In T.B. Ward, S.M. Smith, & J. Vaid (Eds.),
Creative Thought: An investigation of conceptual structures and processes (pp. 209-234).
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Creativity: Shifting Across Ontological Categories Flexibly

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There is a general consensus that the essence of creativity is to be able to view a situation or an object from two different frames of reference, or two "unrelated matrices of thought" (Koestler, 1964). This is sometimes referred to as *restructuring*. Restructuring, thus, is often viewed as being able to see a problem in a "new way" that is fundamentally different. However, defining creativity in this way merely begs the question of what constitutes a "new way," "a different frame of reference," or "an unrelated matrix of thought?"

The goal of this chapter is to provide a specific way of characterizing what a new perspective, a new way, or a new matrix of thought might be. A new perspective is defined here as re-representing an entity or a situation from one "ontological" tree of concepts and categories to another ontological tree of concepts and categories. That is, people might store concepts and situations on associative trees that are ontologically distinct so

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that these distinct ontological trees serve as barriers that restrict our ability to understand and produce creatively. In order to have creative thoughts, we must be able to cross these ontological barriers flexibly. Thus, one definition of creativity is the flexibility with which one can think about a member of an ontological category in the context of another ontological category. I refer to this definition as "shifting across" ontological categories, as "re-representing" a concept from one ontological category to another, or merely as conceptual change. I clarify the meaning of these terms below. First, however, I present a set of terms to describe category attributes.

THE NATURE OF CATEGORY ATTRIBUTES

A category, from cognitive psychologists' point of view, is defined as a set of objects (or entities) that people believe belong together. Thus, to psychologists, a category is a conceptual structure. When people believe that a certain set of objects (or entities) belongs in the same category, they treat new instances of the category as members. This allows people to assign the same label to a new instance of the category and make inductive and deductive inferences to new category members, particularly about nonperceptible properties (Chi, Hutchinson, & Robin, 1989). Thus, there is clearly a cognitive advantage to having categories, as coding new experiences or objects as an instance of a familiar category reduces the demands of the perceptual, storage, and reasoning processes.

Psychologists, addressing the overarching question of what is the process by which people assign entities to categories (most of the psychological literature has dealt with object categories), presuppose the prior question of what constitutes a category. That is, what characteristics or attributes do class members possess that cohere them as a category? For instance, a set of objects that weigh one gram, or a set of objects that are green, does not constitute a category. What attributes, then, give a set of objects or entities the status of categoryhood? In this section, several types of attributes used to characterize categories are briefly discussed in order to clarify their definitions.

Defining Attributes

One possible characteristic of categories is whether the objects or entities satisfy a *defining* set of attributes. Nominal kind categories, such as kinship (e.g., uncle), law (e.g., felony), and geometry (e.g., triangle) have a fixed set of attributes to define them, so that for any object that satisfies all of the attributes of a category, that object must be an instance of that category. Put another way, defining attributes are necessary and sufficient to determine category membership. For example, the concept "grandmother" has the defining attributes of being female and being a parent of a parent. These two attributes are jointly sufficient to determine that any female who is a parent of a parent must be a grandmother.

Characteristic Attributes

A fixed set of defining attributes clearly cannot capture the nature of nonnominal kind categories, primarily because linguists, philosophers, and psychologists have yet to come up with a fixed unique set of attributes for most natural kind categories (McNamara & Sternberg, 1983). For example, there is no fixed set of necessary and sufficient features that can deterministically discriminate a bird from a nonbird. Most people think that birds have the properties of flying and singing. However, one would still classify a bird whose wings have been clipped as a bird. Likewise, although penguins and chickens cannot fly, they are also classified as birds. Moreover, not all instances of a category are treated equally, as would be the case if the definitional view held. Instead, some members of a given category are treated as more typical members than others. A robin, for example, is considered a more typical bird than a penguin. What this means is that people treat different members of a category differently: Typical members can be classified faster, they are rated more highly as an instance of the category for which they belong, and they are retrieved more frequently than atypical members (Smith, 1989). Thus, there is no fixed set of necessary and sufficient features to discriminate members of a category from nonmembers.

Without a unique defining set of attributes, what then determines category membership? People often tend to determine category membership on the basis of nonessential but frequent properties, such as *being sweet* for fruit (Rosch & Mervis, 1975). These nonessential but frequently occurring properties are known as *characteristic* attributes. The more characteristic attributes an instance of a category has, the more *typical* it is, according to people's ratings. Thus, category memberships are sometimes determined by the extent to which an entity embodies the most frequent characteristic features of a category.

Regardless of whether defining or characteristic attributes are used to determine category membership, how are the attributes identified? The consensus is that category membership is determined largely by physical or perceptual similarity. To some degree, category members tend to be more physically or perceptually similar to each other and dissimilar to members of another category. For example, various kinds of dogs look more similar to each other than to cats. The set of all objects weighing one gram, on the other hand, does not meet this criterion of physical similarity, thus, does not constitute a category. Perceptual similarity can refer not only to static features but also to any perceptually observable features, such as behavior (e.g., the attribute "nests in trees" for birds).

Core and Functional Attributes

Although people seem to categorize entities on the basis of perceptual attributes, these perceptual attributes are used primarily for the sake of a quick and expedient categorization of objects, as they are readily available, salient, and easy to compute. However, they are not diagnostic of concept membership. *Core* attributes are those that are usually less perceptual and more hidden; however, they are more diagnostic of category membership. For example, the core attribute of being a bird might be having bird genes (i.e., having been born of bird parents). Sometimes core attributes are referred to as the essence of a concept, or its "real nature." This real nature often refers to its genetic makeup.

Core attributes are unlike defining attributes in that they are not fixed. Whether a given gene is diagnostic of certain diseases or genes are diagnostic of being birds may change when scientists discover some other relevant core attributes (Putnam, 1975). Core attributes are also different

from characteristic attributes in that core attributes are not often observable. Core attributes are moreover different from both characteristic and defining attributes in that we have only a vague idea of what the exact core attributes of any given concept are. However, we do know that they exist, and we appeal to experts to guide and tell us what they are (Malt, 1990).

Core attributes may be correlated to characteristic or perceptual attributes. For example, the concept "man" can be defined in terms of core features like adult, male, and human. However, to identify a person as a man requires characteristic attributes such as hair length, presence of a beard or mustache, and so on. These properties are related, as being a male is partly a matter of hormones, which influence physical features such as facial hair (Wattenmaker, Nakamura, & Medin, 1988).

Functional attributes are basically equivalent to core attributes. The difference is that core attributes differentiate natural kinds, whereas functional attributes differentiate artifacts. Thus, like core attributes, functional attributes also are not fixed. Instead of appealing to scientists who might discover new core attributes, we appeal in this case to the engineers of artifacts to invent new functional attributes.

Abstract, Theory-Based, or Explanation-Based Attributes

One can also propose that categories are determined by some underlying *abstract*, *theory-based*, or *explanation-based* attributes rather than perceptual attributes. (These terms are used more or less synonymously.) Fewer studies have focused on this type of attribute, perhaps because most entities in the world that have abstract similarity also have physical similarity. For example, consider the diet of a class of dinosaurs (such as meat-eating) as an abstract attribute. However, meat-eating dinosaurs do share several similar physical attributes, such as having sharp teeth. No research has explicitly manipulated theory-based (or abstract) attributes from perceptual (or characteristic) attributes. Exceptions do exist, especially in nonnatural kind categories. Physics problems, for example, can be created that have abstract (principle-based) similarity but not physical similarity (Chi, Feltovich, & Glaser, 1981). In this case, whether a problem solver attends to the abstract or the perceptual features depends on the solver's expertise (Chi et al., 1981), or the solver's Scholastic Aptitude Test (SAT) scores (Novick, 1988).

Theory- or explanation-based attributes are generally consistent with some explanation or some prediction based on an explanation. For example, rice cakes, unbuttered popcorn, and grapefruit can form a conceptual category if one can explain their coherence. In this case, their coherence can be explained by "things to eat while on a diet" (a kind of goal-derived category; see Barsalou, 1983). Likewise, symptoms such as dizziness and earache can be conceived of as related if one can provide an explanation for them such as "symptoms that are causally related," whereas such an explanation cannot be provided for symptoms like a sore throat and skin rash (Medin, Wattenmaker, & Hampson, 1987). Thus, the coherence of these category members is not based on any perceptual similarity but, rather, on theory- or explanation-based similarity such as containing close to zero calories (Ross, 1984).

Ontological Attributes

Hierarchical Comparison of Categories

Many of the pertinent questions asked by psychologists as discussed above pertain to the nature of the set of attributes that defines a category per se rather than the relationship among categories. When the relationship among categories is invoked, most of the psychological work conceives of categories as embedded in a taxonomic or hierarchical relationship. For example, bird is a category that is subsumed under the animal supercategory, and robin is subsumed under the bird category, and so on. Thus, much of the classic work deals with the induction possibilities resulting from hierarchical relationships (see Collins & Quillian, 1969), as well as the identification of a level of categories (the basic level) at which people prefer to operate (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). This basic level would, for example, correspond to the bird category as opposed to the animal category. Preference can be easily demonstrated by the fact that people prefer to identify items by their basic level names (e.g., people prefer to call a red, round fruit an "apple" rather than a "fruit" or

a "McIntosh apple"); and people can determine that an object is an apple faster than they can determine that it is a fruit. Rosch et al. (1976) have several other tests of people's preferences for basic level categories. By and large, the only sense in which psychologists have discussed the overall structure of categories is in the context of hierarchies, although there are debates and discussions about the rigidity of the hierarchy and whether some lattice-like structure is also possible (Conrad, 1972)

Lateral Comparison of Categories

Assuming that individual categories are related in a hierarchical way, psychologists, by and large, have not dealt with the nature of the lateral relationship among hierarchical or taxonomic category trees. Lateral comparisons can be posed with two questions. The first is how hierarchical trees differ from each other or (put another way) how categories within *different* trees differ from each other. The second question is how lateral categories within a tree differ (i.e., how do categories on different branches of a given tree differ?).

Suppose we examine two taxonomic trees, such as material substances and processes, as depicted in Figure 1. It is of course not clear exactly how each of these taxonomic trees should be constructed. That is, exactly how should the branches or levels within each tree be constructed? Let's assume, for the sake of discussion, that the trees are organized as shown in Figure 1. How might we define how these trees differ? And how might the categories subsumed under each tree differ? For instance, how might the subcategories *event* (on the PROCESSES tree) and *natural kind* (on the material substances tree) differ (see Figure 1)? And how do categories on different branches, such as natural kind and artifact, differ within a tree? Although psychologists have not thought much about tree differences, philosophers have (see Quine, 1960, p. 275). I refer to trees of this kind (being fundamentally different) here as *ontologies* (or *ontological trees*) and their attributes as *ontological* attributes. Thus, ontologies, as defined here, refer to trees having an entire hierarchy of categories that are fundamentally different from each other. (It is not yet clear whether categories on different branches within a given tree are also ontologically distinct. Two or more categories may be considered ontologically distinct according to

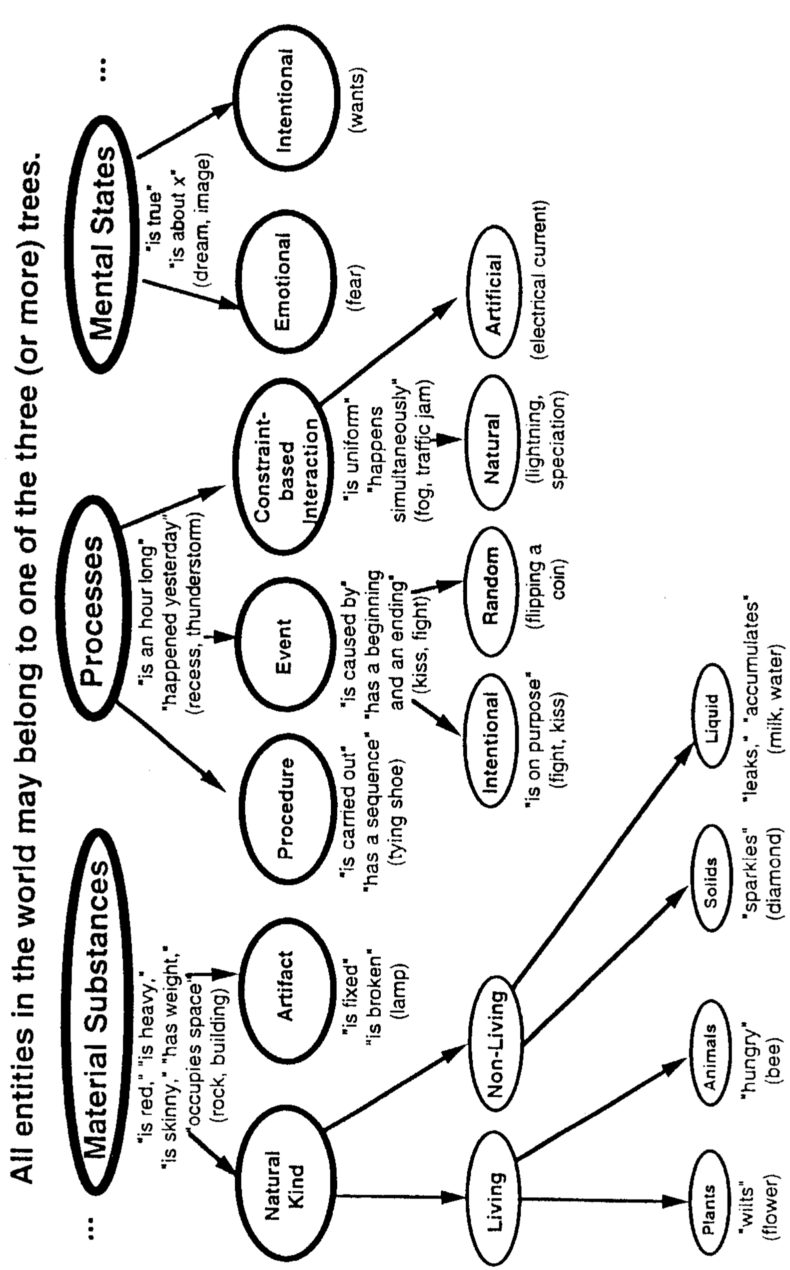

Figure 1

A plausible organization of ontological trees

one empirical test and not according to another. More speculation about this is provided later.)

Lateral Differences Between Trees and Branches

The issue of how to define differences between trees is much more complex than the issue of determining the hierarchical relationships among categories. Hierarchical relationships can be readily defined in terms of the inheritance of generalized attributes. That is, a bird is an instance of the animal category if a bird possesses all the properties that an animal possesses, such as breathes, eats, and so forth. However, it is not as apparent how one would decide that two categories that are not on the same ontological tree are distinct. The reason this is a more complex problem is that it is much more difficult to define difference than sameness. In this context, *sameness* can be defined by an overlap or sharing of attributes; however, *difference* is more problematic because, intuitively, it does not seem to be a matter of degree. Should two entities be considered different if they share no attributes of any kind, or if they share one that is a characteristic, defining, core, or explanation-based attribute? Should they be considered different only if they share some kinds of attributes and not others?

I propose that differences in trees are dramatic (others have used the words "*radical*" and "*fundamental*") in the sense that the trees do not share any *ontological* attributes (Chi, 1992; Chi, Slotta, & de Leeuw, 1994), although they may share other types of attributes,(e.g., characteristic or explanation-based). That is, tree differences can be characterized by the nature of their ontological attributes, which are different from characteristic, defining, core, and explanation-based attributes.

The Nature of Ontological Attributes

An ontological attribute refers to a property that may or may not be possessed by a specific category member but has the potential of possessing it. For example, the class of all physical objects has the potential to possess the property of color, but not all physical objects do. Thus, a piece of glass is often transparent and colorless, but it can be made to have color. Unlike core attributes, ontological attributes are known to the average person, although he or she may not be explicitly aware of them. Although we may not be explicitly aware of ontological attributes, our implicit understanding of them can often be detected by the phrases and predicates we use to describe them. For example, to say "The baseball game lasted an hour" implies that a baseball game is a process, because only processes can have a dynamic time-dependent nature, in contrast to solid objects, which have a static nature.

Before addressing the question of how one determines an ontological attribute of a category or tree (or alternatively, the question of how one decides that a set of entities constitutes a distinct ontological tree), one may want to surmise as to the characteristics of ontological attributes. Assume that the following attributes are some of the ontological attributes of the material substances tree: block, contain, move, rest, consume, absorb, quantify, accumulate, can have color, and so on (Slotta, Chi, & Joram, 1995). (Other examples of ontological attributes or predicates are shown in quotes in Figure 1.) That is, a material substance such as a solid object like a book can block other material substances such as fluids. It can be contained, moved from one location to another (or if it is an animate object it can move of its own volition), or it can have color, and so forth.

Having asserted what some ontological attributes might be for a given tree, one can then further assert that two categories embedded in two separate trees can be said to be ontologically distinct because they do not share any ontological attributes. Philosophers have offered a way to test this by asking people to make judgments about the sensibility of sentences that use predicates from one ontological tree to modify entities on another ontological tree. For example, *an hour-long* is a predicate that may modify any member of the processes tree, but it cannot be used sensibly to modify any member of the material substances tree, such as *dog*, which is a natural kind. Thus, to say that "A dog is an hour-long" is anomalous (known as a category mistake) because even the negation of that statement ("A dog is not an hour-long") is nonsensical. On the other hand, if a member of a category is predicated by an attribute from the same tree, then at worst the statement is simply false, such as "A dog is purple." Such

sensibility judgments have been used by Keil (1979) to determine the (ontological) distinctiveness of branches within the same (substances) tree, such as artifacts and natural kinds. Thus, psychologically, one can determine the distinguishability of branches by using the sensibility test. Keil (1989) also used other tests to show the distinguishability of branches within the same tree. For example, he showed that even 5-year-olds refuse to admit that there are operations that can transform a skunk to a teapot or a toy bird to a real bird.

Physical and Mental Operations to Modify an Entity or a Concept

In the physical world, entities from distinct trees (or even branches on a given tree) remain distinct despite any *physical operations* that can be performed on them. For example, a chair (an artifact) can never be made into a baby skunk (a natural kind) no matter what kind of operation (carving it up, washing it, painting it, etc.) is done to it. I argued earlier that similarly, no piecemeal *cognitive operations* (such as deleting or adding features, generalizing features, etc.) can modify a concept's characteristic, defining, or core attributes so that it changes the tree (or branch) in which the concept is embedded. To modify a concept from being embedded in one tree to another tree, one must modify its ontological attributes. However, ontological attributes are not modifiable, either physically or mentally (see Chi, 1992, for a more extended discussion).

On the other hand, it is possible to cognitively change the representation of a concept through cognitive operations if the changes do not require the concept to be re-represented across branches or trees, but rather, that the representation is merely a migration of the concept from a subordinate to a superordinate node (or vise versa), in a hierarchical manner. When multiple applications of cognitive operations such as deletion and addition of features are executed, the cumulative effect can result in a more well-defined concept, or a more generalized concept. However, all of the added or deleted features have not fundamentally changed the ontological tree in which the concept was originally embedded. This kind of change is referred to as a *belief revision*. There is abundant evidence of the gravitation of concepts from subcategories to superordinate categories, and vice versa, such as learning to differentiate and integrate concepts (Carey, 1985) and learning to integrate humans as one species of animals (see Chi, 1988, for a developmental analysis of how the concept of humans can gravitate from one part of the living things tree to another part). Thus, another way to put it is that once stored on a particular tree, a concept then inherits all of the ontological attributes of that tree. It is completely entrenched in that ontology. To change the ontological tree to which a concept belongs, one would need to modify an enormous number of attributes (in order for the concept to disinherit all of its ontological attributes).

Belief revision is a common kind of change that does not require a change in ontology. Much of learning of concepts is basically belief revision, in which one has to change a number of attributes that one knows about a concept and attach other correct attributes to it instead. For instance, suppose we originally thought that a whale is a kind of fish. There are two ways that this concept can change as we learn more about it. The first way is that we learn more about whales, such as that they breathe through a blowhole, have lungs, bear live young, and are warm-blooded. Over time, our accumulated knowledge about whales will overlap with our knowledge of mammals more than it overlaps with our knowledge of fish. Eventually, the representation of whales will be largely associated with the representation of mammals. Such migration of a concept from one branch to another branch of the same tree seems plausible, as there is a finite number of features to change.

A second way to achieve belief revision is being told directly, for example, that "a whale is a mammal and not a fish." Being told will allow us to directly link the concept whale with the category mammal rather than with the category fish. Thus, a more efficient method to change a concept's ontology might be a wholesale shift through direct instruction, which seems clearly possible for concepts on different branches of a tree (as the example of whale indicates), but would this be possible for concepts on different trees? I discuss this possibility next.

Therefore, changing features of a concept gradually in a piecemeal way (which occurs all of the time in learning and development) may be thought

of as belief revision, whereas shifting a concept from one tree to another can be more aptly conceived of as conceptual change. This view of conceptual change is also shared by Thagard (1990).

CIRCUMSTANCES UNDER WHICH PEOPLE HAVE TO SHIFT ACROSS ONTOLOGICAL TREES

If one assumes that (a) concepts are loosely structured in something like a hierarchy tree; (b) trees are fundamentally distinct from one another; (c) physical entities in the world do not change ontology; and (d) ontological categories in the world correspond to the structure of people's conceptual categories, then why would one ever have to worry about shifting concepts across trees? That is, there should seldom be any need to re-represent or shift a concept from one tree to another tree, unless of course one *misrepresented* a concept in the first place. Surprisingly, however, there are many occasions when one must re-represent an entity from one tree to another. Below, I illustrate two types of occasions. For each of these occasions, the need to shift the representation has to do with the initial misrepresentation.

In Everyday Life

Is there ever an occasion in everyday life when people have to re-represent a concept so that it is stored on a different tree? This can happen on occasions when the superficially perceivable features of an entity mislead people into representing it as one kind of entity when in fact it is another kind. This can readily happen because categorization is often based on visibly perceptible features. Such is the case when whales are mistaken to be a kind of fish. However, because the perceptual features of entities we encounter in everyday life most often correlate with their underlying conceptual identity, it is seldom the case in everyday life that what we perceive misleads our identification. For example, we identify a given animal as a dog because that animal has all the characteristic features of a dog, such as a wagging tail, four legs, and so on. Thus, in everyday life, there are few occasions when we have to shift an entity from one ontological tree to another, although there are occasions when we must shift among branches of a tree, such as in the case of whales. Another more common instance of shifting across branches occurs in literature and films. The necessity of these shifts is sometimes used in literature to create a surprise or a dramatic effect. For example, in the popular children's novel *Indian in the Cupboard,* the central theme of the book is that a toy Indian comes alive. A great deal of suspense of the book is built around the discovery of this "conversion," and the main character is clearly surprised. Other examples include *Velveteen Rabbit.* Similarly, in the film *The Crying Game,* a male character is disguised as a female; the viewers are quite surprised when the disguise is removed, and they must review all of the implications of the prior scenes to determine how the character's being male may have changed them. These kinds of shifts are dramatic (thus, create a surprise reaction) precisely because they cross ontological barriers. Thus, they are much more drastic than mere mistaken identity. Misidentifying one person for another (as often occurs in mysteries) is puzzling and suspenseful, but it is not dramatic, as when one crosses ontological boundaries (such as from an artifact to a live human being, or from a female to a male).

Notice that in all of the examples cited above, either in mistaking a whale for a fish, or in mistaking a male for a female, the changes (such as from a toy Indian to a live Indian) are between branches within an ontological tree. The next context addresses a change in re-representation between trees.

Understanding a Kind of Process

As it turns out, there is an important context in which there is a pervasive need to shift concepts from one tree to another. This is the context in which we have to learn a special class of complex concepts of processes. Before describing what is unique about these concepts of processes, perhaps a distinction should be made among several kinds of such concepts.

Kinds of Process Concepts

There are at least four kinds of process concepts: events, procedures, systems, and constraint-based interactions. I have identified six features that

all seem to be shared by events, procedures and systems, but none of these six features is shared by constraint-based interactions. Table 1 lists these six features, and I illustrate them in the context of an event, a baseball game.

The first feature is having identifiable or decomposable subcomponents. An event, such as a baseball game, can be decomposed into identifiable distinct segments, such as the pitcher pitching and the batter getting to first base. Second, one component (the first pitch) can be identified as the beginning and anther component can be identified as the end. Third, the subcomponents of an event occur in a sequential (unidirectional) order. For example, some distinct identifiable action or situation happens at one instance in time (such as the hitter getting to first base), and another action or situation happens later (the hitter then gets from the first base to the second base and not vice versa). Fourth, besides the initiating causal agent (such as the singing of the national anthem), there is a sequence of contingent or causal subevents within the event itself (e.g., the person on the first base does not get to run unless the batter hits the ball and did not strike out). Fifth, an event has an explicit identifiable goal (e.g., winning the game). Finally, an event typically terminates when the action or movement stops. For example, when the pitcher stops pitching, the game is over.

A system, such as the human circulatory system or a heating system, shares all of these six features of an event. In the human circulatory system, for example, there are identifiable subcomponents, such as the heart and the lung. There is a beginning and an end, such as the taking in of oxygen and the excretion of carbon dioxide. Blood that handles the delivery system flows in a sequential contingent–dependent way. The goal is to deliver oxygen to the organs and remove carbon dioxide from them. If the blood terminates its flow, then the system ceases to operate. Thus, a system has all of the six features of an event. Similarly, a procedure, such as tying one's shoes, also shares all of these six features.

In contrast, however, a constraint-based interaction (CBI) process differs from these three kinds of processes in that it does not share any of the six features. (I henceforth refer to the six features as *event-like features.*) Moreover, many concepts that embody a CBI process also operate at a level that is event-like. That is, concepts that embody a CBI process also have an observable or perceptual level that corresponds to an event, a procedure, or a system.

Take the concept of diffusion as an example. It is a process that embodies both a perceivable level that is event-like and an underlying nonobservable molecular level that is a kind of CBI process. Let us consider the perceptual level of putting a drop of red dye into a container of clear liquid. What is observed at the perceptual level is that the proportion of one kind of molecule (let's say the red dye molecule) migrates from one location to another. Once the red molecules are evenly dispersed in the clear liquid, it looks as if diffusion stops. Thus, at the perceptual level, diffusion looks like an event. Even the standard textbook definitions reinforce this notion when textbooks explain diffusion as the movement of gases and nutrients from areas of greater concentration to areas of lesser concentration.

At the molecular level, however, diffusion is really the random motion of two kinds of molecules. *Diffusion* refers to the process whereby the proportion or concentration of one kind of molecule changes over time as a function of random motion of the molecules. This process does not embody any of the six event-like characteristics (see Table 1). First, it does not have decomposable subcomponents (it is uniform). Second, nor does it have a beginning and an end (it is simultaneous), aside from an initiating causal agent external to the concept of diffusion (such as putting a sugar cube in a glass of water). Third, without any identifiable subcomponents, there is also no unidirectional sequential ordering (it is multidirectional; the molecules move in all directions). Fourth, neither is there a sequence of causal subevents. Diffusion is not caused by any one molecule hitting another molecule thereby causing it to move. Any one minuscule action of one molecule hitting another molecule has meaning only in the context of the rest of the molecules. That is, diffusion is the net effect of multiple independent molecules moving simultaneously. Fifth, there is no explicit goal. Diffusion is a constraint-satisfaction process. Diffusion does not occur for the purpose of reaching a state of equilibrium in which the red dye is equally distributed. Rather, diffusion occurs because the molecules simply move all of the time, and the dispersed outcome of the red molecules throughout the clear molecules is simply a probabilistic outcome. Finally, nothing terminates, although at the perceptual level diffusion may look like it terminates because there is no longer any movement (as when the red dye is equally distributed in the water). At the molecular level, the movement of the molecules continues. Nothing terminates. A better example to illustrate this last point may be the game of tug-of-war. At some point in that game, the two sides are balanced so that there is no further movement from one side to the other side. Nevertheless, the children on both sides continue to pull on the rope to keep the balance.

To sum up, a CBI process is a uniform, simultaneous, and multidirectional process rather than decomposable, sequential, and unidirectional, as are events. That is, the same action (e.g., molecular movement) occurs everywhere. Moreover, it has no explicit goal, nor does it ever terminate. Instead, it can be described as constraint satisfaction or equilibrium seeking. CBI processes of this kind occur in concepts of the physical, biological, and the social sciences, as well as in everyday life. Examples are heat transfer, electrical current, natural selection, diffusion, supply and demand, as well as children's activities such as seesawing and the game of tug-of-war, and everyday occurrences such as a flock of birds flying or a traffic jam.

Table 1

List of Contrasting Features

Event-like features	Constraint-based interaction features
Decomposable	Uniform
A beginning and an end	Simultaneous
Sequential or unidirectional	Random or multidirectional
Contingent or causal subevents	Net effect of independent subevents
Explicit goal	Constraint-satisfaction
Terminates	Continues

Why CBI Concepts Are Hard to Learn

We have postulated that CBI concepts are uniquely different from other concepts of processes. In addition, there is considerable evidence in the science literature showing that CBI concepts are extremely hard for students to learn. One can conjecture four possible reasons why CBI concepts are particularly hard to learn: (a) They tend to be misconceived initially as either a kind of material substance or a kind of causal event when in fact they are a kind of CBI process (see Figure 1). (b) Students are unfamiliar with CBI processes. (c) Students have limitations in the flexibility with which they can transfer between the dual levels of these concepts. (d) Students are not aware that a shift in the ontological class is necessary in order to understand a CBI concept. Each is discussed below.

Misconception of Concepts

Students initially conceive of many physical science concepts as a kind of substance rather than a kind of process, or if they do think of them as a kind of process, they think of them as a kind of event rather than a CBI (Reiner, Slotta, Chi, & Resnick, in press). Take, for example, the concept of heat in mechanics. Students typically think of heat as a kind of flowing substance. Such misconceptions are revealed by the way they talk about heat, such as "shut the window to keep the heat in," as if heat is a substance that can be contained in a room. A more concrete way to capture students' misconception is to analyze the language they use in answering a question, such as which cup—a styrofoam or a ceramic one—will keep coffee hotter if both cups are sealed with airtight lids? We (Slotta et al., 1995) asked this test question of students not to see whether they could answer it correctly but to examine the nature of the reasons or justifications the students gave for their choice. For example, for one student, the prediction was that the coffee in the ceramic mug would be hotter because "the heat in the styrofoam cup is gonna escape . . . because a styrofoam cup is not totally sealed because there's, like, . . . little holes in it." On the other hand, another student predicted just the opposite, that the styrofoam mug would keep coffee hotter because "it would trap the heat better than something ceramic, because ceramic doesn't have like air bubbles

in it that can absorb the heat or the coldness." However, although these two choices of outcomes are diametrically opposite, there is something similar underlying the justifications given. The similarity lies in the consistency with which justifications draw on the ontological attributes of the material substances tree. Thus, the ontological attributes of material substances may be attributes such as "can be moved," "can be contained," "block," and others (Slotta et al., 1995). These ontological attributes can be instantiated by a variety of predicates. The "move" attribute can be instantiated by predicates such as *goes, leaves, flows, escapes.* Thus, students who misconceive of heat as a kind of material substance would describe it with these kinds of predicates. This in fact is exactly what they did. With respect to the answer to the question posed above (which cup keeps the coffee hotter), students justified their explanations by appealing to the material substances attributes: "The coffee in the ceramic mug is hotter than in the styrofoam cup because the heat in the styrofoam cup is *gonna escape.*" "Escaping" applies only to material substances that can move from one location to another. Similarly, the justification given to the opposing choice was "it would *trap the heat* better than something ceramic." Again, trapping the heat means that heat is some kind of material substance that "can be contained." Thus, on the surface, these students' explanations may seem inconsistent, as if they appeal to various knowledge pieces (diSessa, 1993) to justify their views. (In fact, it is possible to get the same student to use different explanations, thus self-contradict.) However, this surface variability actually reflects an underlying commonality or coherence in the nature of their justifications. Thus, one way to capture students' misconceptions is to examine the kind of predicates they use in their justifications, and determine to which ontological class the predicates belong.

Thus far I have developed a theory that predicts how students misconceive concepts. Furthermore, a method was developed to capture the nature of these misconceptions, which reveal a principled way by which they are generated. Because these misconceptions are generated by attributes from a different ontological tree, they defy learning the correct conception, as the inappropriate ontological features have been attributed to them already.

Unfamiliarity With Constraint-Based Interaction Process Concepts

A second possible reason that CBI concepts are particularly hard to learn may be that the schema for this category of concepts does not exist in a student's repertoire, or it is not well defined. As noted earlier, a CBI concept has an alternative set of six features as listed in Table 1. In short, CBI processes possess features that are antithesis of the kind of processes students are more familiar with in their everyday encounters with events, procedures, and systems. It has been shown that when students are taught these CBI features, they can learn and understand physical science concepts significantly better (Slotta & Chi, 1996).

Lack of Correspondence Between the Dual Levels

A third possible reason for the difficulty in understanding CBI process concepts is that their surface manifestation does not correspond to their deeper mechanism. The most deceiving aspect of these CBI processes is that they have an observable level that is event-like. In diffusion, for example, there seems to be an observable unidirection to diffusion. For example, dye dropped into clear water seems to flow from one area to another area. Second, it seems to have a cause, that is, a difference in concentration. Third, diffusion seems to terminate when the dye is evenly distributed. Thus, a CBI process such as diffusion has all of the appearance of a causal event-like process. It is no wonder that CBI processes are misconceived. There lies the rub in the difficulty in learning and understanding such a concept.

The difficulty arising from the misleading surface appearance is compounded by the fact that students may not realize that two distinct sets of attributes govern the surface and the deeper mechanisms. Alternatively, it may be the case that, even if students realize this difference, it may be difficult to shift from one ontological branch (the surface appearance of causal events) to another ontological branch (the CBI process).

Lack of Awareness That a Shift Is Necessary

A fourth possible reason for the difficulty in learning CBI concepts may be that students are familiar with the CBI process category but are not aware that certain concepts belong to it (because these concepts are initially misconceived) and therefore do not realize the need to shift the ontological class in which they should represent a new concept. Thus, students fail to shift because they are not aware that such a shift is necessary. This suggests that if they are told that a shift is necessary, then they can do so readily. This is consistent with the case of changing a whale from a fish to a mammal, as well as changing a toy Indian to a real Indian. That is, we often readily acknowledge that a whale is a mammal once we are told. In both the whale and the toy Indian cases, however, the shift may occur more readily because the category to which it is shifted already exists in one's repertoire. That is, we are already familiar with the category of mammal, so being told that a given entity belongs to it supports the current interpretation. This does not, however, support the second interpretation mentioned above, namely, that it is hard to learn certain CBI concepts because we do not have CBI categorical structure in memory. At this point, however, there is no evidence to discriminate between these separate interpretations.

Thus, there are four reasons why certain physical and social science concepts are hard to learn. The nature of ontological categories plays a role in each of these reasons. First, these concepts are difficult to learn because students misconceive the correct ontological class from which these concepts belong. This conclusion is derived from analyzing the nature of ontological categories, the nature of a certain class of science and social science concepts, and the pattern of misconceptions students hold (Chi, 1992; Reiner et al., in press). Second, these concepts may be difficult to learn because students may not have the features of such a CBI ontological category in their knowledge structure. That is, categorical structure for such a class of concepts does not exist. Evidence for this interpretation is supported by a training study that attempted to teach students the features of a CBI ontological class before asking them to read about CBI process concepts. The training seemed to bolster their understanding of CBI concepts significantly (Slotta & Chi, 1996). Third, the difficulty with which these concepts are understood may be due to the difficulty students have in shifting between the causal event-like surface manifestation of these concepts and the underlying CBI concept. My student and I are currently gathering evidence to examine whether this interpretation is supported. Finally, students may not be explicitly aware of the need to shift their representation of these complex concepts from one ontological tree to another. This awareness interpretation is somewhat supported by our training study of the CBI features (Slotta & Chi, 1996), and anecdotally by evidence such as the ease with which people do shift once they are told about the true ontology of whales.

CREATIVITY

Creativity is required in understanding and in production. The framework presented in this chapter, using the learning of physical and social science concepts as a context, suggests that creativity is the ability to re-represent a concept that one has to understand from one perspective to a "fundamentally different" perspective. This "fundamentally different" perspective can be defined as a difference in ontology. The production of creative "products" can also be defined as the flexible way with which an individual crosses ontological boundaries. Major scientific discoveries seem to require the successful crossing of ontological boundaries (see Chi, 1992; Gentner, this volume).

The way creativity is defined here explains the sudden "aha" phenomenon of creativity, whereby everything all of a sudden seems to make sense. This phenomenon can be interpreted in the context of an ontological shift. This is because once a concept has been re-represented on a different ontological tree, the concept immediately inherits the attributes of that tree. This immediate inheritance can provide the "aha" phenomenon.

Are there more frequent everyday observations of creative products? Re-representing may be more common and less elusive if the ontological categories are well-known. A common occurrence is metaphors in speech. Below, examples are drawn from Lakoff (1987), in which he presented metaphors of anger as heat of a fluid in a container. Anger is an emotion, which can be thought of as occupying the ontological tree of mental states, distinct from material substances as well as processes (see Figure 1). The anger as heat metaphor can be manifested in the following type of comments:

You make my *blood boil.*
Simmer down.
I had reached the *boiling point.*
Let him *stew.*
Keep your *lid on.*

What is particularly interesting is that anger (and thereby heat) is conceptualized as a mass, a kind of material substance, because it takes the grammar of mass nouns as opposed to count nouns: Thus, one can say "How much anger has he got in him?," but not "How many angers does he have in him?" Notice that because people in general misconceive of heat as a kind of substance that can be contained, the metaphor really is analogizing anger to a substance (not a CBI process). Thus, from my previous prediction, a material substances ontology can have ontological attributes of "being contained," as in the way anger is used in "I can barely contain my rage." Moreover, the very fact that a quantifier is used confirms the fact that heat is treated as a kind of substance. Thus, it does seem that a large portion of metaphors are comparisons made between entities across ontological boundaries. The case of heat and anger crosses the boundary between the ontology of mental states and material substances. Thus, the use of metaphors, when it requires shifting across familiar ontological categories, may be a common form of creativity. It is a kind of usage that does not hamper the crossing of ontological boundaries, bolstering the interpretation that familiarity with the categories may be the secret to successful shifting. This suggests that learning complex process concepts can achieve the same ease in shifting, if individuals are taught the category features, as was done in Slotta and Chi (1996).

The goal of this chapter was to provide a definition of creativity as a shift in the way a particular concept is represented. More specifically, the most difficult and perhaps thus the most creative shifts may be those that occur across ontological trees. One can consider these to be "major" shifts. Prominent scientific discoveries tend to fall into this class of creative major shifts. Shifts that cross ontological branches may be more "minor" and occur with less resistance and more frequency, as ploys used in literature and films. Thus, although the sensibility test predicts that both shifts across branches and shifts across trees are ontological, the more stringent tests of learning and understanding of complex CBI processes, as well as the making of major scientific discoveries, predict that crossing ontological trees is more creative and occurs with less frequency.

REFERENCES

Barsalou, L.W. (1983). Ad hoc categories. *Memory & Cognition, 11,* 211–227.

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

Chi, M. T. H. (1988). Children's lack of access and knowledge reorganization: An example from the concept of animism. In F.E. Weinert & M. Perlmutter (Eds.), *Memory development: Universal changes and individual differences* (pp. 169–194). Hillsdale, NJ: Erlbaum.

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

Chi, M. T. H., Feltovich, P., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5,* 121–152.

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

Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction, 4,* 27–43.

Collins, A. J., & Quillian, M. R. (1969). Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behavior, 8,* 240–247.

Conrad, C. (1972). Cognitive economy in semantic memory. *Journal of Experimental Psychology, 92,* 149–154.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2–3), 101–104.

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

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

Koestler, A. (1964). *The act of creation.* New York: Dell.

Lakoff, G. (1987). *Women, fire, and dangerous things: What categories reveal about the mind.* Chicago: University of Chicago Press.

Malt, B. C. (1990). Features and beliefs in the mental representation of categories. *Journal of Memory and Language, 2*(9), 289–315.

McNamara, T. P., & Sternberg, R. J. (1983). Mental models of word meaning. *Journal of Verbal Learning and Verbal Behavior, 22,* 449–474.

Medin, D. L., Wattenmaker, W. D., & Hampson, S. E. (1987). Family resemblance, concept cohesiveness, and category construction. *Cognitive Psychology, 19,* 242–279.

Novick, L. R. (1988). Analogical transfer, problem similarity, and expertise. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 510–520.

Putnam, H. (1975). The meaning of "meaning." In H. Putnam (Ed.), *Mind, language, and reality: Philosophical papers* (Vol. 2, pp. 215–271). Cambridge, England: Cambridge University Press.

Quine, W. O. (1960). *Word and object.* Cambridge, MA: Technology Press of the Massachusetts Institute of Technology.

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

Rosch, E., & Mervis, C. B. (1975). Family resemblances: Studies in the internal structure of categories. *Cognitive Psychology, 7,* 573–605.

Rosch, E., Mervis, C. B, Gray, W. D., Johnson, D., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology, 8,* 382–439.

Ross, B. H. (1984). Remindings and their effects in learning a cognitive skill. *Cognitive Psychology, 16,* 371–416.

Slotta, J. D., & Chi, M. T. H. (1996). Understanding constraint-based processes: A precursor to conceptual change in physics. In G. W. Cottrell (Ed.), *Proceedings* *of the Eighteenth Annual Conference of the Cognitive Science Society* (pp. 306–311). Hillsdale, NJ: Erlbaum.

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

Smith, E. E. (1989). Concepts and induction. In M. I. Posner (Ed.), *Foundations of cognitive science* (pp. 501–526). Cambridge, MA: MIT Press.

Thagard, P. (1990). Explanatory coherence. *Behavioral and Brain Sciences, 12*, 435–502.

Wattenmaker, W. D., Nakamura, G. V., & Medin, D. L. (1988). Relationships between similarity-based and explanation-based categorization. In D. Hilton (Ed.), *Contemporary science and natural explanation: Commonsense conception of causality* (pp. 205–241). New York: New York University Press.