Understanding Constraint-Based Processes: A Precursor to Conceptual Change in Physics

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Abstract

Chi (1992; Chi and Slotta, 1993; Slotta, Chi and Joram, 1995) suggests that students experience difficulty in learning certain physics concepts because they inappropriately attribute these concepts with the ontology of *material substances*(MS). According to accepted physics theory, these concepts (e.g., light, heat, electric current) are actually a special type of *process* that Chi (1992) calls "*Constraint-Based Interactions*" (CBI). Students cannot understand the process-like nature of these concepts because of their bias towards substance-like conceptions, and also because they are unfamiliar with the CBI ontology. Thus, conceptual change can be facilitated by providing students with some knowledge of the CBI ontology before they receive the relevant physics instruction. This CBI training was provided by means of a computer-based instructional module in which students manipulated simulations as they read an accompanying text concerning four attributes of the CBI ontology. A control group simply read a (topically similar) text from the computer screen. The two groups then studied a physics textbook concerning concepts of electricity, and performed a post-test which was assessed for evidence of conceptual change. As a result of their training in the CBI ontology, the experimental group showed significant evidence of conceptual change with regards to the CBI concept of electric current.

Introduction

Toward a cognitive theory of instruction

For decades, researchers have studied the science knowledge of novices and experts in a widespread effort to identify and characterize misconceptions of a broad array of science concepts. At the same time, research has also explored different approaches to science instruction which attempt to take these misconceptions into account. Pfund and Duitt (1988) have produced a catalog of nearly 2000 published studies of students' physics misconceptions and instructional attempts at their removal. One important goal of this research (Resnick, 1983) has been to develop a cognitive theory of instruction, which would provide a detailed description of learning in terms of the student's initial knowledge, and how that knowledge interacts with the instructional message. To date, however, there is no instructional theory, nor any methodology which assures that students entering the science classroom will not finish the semester with the same misconceptions they had on the first day of class.

Any instructional theory requires a theory of conceptual change, which provides a cognitive account of students' initial conceptions and the role they play in the learning processes. Chi (1992; Chi, Slotta and deLeeuw, 1993; Slotta and Chi, 1995), has proposed a theory of conceptual change (described below) that is able to account for several important phenomena in the misconceptions literature. A second requirement is a valid means of assessing student conceptions and conceptual change, which is the focus of recent work by Slotta, Chi and Joram (1995). The present study builds on this background by implementing an instructional approach that follows from Chi's theory, and assessing its effectiveness in terms of conceptual change at an ontological level.

Research on student misconceptions

In reviewing research on science misconceptions, Chi (1992) has observed that some misconceptions are easily removed in the course of instruction, while others are characteristically robust, meaning that they survive even when directly confronted by instruction. In one study (McCloskey, 1982), more than half of the university engineering students were still plagued by misconceptions of the basic concept of force. These "robust misconceptions" are typical of certain physics concepts, and may be partly responsible for the difficulty perceived by students and teachers in the physics classroom. In reviewing the literature on physics misconceptions, Reiner, Slotta, Chi and Resnick (in press) found that students often attribute difficult concepts such as force, heat, light, and electricity with materialistic properties. Slotta, Chi and Joram (1995) asked physics novices to solve conceptual problems involving light, heat, and electric current, and observed a clear bias towards materialistic mental models (e.g., reasoning about electric current in a wire as if it were a fluid flowing inside a hose). Any theory of instruction which hopes to account for these robust naive conceptions must be sensitive to this apparent materialistic commitment.

A theory of conceptual change

Chi (1992; Chi, Slotta and deLeeuw, 1993; Slotta and Chi, 1995) has advanced a theory of conceptual change that is able to account for why some physics misconceptions are robust (and others are not), and why there is an apparent preference for materialistic misconceptions. The theory also affords some predictions about how instruction can best proceed in addressing persistent misconceptions. It is upon one such prediction that the present research is founded.

The theory begins with the assumption that people associate all concepts with distinct ontologies (which can be thought of as fundamental categories), such as *processes*, *ideas*, or *material substances* (throughout the paper, any reference to such ontological categories will be italicized). When a new concept is learned, it is associated with some ontology, which helps the learner understand what kind of concept it is, and what attributes it may possess. Thus, in learning about a new concept such as "osmosis", if person recognizes it (for any reason) as a sort of *process*, then such attributes as "takes some time to occur", and "has a chronological sequence" will become implicitly associated with the concept. Misconceptions arise when a person associates a new concept with the wrong ontology. In learning about the concept of "heat", for example, many children wrongly assume a *material substance* ontology, perhaps because of language conventions such as "close the door, you're letting all the heat out" (Reiner et al., in press). In fact, the concept of heat is more appropriately associated with a *process* ontology, as it is best thought of in terms of the transfer of molecular kinetic energy.

Specifically, Chi has proposed that a particular ontological class of science concepts, which she has called *constraint-based interactions* (a type of *Process*), are characteristically mistaken by novices as possessing the ontology of *material substances*. These are concepts which typically involve constraints such as the equilibration of certain system properties (e.g., inside and outside temperature; voltages; air pressures; etc.) -- properties that are often difficult for a physics novice to perceive. When Slotta et al. (1995) asked physics experts to solve the same conceptual problems that were given to the novices (concerned with topics of light, heat and electricity), their explanations of these problems were consistent with a *constraint-based interaction* ontology, and not a *material substance* one (in contrast with the novices). These observed ontological differences between the conceptions of novices and experts suggests that Chi's account may be accurate: novices may cling to their misconceptions because they are unable to stop thinking of these concepts as material substances.

For example, a student might talk about electric current as "shooting out of the battery", or "leaking out of the wires", even when told explicitly that such descriptions are incorrect. Because of this misconception, the student will experience difficulty in learning about electric current in its scientific sense: as a type of *process* where all of the free electrons in the circuit acquire a uniform velocity component, resulting in a net flow of electric charge through any given point around the circuit. This bias towards the *material substance* ontology may result from a variety of different causes: materialistic biases in language, such as in the heat example above; the dominance of the material substance ontology in our conceptual knowledge, such that it becomes a "default" for novel concepts (i.e., most of our early experience is with material substances and their observed behavior); or the paucity of examples from alternative ontologies (such as that of *constraint-based interactions* ontology). Whatever the origin of this bias, the challenge of teaching certain physics concepts apparently involves convincing students to either relinquish their initial ontological associations, or else gradually forget them.

Methods

Design

The present research applies Chi's theory in a method of instruction whose focus is ontological training. The theory suggests that students may be facilitated in learning *process*-like conceptions if they are first (before any physics instruction) provided with some knowledge of the *Constraint-Based Interactions (CBI)* ontology. We developed a computer-based training module which provides instruction in the *CBI* ontology by means of text and simulations, with no mention of any concepts in electricity. We hypothesize that subjects who receive this *CBI* training will gain some knowledge of the process-like nature of electric current from subsequent instruction in electricity topics. Before receiving the *CBI* training, subjects were pre-tested for misconceptions of electric current, using materials derived from Slotta et al (1995). After the training session, they were provided with instruction in electricity topics, taken directly from a popular conceptual physics text (Hewitt, 1987). Finally, they received the pretest questions a second time, to test for improvement in problem solving, as well as differences in the ontological nature of their explanations. Performance of the experimental subjects was contrasted with that of a control group who did not receive the training module, but instead reviewed a text similar in domain content.

Assessment of conceptual change was performed according to the method developed by Slotta et al (1995), where verbal explanation data is analyzed for its content of a specific set of conceptual attributes that are determined, a priori, to indicate ontologies of *material substance* (*MS*) or *CBI*, respectively. If a subject talks about electric current in materialistic terms, this is taken to reflect an underlying conception of electric current as a *material substance*[1]. Similarly, the use of verbal predicates which reflect ontological attributes of *constraint-based interactions* are taken to reflect the presence of a *CBI* association. We hypothesize that the experimental group will show a transition from the pretest (where they explain problems in terms of the *MS* ontology), to the post-test (where they will draw upon more *CBI* predicates in their explanations).

[1]Note: the use of materialistic words or phrases is not sufficient evidence of a material substance conception. The subject is required to *use* these words or phrases in such a way that s/he predicates the concept with them meaningfully. So the subject's explanation won't necessarily be scored as "materialistic" if she uses the word "moves", whereas if she used the phrase "the electric current moves ___", this would be coded as evidence of a material substance conception.

Apparatus and Materials

***CBI* training module.** This training module consisted of a computer-presented text, which subjects read at their own pace, and which periodically referred to one of several running simulations on the top portion of the screen. Subjects were told that they were learning about "a special type of science concept" called *Equilibration Processes* (which was determined to be a more tenable name than "*constraint-based interactions*"). The training focused on two examples of the *CBI* category - Air Expansion and Liquid Diffusion. The text was organized around four "special qualities" of these *equilibration processes*, which were described as applying to many difficult science concepts.

1. Equilibration Processes have no clear cause-and-effect explanation.
2. Equilibration Processes involve a system of interacting components seeking equilibrium amongst several constraints.
3. In an Equilibration Process, certain constraints behave as they do because they are actually the combined effect of many smaller processes occurring simultaneously and independently within the system.
4. Equilibration Processes have no beginning or ending, even if they arrive at an equilibrium position.

For both topics (Air Expansion and Liquid Diffusion), each of the four attributes was described and illustrated (by means of a simulation). The training text concluded with a summary of all four attributes.

As the reader progressed through the training module, each example (Air Expansion and Liquid Diffusion) was presented in terms of these four attributes, which were illustrated by a running simulation. For the concept of Air Expansion, the simulation consisted of a cylinder-piston system (a rectangle with a moveable "ceiling") with moving air molecules (circles) that collide with the walls of the cylinder and with the piston. When more molecules of air are pumped into the system (by an animated pump which injects more circles into the cylinder), the piston is seen to rise. The first attribute ("no clear cause-and effect explanation") was illustrated by showing students a faulty model that *would* have provided a clear casual account of the piston's rising: marbles (packed circles) were arranged within the cylinder so tightly that they forced against one another; newly added marbles had no room, and thus forced the upper marbles against the piston, which rose. It was pointed out that no such clear chain of cause and effect exists to explain the rising of a piston in a cylinder full of air, and that this special quality is common to all Equilibration Processes (Constraint-Based Interactions). Each of the four attributes was then discussed in turn, defining the *system* (attribute number 2) and its quest for equilibrium, then enumerating the constraints on this process (attribute 3), and stressing the fact that it never arrives at an end-point, but just continuously pursues the equilibrium state (attribute 4).

Pre and post tests. The pre- and post-tests were identical, with eight conceptual problems, each consisting of a simple electric circuit and a question about its behavior. Typically, the subject would be asked whether all the bulbs in a parallel or series circuit would illuminate at exactly the same time when a switch was closed, or whether an illuminated bulb in a circuit would dim or remain the same when a second bulb was added (either in series or parallel with the first) by closing a switch. After choosing an answer for a problem, the subject was asked to explain her response, with frequent prompting to ensure a detailed explanation of what was happening in the problem.

Electricity Text. These materials were seen by both experimental and control groups, and consisted of approximately thirty paragraphs of text drawn from a popular conceptual physics textbook (Hewitt, 1987) and presented in its intended sequence, with the exception that any reference to the famous water analogy for electric circuits was removed.

Subjects

Subjects were 22 university undergraduate students recruited from the University of Pittsburgh and paid for their participation. Male and female students were roughly equal in number, and no subject had any university-level science background, nor any formal training in electricity.

Procedure

Session 1. The study consisted of two sessions, each lasting approximately two hours. In the first session, university students with no science background completed a pre-test consisting of 8 qualitative problems about simple electric circuits. Subjects in the experimental group then received the CBI Ontology Training_Module, which consisted of approximately 25 double-spaced pages of text and two animated simulations, whose purpose was to illustrate elements within the text. As the reader progressed through the training module text, she was occasionally instructed to "click on the simulation button", resulting in some behavior from one of the simulations that was further described and referred to by the text. Subjects in the training module were interrupted periodically by computer-presented explanation prompts, which assured their attention to the content. At the end of the training module, experimental subjects received the training module post-test , which consisted of five broad questions concerning the definition and application of ***equilibrium processes (CBI)***. Subjects were aware of this test at the outset of the training module, which provided some motivation for them to attend to the material. Most importantly, it provided a means of assessing the extent to which subjects assimilated the material in the training module.

Control subjects did not receive the CBI Training Module, and spent the first session reading a completely different text from the computer screen (although the same interface was used). This control text was selected from an existing published science text (Hewitt, 1987) so that it was roughly equivalent to the training module text, both in topic (gases and fluids) and level of difficulty. Subjects who receive this control text were also occasionally interrupted by computer-presented explanation prompts. At the end of the session, all control subjects received the control text post-test, which consisted of qualitative questions concerning the definition and properties of the material described in the control text. Subjects were aware of this test at the beginning of the session, so that it provided some motivation for them to attend to the material.

Session 2. All subjects received the same materials and procedure in session 2, which consisted of a physics text concerning electricity and electric circuits. This was a conceptual treatment of electricity, selected from a well-known published physics text (Hewitt, 1987). In the course of reading through this text, subjects (both control and experimental) encountered occasional explanation prompts. After completing the transfer text, all subjects receive the post-test, which was identical to the pre-test. In parting, subjects were asked to complete an exit survey in which they provided information concerning their high school achievement (grade point average and SAT scores), university grade point average, etc.

Analysis of Conceptual Change

Conceptual change was assessed by analyzing subjects' verbal explanations of pre and post test problems according to the presence of attributes from either the *MS* or *CBI* ontology. The attributes were selected based on previous work by Slotta, Chi, and Joram (1995), who measured the patterns of verbal predication in explanations generated by physics novices and experts in response to a set of similar conceptual problems. Slotta et. al interpreted this predicate-use as evidence of ontological commitments. That is, if a subject said, "The current comes down the wire and gets used up by the first bulb, so very little of it makes its way to the second bulb", then these four (underlined) predicates were taken as evidence that she conceptualized current as a substance-like entity which (1) *Moves*, (2) *can be Consumed*, (3) *can be Quantified*, and (4) *Moves*, respectively. Slotta et. al found that experts used predominantly *process* attributes for their descriptions of electric current, whereas novices relied on *substance* attributes almost exclusively.

The six most common attributes of electric current were chosen from the Slotta et al. (1995) novice explanations as a basis set for the *substance* predicates in the present analysis: *Moves* , *is Supplied* , *is Quantified* , *comes to Rest* , *is Absorbed* , and *is Consumed* . Similarly, the six most common attributes of electric current in the explanations of physics experts were chosen as a basis set for the *process* predicates in the present analysis: *System-Wide* , *Movement Process* , *Uniform State* , *Equilibrium State* , *Simultaneity* , and *Independence* . Given a complete coding of all subjects' explanation data (coding each explanation for the presence of all six attributes in each of the two basis sets), we can quantitatively address such questions as, (1) To what extent do subjects attribute the concept of electric current with substance-like qualities versus process-like qualities? (2) Is a subject's choice of attributes affected by the CBI category training (i.e., is there conceptual change)? and (3) Do subjects who scored highly on the training post-test show more conceptual change than those who did not, as measured by increases in *process* predication or decreases in *substance* predication?

Once all explanations have been coded for the presence of *substance* and *process* attributes, a measure can be derived by simply tabulating the number of predicates from each basis set that were present in an explanation. This sort of "binary" measure loses some frequency information, but avoids many possible distortions, and the need to normalize for protocol length. Thus, if a subject used the *Moves* predicate 15 times in an explanation, it would only be counted once. This results in a maximum score of 6 for both the *Process* and *Substance* attributes (subjects occasionally applied both *process* and *substance* predicates to the concept of electric current in the same explanation). These measures can then be used in quantitative analyses (discussed in Results section: Conceptual Change, below).

Results

Problem Solving Gains

A startling result was that the experimental group showed significant gains in the problem solving task (pre-post test gains), even though this was not a strong goal or prediction of the study. It was not anticipated that a single training session (2 hours) followed by a single session of topic study (2 hours) would have a noticeable impact on students' ability to solve even simple conceptual problems. These test items were intended for use mainly as a means of evoking conceptual discussions and explanations, which are the focus of our analysis of conceptual change. However, experimental subjects showed pre-post test gains of 29% compared to the control group's gain of only 8%. This difference was significant, with $F(1,20) = 6.97$, $p = 0.017$.

Conceptual Change

Both control and experimental groups relied almost entirely on *substance* predicates in explaining their pretest solutions, replicating Slotta et al. (1995). Analysis of post-test explanations revealed the hypothesized conceptual change in the experimental group, who relied greatly on *process* predicates, and very seldom drew upon the *substance* predicates (thus resembling the experts in the Slotta et al. study). Both the increase in *process* predication ($F(1,10) = 39.05$, $p = 0.0002$) and the decrease in *substance* predication ($F(1,10) = 28.5$, $p = 0.0007$) were significant. Control subjects showed no such transition in their preference of conceptual attributes, with no significant differences in level of *process* or *substance* predication. Figure 1 (top of next page) shows a graph of the process and substance predication for the experimental and control groups.

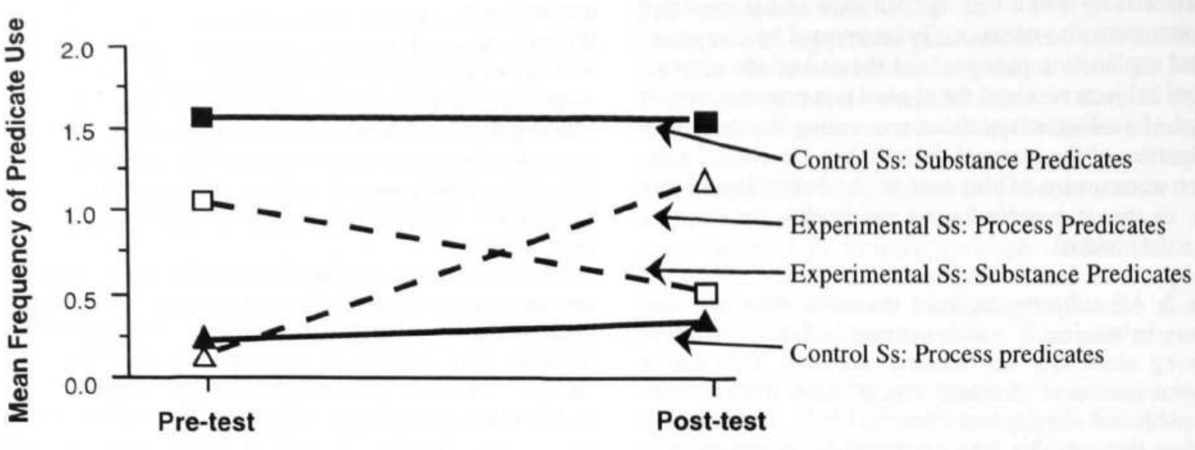

Figure 1. Use of Substance (squares) and Process (triangles) predicates in pre- and post-test explanations.

Because a post-test was administered after the training module (to assess comprehension of, and transferability of the training content), it was possible to split the experimental group into high and low scorers on this test. Figure 2 shows that successful training was indeed a requirement for conceptual change, with the high scoring subjects responsible for nearly all the gains of the experimental group. The interaction suggested by Figure 2 -- between Training Split (high, low, control) and decrease in *substance* predication -- is significant (F(2, 20) = 4.5, p = 0.0200, as is the interaction between Training Split and increase in *process* predication (F2, 20) = 24.7 , p = 0.0001). The low-scoring experimental group did show a reduction in substance predication and an increase in process predication compared to the control group, but significantly less so than the high-scoring training group. In general, all apparent differences between high and low scorers are significant at least to p=0.05.

Discussion

These findings are quite novel to the literature on conceptual change as well as instruction. Many researchers have explored interventions to confront robust physics misconceptions. Yet most have offered interventions which directly target the misconceptions, as if trying to construct the scientific conception from the naive one. Chi's (1992) theory argues that the naive substance-based conceptions should be ignored, and that physics instruction will succeed only to the extent that the student comprehends the novel ontologies involved. We have found that when students are trained in the ontology of *Constraint-Based Interactions*, they show immediate impressive gains in learning the desired conceptions. With only a single focused training session, experimental subjects were able to draw enough new insight from a standard physics text that they substantially revised their responses to conceptual physics problems and (more importantly) offered explanations that were qualitatively distinct from their naive pre-test accounts. Perhaps most important is the fact that the physics training materials were completely unmodified for the purposes of this intervention. Both experimental and control groups received the exact same physics materials, yet control subjects were unable to achieve any substantial progress away from their prior misconceptions.

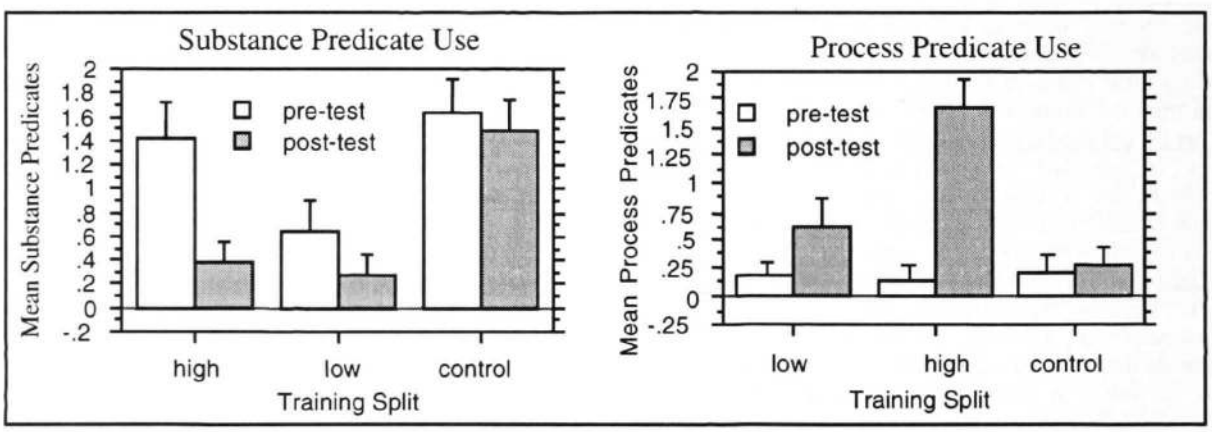

Figure 2. Use of *Substance* (left) and *Process* (right) predicates in pre- and post-test explanations (High vs Low-trained experimental subjects vs controls)

The implications of this research for instruction is that there may be certain types of science concepts which are inherently difficult for the novice because they are so completely foreign -- students have never encountered a concept like them before -- and because the students are already possessed of very familiar and comfortable preconceptions which are qualitatively on the wrong track. Conceptual change in these cases may best be served by early training in the *nature* (i.e., ontology) of these concepts, followed by normal physics instruction. Additionally, it is perhaps more clear now that in some (perhaps the most difficult) cases, students cannot make gradual facilitated transition from their preconception to the "scientific" conception, because the two endpoints are separated by a profound ontological barrier.

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