.

Solomon, J. 1983. Learning about energy: How pupils think in two domains. *European Journal of Science Education* 5:51–59.

Sommers, F. 1971. Structural ontology. *Philosophia* 1:21–42.

Spelke, E. S. 1990. Origins of visual knowledge. In D. N. Osherson, S. M. Kosslyn, and J. Hollerbach, eds., *Visual cognition and action.* Vol. 2, pp. 99–128. Cambridge, Mass.: MIT Press.

Suppe, F., ed. 1977. *The structure of scientific theories.* 2d ed. Urbana and Chicago: University of Illinois Press.

Thagard, P. 1989. Conceptual change in scientists and children. Panel discussion at the Eleventh Annual Cognitive Science Society Meeting, Ann Arbor, Mich., August.

———. 1990. Explanatory coherence. *Brain and Behavioral Sciences* 12:435–502.

Tiberghien, A. 1980. Models and conditions of learning an example: The learning of some aspects of the concept of heat. In W. F. Archenhold et al., eds., *Cognitive development research in science and mathematics.* Leeds: University of Leeds.

Tweney, R. D. 1985. Faraday's discovery of induction: A cognitive approach. In D. Gooding and F. A. J. L. James, eds., *Faraday rediscovered: Essays on the life and work of Michael Faraday, 1791–1867.* New York: Stockton Press.

VanLehn, K. 1991. Rule acquisition events in the discovery of problem solving strategies. *Cognitive Science* 15, no. 1:1–47.

Viennot, L. 1979. Spontaneous reasoning in elementary dynamics. *European Journal of Science Education* 1:205–21.

Vosniadou, S., and W. F. Brewer. 1989. The concept of the earth's shape: A study of conceptual change in childhood. Unpublished manuscript, Center for the Study of Reading, University of Illinois, Champaign, Ill.

White, A. R. 1975. Conceptual analysis. In C. J. Bontempor and S. J. Odell, eds., *The owl of Minerva.* New York: McGraw Hill.

White, B. Y., and J. R. Fredricksen. 1986. *Progressions of qualitative models as foundation for intelligent environments.* Technical rep. no. 6277. Cambridge, Mass.: Bolt, Beranak, and Newman.
Wiser, M. 1987. The differentiation of heat and temperature: History of science and novice-expert shift. In D. Strauss, ed., *Ontogeny, phylogeny, and historical development.* Norwood, N.J.: Ablex.
Wiser, M., and S. Carey. 1983. When heat and temperature were one. In D. Gentner and A. L. Stevens, eds., *Mental models*, pp. 267–98. Hillsdale, N.J.: Erlbaum.