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COGNITIVE UNDERSTANDING LEVELS

Many physical, chemical, biological, and social science concepts, such as heat, electrical current, diffusion, natural selection, and supply and demand have been incredibly hard for students to understand. Many reasons have been offered for their difficulties; these reasons fall into the following four major types. One proposed explanation is that concepts of this kind are complicated, involving many subcomponents, including subconcepts and mathematics. Such a complicated view would propose that if instruction removed the mathematics and focused on clarifying the subconcepts, then learning and understanding would be facilitated. A second explanation is that many of these concepts are abstract often not visible to perception. A remedy then would be to design instruction that could reveal the nonperceptible parts of the concept, or make these concepts more concrete by providing hands-on experiences, or situating the concept in an everyday context. A third explanation is that these concepts tend to be dynamic, whereas our ways of describing and symbolizing phenomena in the world tend to employ static representations. Instructional interventions might facilitate understanding by using dynamic computerized displays. A fourth explanation is that students have naive intuitive understanding that is incorrect, and such naive incorrect understanding hinders their learning of the correct understanding. Such an intuitive knowledge view would propose that instruction should build upon students' existing intuitive understanding, in order to scaffold the students gradually from the naive understanding to the correct understanding. However, all of these instructional tactics, as a whole, have not led to correct and deeper understanding of these complicated abstract, and dynamic (CAD) concepts, thus calling into question the viability of these four explanations. These kinds of CAD concepts are particularly difficult to learn, because there is an incommensurability between the categorical structure or schema to which students attempt to assimilate these concepts and the veridical categorical structure or schema to which they ought to assimilate them. The role of incommensurability in the development of scientific understanding can be illustrated with an analysis of the concept of diffusion.

The CAD concepts cited above are not concepts of concrete objects, nor of causal events, but rather, they are concepts of processes of a specific kind. They are all a kind of process for which the observable percetual global phenomenon emerges from an intrinsically distinct underlying local interacting processes. Take the simplest example of the process of diffusion, say between a red-colored liquid and a blue-colored liquid, initially separated in a flask by a barrier. When the barrier between them is removed, the process of diffusion begins. What one sees is that the red liquid seems to be moving toward the blue liquid and the blue liquid seems to be moving toward the red liquid. When the liquid ends up looking uniformly purple, then the movement seems to stop. Thus, what the students see is the flow of red liquid to the blue liquid area, and vice versa. Moreover, the entire flow seems to stop when equilibrium is reached.

This perception is consistent with the students' interpretation of a text. One high school text explains diffusion (of gases and nutrients in the human circulatory system) in the following way:

> Diffusion of gases and nutrients take place across the thin capillary walls from areas of greater concentration to areas of lesser concentration.

Thus, students do think of diffusion as a process (so they do not have difficulty understanding dynamic concepts per se), whereby molecules move from an area of greater concentration to an area of lesser concentration, until the concentration of the two areas are equal. Moreover, they are perfectly capable of understanding and imagining the molecules underlying the liquid, so it's not as if they have trouble imagining the abstract concept in terms of concrete molecular components. Finally, the complicated view would say that students may not understand diffusion because they do not understand the subconcepts of concentration and equilibrium. However, students often do understand these subconcepts. For example, when asked, "What does concentration mean?" one student from our study (Chi, de Leeuw, Chiu, & LaVancher, 1994) can correctly reply:

> One side is more dense and the other side is less dense. It's trying to get from more dense to less dense. The molecules are farther apart on the lesser side and closer together on the greater side, and there are more of them.

Students can also correctly define equilibrium as when the number of molecules are equal on each side. Thus, students' understanding of the component subconcepts do not appear to be the source of difficulty for their failure to understand the target concept (e.g., diffusion) deeply.

In sum, students are failing to understand these CAD concepts not because they are complicated, abstract, and dynamic. The only remaining explanation left is that students have naive intuitive knowledge that is correct and hinders understanding. The question is why does this intuitive knowledge prevent deep correct understanding of these CAD concepts. The problem with their "intuitive" conception is that they attribute the following properties to the process of diffusion:

They attribute *causality* to why the molecules move in the direction they do (usually the cause is limited space or crowding). They attribute *intentionality* to the process (such as "it's trying to get from more dense to less dense"), as if there is an agent directing the molecules to move in a certain direction, or the idea that there is a *goal* to be reached (the equilibrium state is often thought of as the goal). And, they attribute *squentiality* and/or *chronology* to the process (from areas of high concentration to areas of low concentration). They attribute *distinct actions* to the blue and red liquid (or molecules making up the liquid), as if the blue molecules move in one direction and the red molecules move in another direction. They also believe that the process is *bounded*, so that there is a beginning, defined as the onset, the point at which the barrier in the flask is removed, and an end, the point at which the liquid turns into a uniform bluish purple color; and finally, related to the notion of boundedness is the idea of *termination* of the process of diffusion when no perceptible motion of the blue and red liquid is detected.

From students' naive explanations (see Ferrari & Chi, 1998 for another CAD concept, natural selection), we can see a pattern of attributions that can be succinctly summarized as consisting of the following set of related attributes: distinct actions; sequential/chronological; bounded/terminates; and contingent/causal/intentional /goal-directed (Chi, 1992, 1997; Slotta, Chi & Joram, 1995; Ferrari & Chi, 1998; Slotta & Chi, 1996).

Such a pattern of attribution fits the attributes of a CAUSAL schema. For instance, a CAUSAL event (such as a baseball game) has the properties of having a beginning and an end, it has distinct actions (some players hit the balls, some catch the balls), its subcomponents occur sequentially or chronologically in a contingent and causal way (a player must get to the first base before s/he may try for the second base), each event has an external and explicit goal (trying to get as many runs as possible), and the event terminates when there is no more visible movement (no one else is coming to bat nor running). In contrast, the schema that describes the CAD concepts have an alternative contrastive set of attributes. A process such as diffusion has no beginning and end, instead it is ongoing. Diffusion is the net effect of multiple *independent*, *simultaneous*, *uniform* and (*local*) actions (such as the random movement of molecules). The actions are *not goal-directed*. This means a red liquid molecule, over time, from random movement, may migrate into the blue liquid location; likewise, blue molecules may migrate into the red liquid location, after the barrier is removed. Over time, the net effect is that there are just as many red molecules in the blue liquid location as there are blue molecules in the red liquid location. Hence, there is no intentionality or causality, nor is the movement of any molecule contingent upon the movement of any other molecules. Instead, all actions are independent (rather than contingent), simultaneous (rather than sequential or chronological); and uniform (rather than distinct), in that they all have the same action, which is to move about randomly Moreover, the molecules continue to move even though equilibrium (the obvious stopping of motion of flow) has been reached.

Although researchers often attribute the concept of random movement as a source of difficulty deterring students' understanding of the concept of diffusion, the claim here is that random movement per se is not an attribute of this kind of process, and therefore is also not a source of students' difficulty in understanding diffusion. Random movement happens to be an attribute of molecular motion, which is the particular action of this concept of diffusion. For an alternative concept such as natural selection (of the English peppered moth), the individual action is the eating of a moth by a bird, and not random motion. What is important and difficult to understand is the attribute of multiple, *independent*, *simultaneous*, *uniform* and *local* inter-actions, the totality of which manifests itself in a global phenomenon.

Thus, diffusion is a process that has a set of attributes (noncontingent/acausal; unbounded and ongoing; simultaneous, independent, and uniform actions resulting in a net effect) that is ontologically different from the attributes of (Chi, 1997). The fact a CAUSAL event that diffusion is really a global process resulting from multiple local interactions, and yet students misconceive of it as an event-like causal process, means that students' naive understanding is embedded in a schema that is incommensurate (or ontologically distinct) with the concept's veridical schema (we have called it various names in the past, but let's refer to it here as the EMERGENT schema). When this occurs, that is, when the students misattribute properties of one schema (the CAUSAL schema) to concepts from another ontologically distinct schema (the EMERGENT schema), then students will never understand the concepts deeply. This is because attributes from two incommensurate schemas cannot modify each other's concepts in a meaningful way.

The example above shows incommensurability between a CAUSAL schema and an EMERGENT schema. Incommensurability can occur between various other schemas: substance versus processes (Chi, Slotta, & deLeeuw, 1994), static versus dynamic, artifacts versus natural kind (Gelman, 1988), and animate versus in animate.

Students' naive attributions of characteristics of diffusion, as stated above, are neither haphazard, random, inconsistent, simplistic, peculiar, nor piecemeal. (In fact, these attributions are shared by the majority of the students that we have examined, so that they may be universal.) Rather, these characteristics fit the attributes of a causal, event-like schema. What makes students appear to be inconsistent, either within an individual or among individuals, is that they draw upon any one of the attributes from either the substance or the event schema to generate an explanation, so that they appear to have knowledge in pieces that are inconsistent and contradictory (diSessa, 1993). But in fact, they are extremely coherent and consistent, when one views their responses from the standpoint of a specific schema.

A similar framework has been proposed by Gelman (in press). Gelman distinguishes between core domains and non-core domains. A core domain is an innate skeletal structure that predisposes children to perceive the world in terms of its skeletal features. The existence of innate core domains can be seen by the way very young infants are sensitive to certain environmental inputs and not others. For example, one-month old infants can discriminate and categorize speech sounds (Juscyck, 1996), and five-month-old infants believe that one solid object cannot pass through another solid object (Baillargeon, Spelke, & Wasserman, 1985). These kinds of evidence suggest that there already exist mental structures that predispose infants to be sensitive to environmental inputs that are relevant to these structures. In our framework, we might say that the nature of students' naive conceptions, in mistakenly conceiving of CAD concepts as either causal events or concrete substances, arise from the erroneous assimilation of these processes into existing core domains. In order to learn a non-core domain, such as a CAD concept, specific formal instruction may be required. However, since the skeletal structure of a non-core domain is not innately available, one can only expect correct understanding and deep learning if the domain-relevant content knowledge (such as diffusion or natural selection) is taught after the domain-relevant skeletal structure (the EMERGENT schema) is already in place, so that the learners can assimilate inputs into existing skeletal structures. We have proceeded in exactly this vein, and achieved surprising deep understanding, in the context of learning about the CAD concept of electrical current (Slotta & Chi, (1996).

To summarize, CAD concepts are hard to learn not because they are complicated, abstract and dynamic per se, nor because students have naive intuitive notions that are incorrect. Rather, CAD concepts are hard to learn because the students' naive intuitive notions are not merely incorrect, but more importantly, they are incorrect in that they are subsumed within a schema that is incommensurate with the schema to which they should be correctly subsumed. Thus, instructional intervention should focus on creating and activating the appropriate EMERGENT schema to embed understanding of CAD concepts, rather than building from their existing naive conceptions that have been embedded in an incommensurate schema.

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