Barriers to Conceptual Change in Learning Science Concepts: A Theoretical Conjecture

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Abstract

This paper identifies and characterizes the existence of a specific class of "constructs" which may be particularly difficult to learn and understand. Their difficulty necessitates conceptual change, which is a form of learning which we define in the context of this class of constructs. Our explanation seems to fit a diverse set of data concerning the difficulty in learning science concepts of this nature. Instructional implications for how we can overcome this barrier to conceptual change will also be entertained.

Introduction

Many "constructs" in physics (e.g. heat and electrical current), in biology (e.g.,natural selection), and in the social sciences (e.g., supply and demand in microeconomic), are particularly hard for students to grasp. While more detail will be provided below as to the exact nature of this class of difficult-to-learn constructs, it is important to establish the psychological reality that certain constructs are indeed notoriously difficult for students to apprehend. This can be established in numerous ways, such as that students display characteristic misconceptions that are difficult to remove by instruction, ignore or reject any evidence that contradicts their misconceptions, and fail to apply classroom instruction about these constructs to informal reasoning problems in which they are relevant. Evidence for all of these behaviors can be found abundantly throughout the education literature concerning science misconceptions (see reviews by Reiner, Slotta, Chi, & Resnick, 1992).

Perhaps the reasons for students' difficulties are obvious: these constructs are often abstract, mathematically defined, and not directly observable. However, our theoretical analyses (Chi, 1992; Chi, Slotta & deLeeuw, in press) suggest that these obvious reasons are not fundamental in accounting for the constructs' difficulty, since many other scientific constructs are equally abstract, mathematical and unobservable, but are learnable nonetheless (in the sense that misconceptions are more readily removed, etc.). For example, the concept of density appears to pose minor problems for students, as compared to that of weight; likewise with the notion of an electron, which is straightforward in comparison to that of electrical current. Rather, we believe that certain constructs are difficult to learn and understand because their underlying characteristics are completely alien and dissimilar to other concepts which students have already learned and represented in memory. This suggests that they cannot be learned by the normal processes of learning, rather, they first require conceptual change.

It is important to distinguish the process of learning versus conceptual change. We first assert a fundamental assumption that all learning is basically an assimilation of a concept into an existing structure in memory. Such assimilations can result in refinement, generalization, or creation of a new structure similar to an existing structure (as in the case of analogical learning) and so forth. This is a fairly universal assumption about learning (see Schank, 1986, as well). Having asserted this assumption, conceptual change must occur when a to-be-learned concept cannot be fitted into any structure that already exists, or alternatively, the to-be-learned concept is mistakenly assimilated into a wrong structure. Viewed this way, conceptual change refers to the need to *switch* to assimilating a new concept from one structure into another structure. Hence, this *switching process* is the process of conceptual change, whereas processes of learning, as normally conceived in the literature, refer to operations such as accretion, tuning, generalization, discrimination, proceduralization, analogy, and so forth. Defining it this way focusses the problem *not* on what processes constitute conceptual change, but rather, to the problem of when does a person realize that s/he needs to switch. Below, we present arguments for circumstances when this may occur, namely, when a student is learning one of these "constructs".

Our theory of conceptual change, necessary for learning constructs of a certain type, relies upon three suppositions: an epistemological one concerning the nature of entities in the world, a metaphysical one concerning the nature of certain science and social science constructs, and a psychological one concerning the nature of conceptual knowledge. We will briefly lay out these three suppositions, whose conjoint frames an initial explanation of why some constructs are difficult to learn, when conceptual change is necessary, and considers how instruction might overcome such barriers. Although the theory explains the difficulty in learning any construct that has these characteristics, a great deal of the discussion focuses on physics concepts, only because the majority of evidence in the literature is collected in that domain.

An Epistemological Supposition

The first supposition states that entities in the world may be viewed as belonging to different fundamental or "ontological" categories. While this statement is simply a definition of the concept of "ontology", what is more important is the character of these ontological categories. Three primary ontological categories are depicted in Figure I: MATTER, PROCESSES and MENTAL STATES. There may be others as well. There is also a hierarchy of subcategories embedded within each of these major categories (e.g., PROCESSES is divided into Events, Procedures, and Acausal Interaction; MATTER is divided into Natural Kind and Artifacts). These subcategories are shown in the Figure, with category members appearing in parentheses and ontological attributes appearing in quotes. Since we are early in the process of laying out the ontological tree in detail, we are not committed to this exact tree, nor necessarily that it be hierarchical. Other organizations are possible. Keil, (1979) for instance, following Sommers (1963), divides OBJECTS (corresponding to our MATTER category) into the Solids and Aggregates subcategories. However, most importantly in our view, Keil and others have omitted the primary category of PROCESSES, whose subcategory of

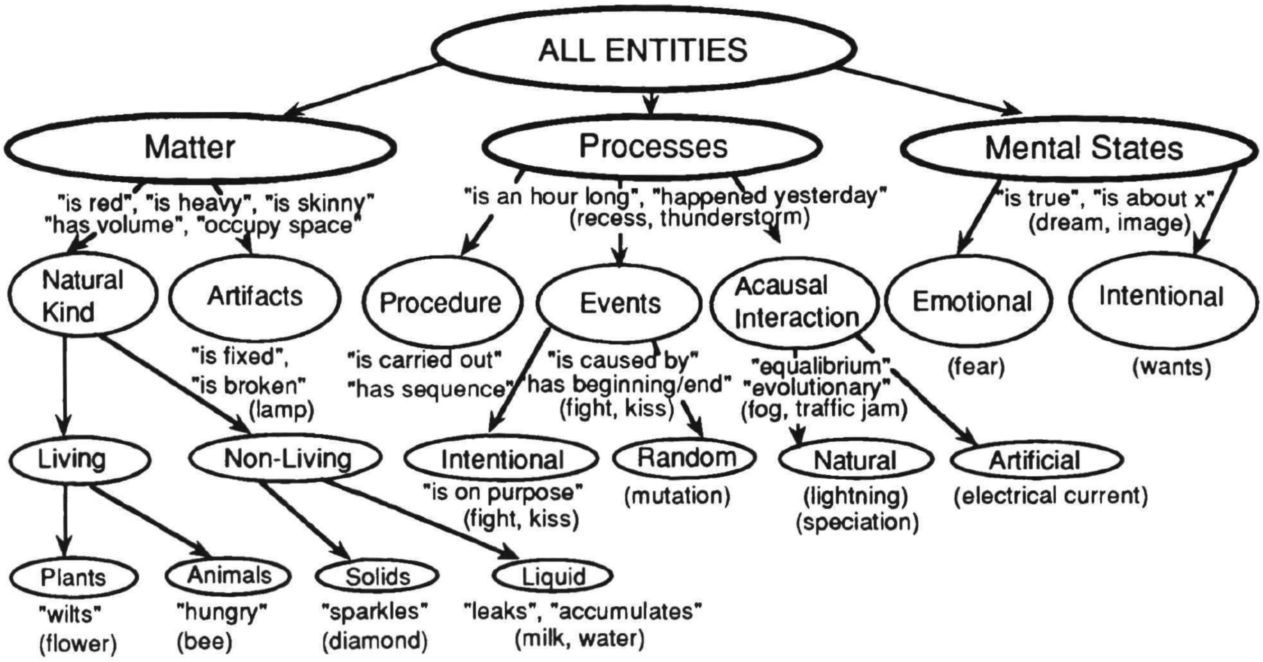

Figure 1. One possible categorization scheme. Categories which are separated horizontally on the tree are ontologically distinct.

Acausal Interactions is prominent in our account of intuitive physics knowledge. Actually, for the purpose of present discussion, we need to focus only on the distinction between two primary categories: Matter and Processes.

Carving up the world according to ontological categories as opposed to some other categories merely means a different set of attributes may be needed to determine category membership. An ontological attribute is a property that an entity *may potentially* possess as a consequence of belonging to that category (or any of its subordinates). This contrasts with the notion of either defining or characteristic attributes, which are attributes that a category member either must have, or most likely has, respectively. Thus, an ontological hierarchy of categories defines the world of entities in its most fundamental sense – in terms of their basic "essence".

PROCESSES differ ontologically from any category of MATTER. *Differences* between ontological categories can be operationally defined by their non-overlapping sets of ontological attributes. For example, in Figure l, "hungry" can be applied to the category of Animals and all its subcategories, such as Humans. Therefore, Animals and Humans are not ontologically distinct. Basically, two categories are ontologically distinct if they occupy parallel (meaning horizontally separate) branches of the hierarchical tree. In other words, two categories are ontologically distinct if the attributes of one category cannot be applied to members of another category. Returning to the differences between MATTER and PROCESS category members, "an hour-long" is a predicate that may modify a member of the Event category, but cannot be used sensibly to modify any member of the MATTER category, such as a dog. 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 ontology, then at worst the statement such as "a dog is purple", is simply false, but plausible. The psychological reality of the distinctness of ontological categories can be tested precisely by predicating an ontological attribute onto a category member, and asking people to judge whether such a statement is sensible or anomalous (Keil, 1979).

A Supposition about the Nature of Physics Concepts

We propose that many physics concepts belong to a subcategory of PROCESSES which we here call Acausal Interactions, a relatively unfamiliar and elusive ontological category. We first illustrate members of this Acausal Interactions category by way of examples. Consider the concept of gravitational force, which involves a mutual attraction between two massive objects directed between their respective centers of mass. There is no direct causal agent of this force, at least within the formalism of classical mechanics. Similarly, an electrical current exists whenever electrically charged particles are free to move in the presence of an electric field. This can be seen as an interaction between the source of the field (e.g., some difference in electric potential between two points in space) and the moving charged particle, again with no particular causal agent involved. The same sort of reasoning can be applied to the concepts of heat, light, and others, whose veridical (scientific) conceptions thus belong to the Acausal Interactions category.

Although concepts and constructs in the Acausal Interaction category are acausal, in the sense that they proceed strictly according to constraining relations among their components, and not because some external agent or internal intention is driving them, certainly some causality, *external to the construct,* may be operating in defining the *onset* of the process. For example, in electrical current, an external causal agent can be the flipping of a switch to connect a battery to the circuit; similarly, the evolution of the English peppered moths, from being relatively lighter colored to darker in color, can be seen as causally related to the smoke from nearby factories. However, smoke itself did not literally change the color of the moths; it was the external agent which caused a change in the moths' environment, after which the acausal process of natural selection proceeded to change the color of the moths. These constructs become defined only after such initial external causes, but the constructs exist from then on in the absence of any causes. Thus, evolution is the name that refers to the acausal construct which describes the chain of events culminating in the survival of darker moths and the gradual elimination of lighter moths. Each event within the chain may also contain local causal agents. For instance, the elimination of an individual moth is itself an event which has a cause: some bird or other predator ate a light-colored moth. Thus, these constructs can become defined after such initial external causes, and they can also contain causal elements, but the constructs themselves exist in the absence of any causes.

A second way to characterize the attributes of this Acausal Interactions category is to contrast them with other Process subcategories, such as Events. Two major attributes are salient. The first one was alluded to in the aforementioned paragraph, concerning the lack of a causal agent, whereas most Events do have a causal agent. The second salient attribute can be described in the following ways. Acausal Interactions have no obvious beginning or ending, in contrast to Events. For instance, in the Event of a baseball game, certain things happen in the beginning of the game, and other things happen at the end, so that there is an orderly sequence of the component processes. Acausal Interactions do not have this kind of predictable progressive quality: There is no characteristic pattern over time or space, because the process is *uniform* and *simultaneous* everywhere. Thus, some of the terms or attributes that can be used to describe an Acausal Interaction are: no beginning or ending, no progression, uniform magnitude, simultaneous, static, on-going, steady state, and equilibrium. There may be others as well.

A third way to describe the nature of these difficult-to-learn constructs is to state what they are *not*. We do so to emphasize the properties that students often inappropriately attribute to them. First, these constructs are *not* kinds of matter or material substances; nor are they properties of matter. They are not objects or attributes of objects; nor do they behave as objects. For example, electrical current is not an object, a collection of objects, or a fluid; neither is supply and demand, or mutation. Second, these constructs are *not* emotional states, such as feelings, attitudes, or intentions. Third, they are *not* mental states or abstract ideas like *liberty* or *beauty*. *Beauty* is subjective and can vary from one person to another, whereas electrical current can be measured objectively. Fourth, they are *not* events, like baseball games or a class lectures. Events typically have a characteristic temporal progression, and often have causal agents. Finally, these constructs are not procedures, which usually are goal-driven sequences of actions, often with an end-product, such as tying a shoe or making a sandwich. We believe that students' existing conceptual knowledge is made up of many many instances of at least these five general categories of knowledge (matter, emotional states, abstract ideas, events, and procedures). Our basic theory is that students will therefore try to assimilate novel constructs by attributing properties of these categories to them. New science constructs belonging to one of these five categories are more easily learned than constructs which do not belong. Because those constructs which do not belong are nevertheless assimilated into one of these five familiar categories, and regarded, for example, as "Things" or "Events", learning their actual meaning becomes all the more difficult.

We now summarize the characteristics of these difficult science constructs (i.e., what they *are*). First, they are often invented by scientists, and hence a student is not likely to encounter or induce them on his/her own by simply observing the environment. Second, these constructs also often embody dynamic occurrences and interactions of several underlying components, and are thus processes by nature, but of a different variety than events and procedures, which are also processes. For instance, the law of supply and demand is a relational process involving many factors and many participants, the totality of which cannot be observed, nor are the individual component processes discernible. Third, although these constructs usually refer to processes of interaction, they do not involve a causal agent. They are acausal, in the sense that they proceed strictly according to constraining relations among their components and component processes, and not because some external agent or internal intention is driving them. Certainly, some causality, *external to the construct*, is involved in defining the onset of these construct. For example, in electrical current, an external causal agent can be the flipping of a switch to connect a battery to the circuit; similarly, the evolution of the English peppered moths from being relatively lighter colored to darker in color can be seen as causally related to the smoke from nearby factories. However, smoke itself did not literally change the color of the moths; it was the external agent which caused a change in the moths' environment.

Often, constructs of this kind describe the interaction of multiple components until some kind of equilibrium or steady state is achieved. Electrical current, for example, occurs system-wide in a circuit where certain conditions (i.e., an electric potential difference) exist which influence charge-bearing particles (i.e., electrons) to move in a certain direction. Electrical current is a scientific construct which serves to quantify the net statistical motion of electric charge past any specific point in the circuit (as opposed to the motion of electrons, which move in all directions within the wire, even when an electrical current exists within the circuit). Hence, electrical current is a name given to an equilibrium relation between properties of the wire and certain system-wide conditions and constraints imposed on the wire. In the domain of economics, the cost of an item changes predictably as a function of its supply and demand, meaning that changes in supply or demand will eventually bring about a new equilibrium cost for the item. Here also, once the system variables have been set, there is no causal agent in this process of interaction.

This characterization of Acausal Interactions is quite broad, and applies to science concepts outside of physics as well. For example, within the topic of evolution there are Acausal Interactions crucial to a complete scientific understanding, such as mutation, genetic equilibrium seeking, and so on. Thus, concepts of the Acausal Interaction category are not limited to disciplinary bounds, although it may be the case that there are more of them in physics than in other domains of science.

A Psychological Supposition about the Nature of Intuitive Physics

The psychological supposition concerns the ontological status of naive physics knowledge. Students tend to consider concepts such as heat, light, forces, and electrical current as belonging to the MATTER category, either as material substances, or as properties of material substance (Reiner, Chi, & Resnick, 1988; Reiner, Slotta, Chi & Resnick, 1992). For example, students often think of force as a kind of impetus imparted to a body, or as an intensive property that a body can possess (similar to velocity), and they believe that this impetus (or "oomph") can be used up. Thus, force becomes the causal agent for movement, or it is a property of an object, or it is substance itself. Examples of this kind of misconception are rampant in the science education literature. Pfundt and Duit (1989) have catalogued over 1500 studies which address misconceptions of this and related natures. Substance-based misconceptions, in particular, are prevalent and homogeneous across *several* physics concepts, as synthesized and reviewed in Reiner, Slotta, Chi and Resnick (1992).

The Incompatibility Hypothesis

The conjoint of these three suppositions provides the following theoretical framework (using physics learning as an example): first, there is an ontological category called Acausal Interactions which physics novices have little knowledge about, but to which the veridical physics concepts belong; second, novices have encoded and interpreted their daily experiences in the physical world as belonging to the MATTER (and sometimes Event) category. Misconceptions in naive physics are a result of the mismatch or *incompatibility* between the representation the student has of phenomena in the world (e.g., as MATTER or Events) and the veridical ontology of the associated physics concepts (e.g., Acausal Interactions). Since learning is primarily the assimilation of new knowledge into an existing knowledge structure, this would imply that physics concepts are preferentially encoded into the MATTER ontological category. Doing so would prohibit accurate understanding of physics concepts, which veridically should be assimilated into the PROCESS category and Acausal Interaction subcategory in particular. Thus, to learn physics concepts of this nature requires that the Acausal Interaction category be activated and developed in order to assimilate veridical conceptions of physics.

This view of learning physics suggests that it is not possible to *refine or develop* intuitive knowledge to the point that it becomes the veridical physics knowledge; entities on separate ontological trees cannot be merged since they cannot inherit each other's attributes. For example, the danger in using the analogy of flowing water to instruct about electrical current is that students will continue to assimilate newly taught information about electrical current into the ontological class of MATTER. If students assimilated new information about electrical current into the Liquid subcategory (see Fig. I, near bottom), then the concept might also inherit properties such as "has volume", "occupies space", and other ontological attributes of the MATTER category. This explains why misconceptions about electrical current often include statements such as "it can be stored in the battery" or "it can be used up". Therefore, when initial conception is mis-categorized, then conceptual change or *category switching*, is required in order to fully understand the concept. *Radical* conceptual change, as referred to by Carey (1985) and others with respect to scientific revolution, fits perfectly with the notion of switching across ontological trees. It is not clear at this point the degree of radicalness if switching occurred within the same tree, but across parallel categories. Certainly, changing category membership among categories on the same vertical branch, would not constitute conceptual change.

Some Instructional Considerations

Students not knowledgeable about the existence of a category of constructs such as "acausal interactions" have a tendency to assimilate new to-be-learned concepts of this kind into the wrong category, such as Matter. Such mis-assimilation prevents the student from learning the veridical conceptions, since all the incorrect ontological attributes will be inherited along with the mis-categorization. Thus, misconceptions are maintained, and remain robust. To overcome such barriers to conceptual change, students must be taught about the existence and characteristics of such a category of constructs, so that they are made aware of the need to switch the category to which new concepts of this nature are to be assimilated. This conjecture is also consistent with findings in the literature showing that other instructional techniques, such as reciprocal teaching, often fail to induce conceptual change for science concepts. Our theory would suggest that such instructional techniques fail because it is almost impossible for students to realize, on their own, the existence of such a category, and the incompatibility between their conceptions and the veridical conceptions, in terms of which ontological category they belong.

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