Helping students understand challenging topics in science through ontology training

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Abstract

Chi (2005) has proposed that students experience difficulty in learning about physics concepts such as light, heat, or electric current because they attribute these concepts with an inappropriate ontological status of *material substances* rather than the more veridical status of *emergent processes*. Conceptual change could thus be facilitated by training students in the appropriate ontology prior to physics instruction. We tested this prediction by developing a computer-based module where subjects learned about emergent processes. Control subjects completed a computer-based task that was uninformative with respect to ontology. Both groups then studied a physics text concerned with electricity, including explanations and a post-test. Verbal explanations and qualitative problem solutions reveal that experimental students gained a deeper understanding of electric current.

Introduction

Students' understandings of concepts like force, light, heat, or electricity are well-established and quite distinct from the conventional scientific views offered by instructors. For decades, cognitive and science education research has examined the science knowledge of novices and experts in a widespread effort to identify and characterize preconceptions of various science concepts. Many of the earliest studies of naive science conceptions (e.g., King, 1961; Kuethe, 1963; Doran, 1972; Viennot, 1979; Minstrell, 1982; Shipstone, 1984) sought to document the existence of firmly held preconceptions or so-called "robust misconceptions" that are particularly resistant to instruction. Not surprisingly, a consensus has emerged that "young children do have firmly held views about many science topics prior to being taught science at school" (Osborne & Wittrock, 1983, p. 489). This simple but important statement is reflected by nearly 6000 published studies of students' misconceptions and instructional attempts at their removal (Pfundt & Duit, 1988; Duit, 2004).

Research on student misconceptions has focused primarily on those concepts for which students exhibit robust misconceptions. In reviewing a wide range of such studies, Reiner, Slotta, Chi and Resnick (2000) found that students often attribute difficult concepts with materialistic properties. They reviewed numerous studies that were concerned with physics novices' conceptualizations of force, light, heat, and electricity (all of which are notoriously difficult concepts), and found a pattern of robust misconceptions across all these topics. Specifically, Reiner et al. (2000) observed that physics novices tend to think of these concepts as if they are material substances, or have certain properties of material substances. This conclusion was based directly upon arguments offered within the research articles they reviewed, as well as on inferences from particular attributions in the misconceptions that were reported. For example, if a novice reasoned that a moving object slows down because it has "used up all its force," this reasoning was taken as evidence of a substance-based conception of force – in contrast to the more conventional view of force as a process of interaction between two or more objects. Similarly, Reiner et al. (2000) observed that novices' conceptualizations of heat were drawn from reasoning that involved heat (or cold) being "blocked" or "trapped," suggesting a substance-like view. The Reiner et al. (2000) review established a pattern across concepts, suggesting a common origination of naive conceptions. Any theory of conceptual change is therefore challenged to account for this pattern of misconceptions, and ideally to respond with an effective method of instruction that responds to the robust substance-like nature of conceptualizations in these various topics.

Ontological Attributions

Chi (1992; 1997) has hypothesized that some misconceptions are robust because they involve changing one's commitment about the ontological nature of the concept. This view assumes that people associate concepts with distinct ontologies (c.f., Keil, 1981), such as *processes, ideas,* and *material substances* to name a few. (Throughout the paper, ontological categories will be italicized) When encountering a novel concept, the learner forms an ontological commitment that guides his or her understanding of fundamental aspects of that concept and leads to attributions of features or properties. Thus, in learning about a new concept such as osmosis, a person may commit to a *process* ontology,[1] which implies the attribute "occurs over time," since this is a common characteristic of all processes. Misconceptions result from commitments to an inappropriate ontology. In learning about the concept of "heat," for example, many children assume a *material substance* ontology, perhaps because of language conventions such as "close the door, you're letting all the heat out." However, in the scientifically normative view, the concept of heat is associated with a *process* ontology, as it involves the transfer of kinetic energy between molecules (Slotta, Chi & Joram, 1995). Unfortunately, once an ontological commitment is made with respect to a concept, it is difficult through any stages of mental transformation to change our fundamental conception from a *substance* to a *process* (Chi & Roscoe, 2002). Thus, ontologically misattributed concepts would require an extraordinary process of conceptual change.

Further contributing to the robust quality of such alternative conceptions is the fact that students may lack any notion of the appropriate ontology with which certain concepts should be attributed. Chi (2005) has proposed that many concepts of this nature are not only *processes* (as opposed to *substances*), but moreover, they are a specific kind of *processes* that she calls *emergent* (as opposed to *direct*), which are particularly for students to understand in a scientifically normative way. These processes typically involve emergent properties of a system, such as equilibrium states or net statistical changes of certain system properties (e.g., inside and outside temperature; voltages; air pressures; etc.). Such emergent relationships are often difficult for students to understand, in part because they can involve misleading perceptual correlates. For example, the diffusion of a beaker of blue liquid through a valve into a beaker of clear liquid suggests a simple *direct* causal mechanism where the blue liquid continues flowing into the clear liquid until an equal amount exists in both beakers, when the process comes to a halt. However, while this appears to be a *direct process* where blue liquid flows from one side of the beaker to the other, it s actually a much more complicated *emergent process,* resulting from the continuing action of dyed water molecules that move independently of one another, but statistically even out in the two sides of the beaker over time. The movement of these molecules, and indeed the process itself, continues indefinitely, even after the equilibrium state has been achieved. Chi (2005) has identified such processes as *emergent* (as opposed to *direct)* ones, because their observable, “macro level” patterns are seen to emerge from the lower, or “micro level” in a characteristic way. Moreover, the need to focus on two or more levels in emergent processes may also contribute to students’ difficulties (Wilensky & Resnick (1999).

Chi (2005) explains that *emergent processes* are particularly troublesome for students to understand because they misattribute the concept’s ontological nature, either as a *material substance* or as a kind *of direct causal process*. Other examples of *emergent processes* that have been studied by researchers include natural selection (Ferrari & Chi, 1998; Hallden, 1988; Jensen and Findley, 1996), light (Slotta, Chi & Joram, 1995), traffic jams (Resnick, 1996), heat and temperature (Wiser & Carey, 1985; Wiser, 1996); and electric current (Joshua & Dupin, 1987; McDermott and Shaffer, 1992; Slotta, Chi and Joram, 1995).

Assessing Ontological Commitments

Chi’s account of misattributed ontology suggests that novices may need to revise their ontological commitment in order to understand the scientifically normative view of certain concepts, and escape the reasoning errors that follow from their initial misclassification. In order to investigate such a claim, we require an assessment of a student's ontological commitments, which will allow us to measure what those commitments are and whether they have changed as a result of an instructional intervention. Slotta, Chi and Joram (1995) developed such a methodology, based on a content analysis of students' verbal explanations, which provided a source of inferences concerning ontological commitments. For example, if a student explains that light or heat can be blocked by a wall, we infer that the student's underlying conceptualization must have some properties of *material substances*, which possess an ontological aspect that can "move," "be blocked," "be contained," etc.

Slotta et al. (1995) sought to differentiate novices' and experts' conceptions of light, heat and electric current. When physics novices were asked to solve conceptual problems involving these topics, they demonstrated a clear bias towards *substance-like* mental models (e.g., reasoning about electric current in a wire as if it were a fluid flowing inside a hose). This result was determined by presenting subjects with isomorphic pairs of problems, one of which was concerned with an *emergent process* concept (e.g., light, heat, or electric current), and the other a *material substance* isomorph of that problem (e.g., water), assuming the relevant physics concept was viewed as a *material substance*. For example, a problem involving an electric circuit with several bulbs in series was accompanied by a corresponding isomorphic problem involving water flowing through a hose with several sprinklers in series -- assuming the physics novice thought of electric current as something like a flowing fluid. Such isomorphic pairs of problems were constructed with several choices of answers, so that similar answers to the problems would reflect similar conceptual reasoning (e.g., "the bulbs closer to the battery come on before the bulbs farther away" is similar to "the sprinklers closer to the faucet will come on before the sprinklers farther away"). That is, choosing the answer "the bulbs closer to the battery come on before the bulbs farther away" is incorrect, but choosing it implies that subjects are analogizing it to the "sprinkler" problem. In reasoning about such problems, novices preferred the *substance-like* models, leading to incorrect choices of the solution that were consistent with the correct choices to the corresponding *material substance* isomorph problem.

Slotta et al. (1995) looked more deeply into students' ontological commitments by examining patterns of verbal predication in the language used by physics novices and experts as they explained their solutions to these problems. This analysis drew inferences about a subject's ontological commitments based on the presence of particular verbal predicates in his or her explanation. For example, 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 subjects conceptualized current as a *substance-like* entity with attributes of (1) "moving,"(2) "can be consumed,"(3) "can be quantified," and (4) "moves." respectively. By measuring the degree to which subjects used these attributes in explaining their answers to a variety of conceptual problems, it was possible to quantitatively address the question of ontological association.

Figure 1 displays the average level of *process* and *substance* predication used by experts and novices in the Slotta, et al. (1995) study. Whereas novices relied almost exclusively on *substance* attributes regardless of problem types, with very little use of *process* attributes (see the two parallel solid lines), experts used the same high levels of *substance* attributes for the substance concept problems but chose more *process* attributes for the physics concept problems. Furthermore, the pattern of *substance* predication (e.g., across all the *substance* attributes assessed: Moves, Consumed, Quantified, Blocked, etc.) was quite similar for novices between the physics concept problems and their material substance isomorphs. Thus, not only were the novices' multiple choice responses similar between the two members of an isomorphic pair of problems, so was the pattern of verbal predication within their explanations. This analysis provided evidence that novices attribute properties or behaviors of material substances to certain physics topics, while expert conceptualizations of the same topics show no sign of a *substance-like* ontology, but rather appear to be consistent with a *process* ontology.

Insert Figure 1 about here

Testable Predications about Instruction for Conceptual Change

Chi's framework suggests that students would be less likely to make faulty ontological commitments if (a) they were prepared with some knowledge of the appropriate ontology before instruction about those concepts, and (b) their initial experience with (or instruction about) the concepts did not provide any suggestions of the wrong ontology. But students of almost any age have had some exposure to concepts of electricity, and those initial exposures were most likely suggestive of *substance* ontology rather than that of *emergent processes*. Young children are almost certainly exposed to substance-based language and conceptualizations regarding topics in electricity (e.g., "the battery is out of juice"). Thus, students probably enter instruction already in possession of the substance-based misconceptions that we wish to avoid, as shown in the Reiner et al. (2000) review.

We must therefore ask whether points (a), providing some knowledge of the appropriate ontology before instruction of a specific concepts, and (b), barring any association with the wrong ontology, could also apply to the removal of misconceptions and not just in their prevention. Of course, it remains an open question whether or not any conception is actually removed, or whether these early concepts are simply subordinated to the normative conceptualizations over the course of instruction. Indeed, there is some evidence (Clement, 1987; McDermott, 1979; Slotta, Chi & Joram, 1995) that physics experts do maintain substance-based conceptualizations in parallel with their more normative *process-like* views. In their everyday reasoning, physics experts often use substance-like models of heat, light, and electricity, although they are well aware of the limitations of such models, including when the models should be abandoned (Slotta, Chi & Joram, 1995). Thus, if the early *substance-like* conceptions are not actually removed or replaced, we can interpret conceptual change as a matter of developing new conceptualizations alongside existing ones, and understanding how and when to differentiate between alternatives. Nevertheless, the problem remains the same: How do we prevent the instruction of a physics concept that is of the *process-like* ontology from being assimilated into a student's pre-existing *substance-like* conceptualizations?

This paper assumes that physics novices possess *substance-based* conceptualizations of electricity, based on prior research by Slotta, Chi and Joram (1995) and Reiner et al (2000). We hypothesize that we can help novices develop an understanding of the *process-like* nature of electric current by first providing them with some training about the target ontology (*emergent processes)* followed by direct instruction about electricity that avoids any use of terms or analogies that might promote the *material substance* ontology (e.g., the water flow analogy).

Overview of the Study

In order to test this hypothesis, a training study was designed in which one group of physics novices received direct training about the *emergent process* ontology, followed by an instructional text concerning electric current that omitted any suggestion of a *material substance* ontology. A control group received no training in the *emergent process* ontology, performing a control task instead, and then read the same instructional text about electric current as the experimental group. The question of interest is whether the experimental group demonstrated conceptual change, as measured by a shift in their ontological associations for the concept of electric current. Subjects' conceptualizations of electric current were measured by a pre-post test consisting of eight qualitative physics problems concerned with electric current, for which subjects selected a response from multiple choices, then verbally explained their reasoning in an interview format. Subjects' choice of response to these problems, as well as their verbal explanations, provided measures of their ontological commitments at pre- and post test, enabling comparisons between control and experiment groups, and assessment of the impact of ontology training.

An essential feature of the design is that both the experimental and the control groups received exactly the same instruction about the target concept of electric current. The two groups differed only in that the experimental group received prior instruction about the *emergent process* ontology. This training included no mention of electricity, nor any foreshadowing of its application to electricity concepts. The role of the ontology training was to provide the students with some knowledge of the *emergent process* ontology so that they might better succeed in making the correct ontological attribution when subsequently learning about the concept of electric current.

Assessment of conceptual change was performed by analyzing verbal explanation data for the presence of two specific sets of ontological attributes based on the attributes used by Slotta et al., 1995), indicating subjects' commitment to a either a *material substance* or an *emergent process* ontology, respectively. Thus, if a subject explained problems concerning electric current using verbal predicates relevant to a material substance, this was taken as a measure of an underlying ontological commitment a *material substance*[2] view of the concept. Similarly, the use of verbal predicates reflecting ontological attributes of *emergent process* is taken to reflect the presence of an *emergent process* association. It was predicted that the experimental group would show a transition from the pre-test, where they explained problems in terms of a *substance* ontology, to the post-test, where they drew upon *emergent process* predicates in their explanations. In addition to this analysis of ontological commitment, the pre- and post-tests were also scored for accuracy of responses, as the tests consisted of qualitative problems physics problems that were designed to be sensitive to the existence (or removal) of substance-based misconceptions of electric current.

Method

Subjects

Subjects were 24 university undergraduate students (15 female, 9 male) recruited from the University of Pittsburgh and paid for their participation. Subjects had no university-level science background or any other formal training in electricity. Table 2 provides a profile of the mean SAT scores and grade point averages for subjects in the experimental and control conditions. The table is not complete, because these figures were determined from an exit survey that some subjects could not accurately complete. The "n-value" listed below each figure in the table represents the number of subjects who responded confidently to that item, from which these means were computed (out of a total possible of 12). While these figures were obtained informally, they provide a qualitative sense of the subjects who participated in the study. Note that the subjects in the control group had slightly higher scores on four of the five measures.

Insert Table 2 about here

Materials

Materials used in this study include: pre- and post-tests of electricity concepts; the *emergent process* ontology training module (interface, simulations, and training module text); the control module; the training module post-test; the control module post test; the physics learning text (in topics of electricity); and the physics learning post-test.

Pre-test (and post-test).

Pre-test and post-test items were identical, consisting of eight conceptual physics problems, each of which involved predicting the behavior of a simple electric circuit. The problems were based on the most successful items (i.e., the most highly diagnostic items) from the materials of Slotta et al. (1995), which made use of circuits with multiple bulbs, connected either in series or parallel. For example, in Figure 2 the subjects are asked to predict whether the bulbs will illuminate at the same time, or with slight time differences once the switch in the circuit is closed. After selecting a response from the multiple choices, subjects were asked to verbally explain the behavior of the circuit to justify their choices.

Insert Figure 2 about here

The test items were designed so that different responses corresponded with different conceptual models of electric current. For example, response "a" in the problem shown in Figure 2 is consistent with the substance-like conception of electricity as a fluid that flows through hose-like wires. Slotta et al. (1995) observed that novices who chose this response also explained the problem using patterns of language very similar to those they used in explaining the problem's material substance isomorph (which consisted of a hose with multiple sprinklers in series).

While using the same items in the post-tests as employed in pre-test did introduce an aspect of familiarity with the post-test items, subjects were observed to carefully deliberate their responses to each item in the post-test, even if they recognized it from the pre-test. The advantage of using the same items on both tests is that it allowed a contrast of the verbal predication measures, which might change unpredictably with a novel set of post-test problems. If a subject uses different patterns of verbal predication in explaining the same problem two different times, we can infer more strongly that the subject's conception of the problem has changed. In contrast, different patterns of verbal predication in the explanations of two different problems could simply be a consequence of differing surface features within the problems.

Emergent Process training module.

The training module consisted of a computerized instructional module that presented textual material to be read by the student at his or her own pace, where this textual material periodically referred to one of several running simulations on the top portion of the screen. Figure 3 displays a screen capture of the interface used in the training module. Notice the buttons that can be selected with the mouse to move between pages of text, as well as to interact with the simulations. The "Simulation" button was not selectable if the subject was not reading a portion of the text that required interaction with the running simulations. Simulations continued to run at all times, even when the Simulation button was disabled. Thus, during the portion of the training module that dealt with properties of air expansion (discussed below), the animated air molecules displayed in Figure 3 continued to bounce around the inside of the piston in the upper portion of the computer display. This provided the subject with a sense of the ongoing nature of *emergent process*.

Insert Figure 3 about here

The purpose of the training module text was to communicate four attributes of the ontological category of *emergent processes* in such a way that the subjects could understand and even apply the content of the text. This goal was met by focusing on two distinct examples of *emergent processes* – air expansion and liquid diffusion – both of which are quite distinct from electric current. The text pointed out four “special qualities” of these concepts, noting that those properties pertain to an entire class of difficult science concepts, which were referred to as "Emergent Processes.”

The four ontological attributes used to describe air expansion and liquid diffusion were those determined by Slotta et al. (1995) to be most relevant to the *emergent process* concept of electric current. It is possible that there are additional attributes that characterize *emergent processes*, but it was important to instruct subjects with easily recognizable and accessible attributes that apply to the concepts in the training module text, as well as to the transfer concept of electric current. In the order they are presented within the training module, these four attributes are:

1. <u>System-wide:</u> Emergent Processes have no clear cause-and-effect explanation.
2. <u>Equilibrium-seeking:</u> Emergent Processes involve a system of interacting components seeking equilibrium amongst several constraints.
3. <u>Simultaneous and independent:</u> In an Emergent 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. <u>Ongoing:</u> Emergent Processes have no beginning or ending, even if they arrive at an equilibrium position.

The training module first explained the general properties of *emergent processes* ontology (e.g., “Emergent Processes have no beginning or ending”), followed by an explanation and simulation of how this property applied to each example (e.g., “The molecules in the air cylinder will continue bouncing around, even after the piston has reached its equilibrium height”). After all four attributes had been presented in the context of an example, each of the attributes was reviewed once more in the abstract. In this way, it was hoped that subjects could learn the ontological attributes in a somewhat abstracted sense, by receiving both their general definition and their specific instantiation. The ontology training module presented the example of air expansion first, including text and simulations, followed by the example of liquid diffusion, thus providing the experimental subjects with two distinct instances of the *emergent process* ontological category.

For the concept of air expansion, the simulation (Figure 3) 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 (injecting more circles into the cylinder), the piston is seen to rise. This “macroscopic view” of the system was supplemented with simulations of a microscopic view in order to illustrate the four ontological attributes. For example, the first attribute, "no clear cause-and effect explanation," was illustrated by showing students a faulty model that would provide a direct causal 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 then rose. The text 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 *emergent processes*. Each of the four attributes was discussed in turn, defining the system, its equilibrium, the constraints on the process, and the fact that it never arrives at an end-point, even once equilibrium has been achieved.

Training text explanation prompts.

Throughout the ontology training, subjects were occasionally prompted to verbally respond to questions that appeared as part of the computer dialog (all explanations were tape recorded for later analysis). These questions prompted subjects to explain an important part of the text that he or she may not have completely understood (e.g., "can you name all of the forces acting on the piston?" or "Why does the piston eventually begin to fall?") These explanation prompts were designed to ensure a more complete understanding of the material, since prompting subjects to explain have been shown to be beneficial to understanding (Chi, de Leeuw, Chiu & LaVancher, 1994).

Training post-test.

Experimental subjects were told at the beginning of the training module that, when finished, they would be asked several questions to determine their comprehension of the text. The first two questions of this test asked subjects to recall the four basic properties as they applied to the two examples used in the training module (air expansion and liquid diffusion). The final four items were related to a transfer problem (predator-prey populations), which was described in some detail. Subjects were requested to apply each of the four properties of *emergent processes* to their understanding of this new example. The four properties were listed overtly, so that the problem was solely one of applying them to the new example. This training post-test served to measure how well subjects had understood the training module content. This was important, since one would not predict any positive effect from a training session where the subject did not comprehend the training content. Indeed, the results of this training post-test allowed a contrast between those experimental subjects who understood the training material and those who did not.

Control module.

Control subjects received a different training module, administered on the same computer interface, so as to control for the training medium (i.e., computer-based). This text was also concerned with air expansion and liquid diffusion, so as to control for training topic, although its focus was more broadly related to basic concepts of solids, liquids and gases, and their behavior. The control text was drawn directly from a popular conceptual physics text (Hewitt, 1987), as well as a second text book (Towle, 1989) for the pages relating to liquid diffusion.

Control text explanation prompts.

Throughout the control task, subjects were occasionally prompted to verbally respond to various questions that appeared as part of the computer dialog (all explanations were tape recorded for possible later analysis). These questions prompted subjects to explain important parts of the text (e.g., Why does water have a higher specific heat than sand?) These "explain questions" were drawn directly from the same book as the text itself (Hewitt, 1987), as the author provides several "Questions" highlighted within the text and at the end of the chapter.

Control text post-test.

Control subjects were told at the beginning of the control module that, when finished they would be asked several short questions to determine their comprehension of the text. The purpose of these questions was to ensure that the subjects attended to the material, as well as to provide some measure of how well the material was actually understood. All of these test items were drawn from the "Think and Explain" questions at the end of the Hewitt (1987) chapters.

Electricity text.

This text provided the instructional materials concerned with electric current, and was drawn from Hewitt's (1987) Conceptual Physics, chapters 33-35. By removing several tangential sections (e.g., one concerning Van de Graf generators and one concerning the difference between ac and dc current), as well as the questions and answers provided within the chapters, it was possible to condense the text into approximately fifteen full-length pages which covered the basic theory of voltages, current, resistance, and simple resistive circuits. This length of text was manageable for subjects in a single 60-90 minute session (depending on reading speed). As presented by Hewitt, the text included many references to the water analogy of electric current, which is a common instructional analogy used in the teaching of electric circuits. Because of theoretical concerns, all material substance analogies (totaling less than 5 percent of the overall text) were removed. The resulting electricity text was read by the subjects in the form of photocopied paper, in a 3-ring binder, with approximately one paragraph of text per page.

Electricity text explanation prompts.

Throughout the electricity text, subjects were occasionally asked to verbally respond to a prompt for explanation of the material. All explanations were tape recorded for possible later analysis. These questions were designed so that they targeted aspects of electric current that correspond to the ontological attributes instructed in the training module. For example, at one point in the text, the author talks about the actual speed of an electron through the wire as being "slower than a snail's pace," and explains that individual electrons do not actually flow through the wires, but instead that a net statistical drift is imposed on all the electrons. At this point, it was advisable to insert an explanation prompt, asking the subject to explain this in his or her own words.

Design

Twenty-four subjects were assigned randomly between the experimental and control groups. There were both within-subject and between-subject aspects to this design. Within-subject aspects were concerned with pre-post test differences, and between-subject aspects were concerned with experimental-control differences. Two sorts of dependent measures were obtained from the data: pre-post test gains and verbal predication measures. The study consisted of two sessions (see Table 1), each lasting between one and two hours (subjects were self-paced, and varied in reading speed).

Insert Table 1 about here

Procedure

Session 1.

All subjects began Session 1 by receiving instructions about the general course of the two-session study. They were then given the pre-test, and were encouraged by the interviewer to provide a causal account of the overall problem and their chosen solution, rather than a simple justification for their choice. After completing the pre-test, they were left alone at the computer to proceed through either the training module or the control module. Throughout the training module, subjects were occasionally interrupted by computer-presented explanation prompts that were meant to assure some level of attention was paid to the content. All sessions were audio recorded in order to capture their responses to the occasional explanation prompts. The interviewer was in the next room during the computer-mediated portion of this session, so that any problems or questions could be immediately addressed. Subjects were also informed that a post-test would be administered after the session, covering the content material. This training post-test helped assure attention to content, but most importantly, provided a means of determining which subjects comprehended the training and which did not.

Control subjects spent the first session working through the control module, which presented material in a related theme using the same computer mediated format. While reading this control text, subjects were occasionally interrupted by computer-presented explanation prompts. At the end of the session, all control subjects received the control post-test, which consisted of qualitative questions concerning the definition and properties of the material described in the control text. Subjects were informed that they would be given this test, assuring some motivation for them to attend to the material. Additionally, it provided some means of assessing the extent to which subjects were able to learn the material in the control text

Session 2.

Experimental and control subjects received identical materials and procedure in Session 2, consisting of the electricity text and electricity post-test. Subjects were instructed to try to apply what they learned in Session 1 to what they would read in the present session, wherever it was relevant. In the course of reading through this text, subjects encountered occasional explanation prompts, which helped them reflect on their understanding and assured that attention was paid to the content. After completing the electricity text, all subjects received the post-test, which was identical to the pre-test. Finally, 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, and qualitative feedback about their perceptions of the study.

Results

Comparison of pre-post scores

Choosing the correct answer on the pre- or post-test item (e.g., saying that all the bulbs in Figure 2 illuminate at exactly the same time) does not mean that a person has a scientifically normative understanding of electric current. For example, our visual impressions from the lighting of Christmas lights or multiple lights in a room are those of simultaneity. Thus, everyday phenomena could lead some students to choose the right answer without possessing the conceptualization required for an accurate explanation. However, choosing the wrong answer (e.g., saying that the closer bulbs illuminate earlier, or glow brighter than those farther away) is more likely an indication of an underlying conceptualization. Thus, a reduction in such responses at post-test by the experimental group could be interpreted as an effect of the *emergent process* training. Despite the small number of items on these tests (reflecting our emphasis on explanations), a contrast of pre- and post-test scores revealed significant improvement for the experimental group. (See Figure 4.) Experimental subjects showed pre-post test gains of 29% compared to the control group's gain of only 9%. This difference was significant, with F(1, 22) = 6.765, p = .0163. The difference in pre-test scores suggested by the Figure is not significant, and the conditions of administering the pre-test were identical between experimental and control groups.

Insert Figure 4 about here

Interestingly, experimental subjects' improvement on the post-test depended on how well they understood the training material. The training materials were challenging for subjects, requiring them to learn general principles about a new type of concept, as well as specific examples of systems that seek equilibrium amongst constraints. The training post-test was also quite difficult, requiring subjects to transfer what they had learned to a new example of *emergent processes* (predator-prey populations). Splitting the training group into high and low scorers on the training post-test (which measured how well they remembered and applied the training), Figure 5 shows a breakdown of the Figure 4 results into 3 groups: high-training; low-training; and controls. Those subjects who scored the highest on the training post-test achieved greater gains during the second session of the study. The interaction of test score with training group was significant, with F (2, 21) = 13.847, p = 0.0001.

Insert Figure 5 about here

The greater gains made by the "high-training" portion of experimental group are not simply due to those subjects being brighter or more motivated, resulting in their superior performance on all aspects of the study. The high training group actually had lower scores on four of the five profile measures that were collected during the exit survey:. high school grade point average, verbal and math SAT test scores, and university grade point average [3] While most of the high-ranking experimental subjects did become part of the "high training" group (i.e., the group who scored best on the training post-test), there were some exceptions. Ranking alone was not as successful in predicting improved test scores as was the training post test; this interaction is not as great as that shown in Figure 5, with F (2, 21) = 3.457; p = .05. Thus, comprehension of the training module content was a better predictor of pre-post improvement than student ranking.

Verbal Predication in pre-test and post-test explanations

The qualitative reasoning gains described above suggest that training in the *emergent process* ontology facilitates learning of specific physics concepts. Yet, pre-post gains on multiple choice items provide only a limited measure of conceptual change--particularly with regard to subjects' ontological commitments. Subjects' explanations were therefore analyzed for patterns of verbal predication. Each explanation was coded for the presence of 6 different attributes from either a *process* (used here as a shortened reference for *emergent process*) or a *substance* conception of electric current. The six most commonly used attributes for descriptions of electric current were chosen from the Slotta et al. (1995) novice explanations as a representative set of *substance* predicates: Moves (M), is Supplied (S), can be Quantified (Q), comes to Rest (R), can be Absorbed (A), and can be Consumed (C). Similarly, the six attributes used most commonly by experts in their descriptions of electric current were chosen as a representative set of process predicates: System-Wide (SW), Movement Process (MP), Uniform State (US), Equilibrium State (EQ), Simultaneity (SIM), and Independence (IND). The presence of any predicate from one of these was interpreted as evidence of the corresponding ontological commitment.

A complete coding was performed of all subjects' explanations for the presence of the six predicates from each of the two sets. This coding provided a measure of the extent to which subjects attribute the concept of electric current with substance-like qualities versus process-like qualities. Each explanation was coded for the presence of verbal predicates that reflected one of the ontological attributes from the *process* and *substance* sets. A variety of verbal predicates would reflect the "Moves" attribute, for instance: goes; comes; travels; shoots; etc. Slotta et al. (1995) provide a detailed discussion of this analysis, including a discussion of the challenge of drawing valid inferences from patterns of verbal predication. For each explanation, a tally was kept of how many of the six attributes were employed by the subject, resulting in a maximum score of 6 for each of the two ontological sets. While multiple occurrences of any attribute were ignored in this measure, Slotta (1997) did explore various alternative measures using the same data set. It was found that the results from comparisons of explanation data (e.g., pre-post changes, or Control vs. Experimental group comparisons) were largely insensitive to the measure employed. The present measure of simply tallying which of the 6 measures were used by a subject within each explanation was the most parsimonious, and therefore was selected for the present paper. Slotta et al. (1995) also present some discussion of the derivation of summative measures from such tallies of predicate codes. This measure of verbal predication allows for analyses of questions concerning the ontological associations made by members of the experimental and control groups.

Reliability of coding was established through a second independent coding of 50% of all explanation protocols. A second coder was provided with written training (approximately 6 double-space pages) and discussion (approximately 30 minutes) concerning the 6 attributes from each of the two basis sets (12 coding items in all). This second rater coded two complete subject protocols (pre- and post-test explanations, amounting to 16 problem explanations for each subject), and was given feedback on her coding. At this point, she was provided with four complete subjects: two controls and two experimentals, with no knowledge of either the subject’s group (control or experimental) or condition (pre- or post-test). The blind coding of these protocols was compared in detail with the primary coding, and each coder was found to have agreed with more than 90 percent of the other’s codes. An item was only counted as agreed upon if the same portion of protocol was assigned the exact same code by each coder. The two coders discussed their differences, and the second coder was provided with the protocols from an additional 8 subjects, resulting in a total of 12 subjects, or 50 percent of all protocol data. These 16 subject protocols (pre- and post-tests for each of the 8 subjects) were again coded blind to condition and group. This second trial found greater than 95% agreement in codes; thus the remainder of all coded subject protocols was judged to have been coded reliably.

Comparisons of pre-test to post-test explanations

When the verbal explanations were coded for the presence of all attributes in both representative sets, the pattern of results (Figure 6) replicated the expert-novice pattern reported by Slotta et al. (1995 – see Figure 1). First, both control and experimental groups relied almost entirely on *substance* predicates (the squares in the Figure 6) in explaining their pretest solutions. Second, like the novices in Figure 1, the control subjects (the solid lines) showed little change from pre-test to post-test in either their predominant use of *substance* predicates or their scarce use of *process* predicates. Finally, like the experts in Figure 1, the experimental subjects (the dotted lines) discriminately used more *substance* predicates in the pre-test and more *process* predicates in the post-test.

Statistical comparison of the predicate use within post-test explanations revealed the hypothesized conceptual change in the experimental group, who relied greatly on *process* predicates (the triangles), and very seldom drew upon the *substance* predicates. Both the increase in *process* predication (F(1,10) = 31.04, p = 0.0002) and the decrease in *substance* predication (F(1,10) =20.17, p = .0012) 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.

Pre-test explanations.

The experimental and control subjects relied almost exclusively on substance predicates in their pre-test explanations, replicating Slotta et al. (1995). There were no significant differences between groups in the degree to which substance or process predicates were applied to the concept of electric current. Pre-test explanations tended to characterize electric current as a substance that emerges from the battery once the switch is closed, progresses around the circuit, and gradually diminishes in size or strength as it is consumed by successive bulb within the circuit, until finally its remainder drains back into the battery. Table 3 provides four sample explanations of the problem shown in Figure 1 (two from experimental subjects and two from controls) which closely resembled the novice explanations reported by Slotta et al. (1995).

Insert Table 3 about here

Post-test explanations.

Subjects in the training condition showed significant changes in the way they explained post-test problems such as that of Figure 2. These changes were consistent with the hypothesized conceptual change: away from a *substance*-based, and towards a *process* view. Table 4 provides four representative explanations of the "ten-bulbs problem" of Figure 1, taken from the same four subjects displayed in Table 3. The explanations of the experimental subjects now refer to a system-wide process occurring throughout the circuit, and involving simultaneous activity at all ten bulbs. The control subjects often answered this problem correctly, since it was treated explicitly within the physics text. However, the fact that control subjects can sometimes know the correct response to qualitative problems only highlights the importance of appropriate assessment of subjects' underlying conceptions, such as performed in the analysis of verbal predications performed above. Control subject explanations typically retained their substance-based flavor, even though they often become more sophisticated and logically sound, as in the case of subject C-12 (shown in Table 4).

Insert Table 4 about here

Just as the high-trained experimental subjects (those who scored higher than the median on the training post-test) showed more gains in the problem solving measure than their low-trained counterparts, they also showed a more pronounced shift in their use of language reflecting ontological commitments. Figure 7 shows that successful training was indeed a precursor to conceptual change, with the high scoring subjects responsible for nearly all the gains of the experimental group. The upper panel of Figure 7 shows the decrease in subjects' use of *substance* attributes, while the lower panel shows their increase in the use of *process* attributes within their explanations. The interaction suggested by Figure 7 -- between Training Split (high, low, control) and decrease in *substance* predication -- is significant (F(2, 21) = 7.57, p = 0.003, as is the interaction between Training Split and increase in *process* predication (F(2, 20) = 35.89, p = 0.0001). The low-training experimental group did show a reduction in *substance* predication and an increase in *process* predication compared to the control group, but not as much as the high- training group. This result shows a connection between the effectiveness of the training (how well a subject did on the training post-test) and the conceptual change resulting from the electricity text.

Insert Figure 7 about here

Discussion

This study provides empirical support for a theoretical account of conceptual change in learning complex science concepts (Chi, 1992; 1993; 1997; 2005; Chi & Slotta, 1993; Ferrari & Chi, 1998; Slotta & Chi, 1996; Slotta, et al., 1995). This account specifies an ontological boundary between two explanatory frameworks: students' common conceptions and the scientifically normative ones. Once a student associates a concept with a particular ontology, he or she will try to understand subsequent instruction in terms of that association, which will be troublesome to the extent that there is a mismatch between the preexisting ontological commitment and that adopted by the instruction. Thus, certain concepts are traditionally more difficult for students to learn than others because students are more likely to associate them with an incorrect ontology. Chi has argued (1992; 1993; 1997; 2005) that students are inclined to conceive of concepts such as heat, light, force and electric current as a kind of *material substance*. This inclination may result from a variety of different (and not unrelated) causes: materialistic biases in language; the predominance of the material substance ontology in our conceptual knowledge, such that it becomes a "default" for novel concepts; or the paucity of examples from alternative ontologies (e.g., the *emergent processes* ontology). Whatever the origin of this bias towards a *material substance* ontology, the challenge of teaching certain physics concepts may entail helping students either to relinquish their initial ontological commitments, or at least to embrace distinct, new conceptualizations that are consistent with the target ontology.

Previous research in the areas of cognitive and conceptual development (e.g., Carey, 1985; Keil, 1989) has demonstrated that children form deep ontological commitments, which can influence subsequent conceptual learning. Further, Chi's prior research in the development of expertise (Chi and Koeske, 1983; Gobbo & Chi, 1986) has shown that children's development of expertise closely resembles that of novices. Thus it is a reasonable to expect that novices' conceptual development would be constrained by their own prior ontological commitments.

We hypothesized that direct instruction of an ontological class (e.g., *emergent process)* could improve subsequent learning about concepts within that class, particularly in cases when the learner had been unfamiliar with the target ontology, or drawn toward an alternative ontology as a result of surface phenomena or linguistic cues. Our empirical approach was to improve the effectiveness of physics instruction by adding some preliminary instruction about the relevant ontology of *emergent processes*, including the relation of this ontology to complex dynamical systems that are common in many domains of science. An interesting notion is that the physics instruction itself (e.g., of electric current) may not need to be altered or tailored in order to benefit from such a treatment. The present study demonstrated this approach, as experimental subjects were observed to talk and think about electric current in fundamentally different terms than control subjects -- even though the two groups received the same curricular materials in the topic of electricity. Thus, preliminary training about the *emergent process* ontology led to significant improvements in the learning of a traditionally challenging topic, as measured by problem solving as well as explanation data.

The results presented above suggest that is possible to facilitate conceptual change in a difficult physics concept by first providing training in the concept's target ontology, followed by normal instruction in the topic. An alternative interpretation might be that it is far easier than we conjecture to prompt subjects for alternative conceptualizations. Perhaps we could have gotten a similar pattern of results by simply encouraging students not to adopt the substance view and instead to think of electric current as a kind of process. The pattern of results suggests that ontology training played a substantial role in subjects' ability to shift their conceptualizations, however. Those subjects who received and understood the training (the "high training" sub-group) showed greater gains in their problem solving (Figure 5) as well as their explanation data (Figure 7). This finding is not likely a simple result of differences within the experimental subjects' ability, since there were no differences in academic achievement (e.g., high school and university grade point average) or test scores (math and verbal GPA) between students in these two sub-groups. Moreover, the "low training" sub-group slightly outperformed the "high training" sub-group on pre-test measures.

Our analysis of pre-test explanations replicates Slotta et al. (1995) with regard to their observations about novice conceptions of electric current and implements their suggestion that the observed expert-novice differences could provide a means of assessing conceptual change. While this suggestion was intuitive, a possible objection was that experts used different language in their explanations for some other reason (e.g., they were older or smarter). While such objections were countered by the observation that experts did not differ from novices in their explanations of the *substance* problems, the argument for an account of conceptual change was still somewhat indirect. In the present research, however, a novice's pattern of explanations is actually observed to change (i.e., within a single subject, and not between novices and experts). The pattern of means displayed in Figure 6 is strikingly similar to that reported by Slotta et al. (1995, and shown in Figure 1). Finally, the comparison of explanations offered by high and low training sub-groups (Figure 7) provides even further support for the argument that *emergent process* ontology training can mediate conceptual change.

Implications for Instruction

The application of cognitive theory to real-world instruction is never a straightforward process. It involves applying basic ideas about learning and instruction to the complex issues of instruction within a particular domain, where many barriers to learning are outside of the cognitive realm. One important idea that is supported by this study is that learning in some conceptual domains may require specific attention to ontological issues, while in others concepts the learning may be straightforward in terms of ontological attributions. Before designing instruction for a specific science topic, we must first determine whether students are required to undergo a change in their ontological commitments for that topic. In some topics (e.g., the human circulatory system, see Chi, 2000a; 2005), students' preconceptions will require substantial revision in the course of instruction, but never an ontological shift in the nature of their conceptualizations. For example, in students' initial conceptions of the circulatory system, the "heart" may be misconceived as a source of blood, and not as a pump, but it is still thought of in terms of the correct ontology[4]. In these cases, even though students' initial incorrect ideas require revisions (Chi, 2000a, 2000b), they do not require the crossing of ontological boundaries, and thus the ontology training approach would not be recommended. The important notion here is that educators need to first recognize whether or not they must address students' ontological commitments about a given concept.

In the instruction of physics concepts that are *emergent processes* (e.g., electric current, heat, light, force, diffusion, or heat flow, as well as notoriously challenging topics from other domains such as supply and demand, or natural selection) the initial conceptualizations held by students may require a shifting of ontological commitment. The present research suggests that in such cases teachers should not try to "bridge the gap" between students' misconceptions and the target instructional material, since there is no tenable pathway between distinct ontological conceptions. For example, students who understand "force" as a property of an object cannot come gradually to shift this conception until it is thought of as a process of interaction between two objects. Indeed, a students' learning may actually be hindered if they are required to relate scientifically normative instruction to their existing conceptualizations. Instead, our research suggests that instruction should stress the basic ontological characteristics of the concepts,[5] targeting students' existing conceptions indirectly by carefully avoiding any language, analogies, or phenomena that might otherwise reinforce the *substance-based* view. Additionally, instruction should explicitly draw attention to fundamental (ontological) aspects of the concepts in order to help students formulate new conceptions that adhere more closely to the scientifically normative view (and hence – an *emergent process* ontology).

Physics instruction is complicated by the fact that students' initial ideas about certain topics are fundamentally mistaken in terms of their ontological commitments. Further, these ontological commitments are continually reinforced by everyday language, terminology, cartoons, etc. We argue that in order to confront this challenging instructional context, students must first acquire some familiarity with the *emergent process* ontology, followed by instruction that deliberately targets the new ontology. In the present research, these conditions were achieved by means of an ontology training lesson, followed by physics instruction in which all reference to the *material substance* ontology was carefully avoided (e.g., the famous water analogy of electric circuits). In order to apply such an approach in classroom instruction, teachers and curriculum designers must first discern whether a concept is likely to have been ontologically misplaced by the student, then proceed with a two-phased approach: first, familiarize the student in the target ontology, providing some knowledge of the ontological characteristics and engaging the student in reasoning about those characteristics; second, provide instruction which specifically addresses the ontological nature of the concept and (more importantly) avoids any reinforcement of the inappropriate ontology.

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1 We are not addressing the issue of how such ontological associations are actually formed (e.g., through linguistic associations vs. characteristic features).

[2] 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.

[3] This score was obtained from incomplete data on all measures listed. For each measure (e.g., verbal SAT), all subjects who provided that measure were rank ordered. Thus, if nine out of the twelve experimental subjects had provided their verbal SAT scores, they would be ranked as 1/9, 2/9, etc. Such numerical rankings were obtained for each of the four measures, and were then averaged for each subject across all the values available. The highest possible ranking would thus be 1.0 (if a student had been ranked first in all of the measures she provided). 17 subjects provided all four measures; 3 subjects provided only three measures; 3 subjects provided only two measures, and 1 subjects provided only one of the measures. Other rank scores were explored to see if any significant changes occurred within the data (e.g., scores based solely on SAT scores), with no noticeable differences. The score developed and used here is successful in ranking subjects with respect to one another, based on four separate measures, and tolerating incompleteness in the survey data.

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[4] Note that the flow of blood in veins is a substance-based concept, as compared to the flow of electrons in wires – which is the very misconceptions that we are reporting about in this paper. Electrons do not flow in a wire in the same way that blood flows in a vein – although people easily think of them flowing that way. Instead, there is little to no movement of electrons (although they are all moving very quickly in random directions, with a small statistical drift in one direction). Then net result is a complex "emergent process" – which makes electric current one of the most challenging concepts to teach, in comparison to the circulatory system, which is quite easy to instruct. The contribution of our paper is that ontological commitments provide an account for why these two concepts differ in their level of difficulty for students and teachers. Chi (2005) provides much more detailed descriptions of the subtle differences between the different ontological classes.

[5] Note: such avoidance of students' alternative conceptions is only suggested in these special cases where they have made an ontological error in their initial conceptualizations. All other cases of instruction will certainly profit from the process of demanding that the student reconcile existing conceptions with new phenomena and principles, as occurs in the process of self-explanation (see Chi, 2000a).

Table 1

Overview of experimental design. Two groups of subjects (experimental and control) participated in two sessions, each lasting approximately 2 hours. The second session was identical for the two groups.

	Experimental Ss	Control Ss
Session One	**Pre-Test:** Ss solve and explain eight qualitative electric circuits problems (20 min)	
	Training Module: Computer-based training module in *Emergent Process* ontology	**Control Module:** Computer-based control module in related science concepts (approx. 1 hour)
	Training Post-Test: to assess training module (approx. 20 min)	**Control Post-Test:** to assess control module (approx. 20 min)
Session Two	**Learning Module ("electricity text")** Ss read roughly 25 pages of text from Hewitt (1987), covering topics in electricity (approx 1.25 hours)	
	Post-Test: Identical to Pre-Test (same eight problems and procedure)	

Table 2

Subject data from exit survey used to construct a quantitative ranking score for each subject. Each cell reports the mean score and the number of respondents on the survey for that measure.

	Total N	**Standardized Test Score (SAT verbal)**	**Standardized Test Score (SAT Math)**	**High school grade point average**	**University grade point average**	**Years in University**
Experimental Subjects	12	495 (n = 10)	485 (n = 10)	3.26 (n = 10)	2.53 (n = 12)	2.2 (n = 12)
Control Subjects	12	537 (n = 8)	506 (n = 8)	3.01 (n = 11)	2.94 (n = 11)	2.4 (n = 11)

Table 3

Representative pre-test explanations of the "10 bulbs" problem shown in Figure 1. Experimental subjects E8 and E11 resemble control subjects C2 and C12, as both describe a substance-like conception of "electricity" that flows in wires.

Subject E-8:

> The light bulbs that are closer to the battery will illuminate slightly before those that are farther away, because the current will reach them, the ones that are closer, before it reached the ones that are farther away.

Subject E-11:

> In actuality, the ones closer to the battery would come on first, because the electricity gets to them first. Because the electricity travels along. It travels. Its like, its a real thing. It travels.

Subject C-2:

> I'd have to say that the bulbs closer would illuminate slightly before those farther away... I'm assuming it'll zig zag, but then who's to say that it'll go right then left, then right, then left. I think, once you connected the switch, the electricity would travel through the closest loop, then back to the battery, and that it would omit all the rest of the bulbs. So the first light would come on before all the rest. And then maybe it could generate more -- go out to the other bulbs and turn them on that way.

Subject C-12:

> The light bulbs closer would illuminate before those farther away. The electricity from the battery, or whatever -- the juice from the battery (laughs) -- goes to the first light bulb, then back down like this, and then I think it just goes up and down through the wires like this (draws).

Table 4

Representative post-test explanations of the "10 bulbs" problem for the same four subjects shown in Table 3. Note, all subjects managed to answer correctly, but experimental and control explanations differ markedly.

Subject E-8:

> All the bulbs will illuminate at exactly the same time, because, um, the charge is traveling throughout, again, throughout the whole circuit. All the electrons are still -- even in parallel circuits -- are still everywhere in the circuit.

Subject E-11:

> All the light bulbs will illuminate at exactly the same time, because they're all getting the exact same current at exactly the same time, because they're all getting the same push of energy.

Subject C-2:

> Um we can say that the bulbs will all come on at the same time, because you're completing the circuit of electricity which runs through each bulb. Like, the battery puts out a certain amount of electricity when the switch is connected, and it gets spread out through each bulb, but if you added up all those electricity within each bulb or wire, it would add up to the whole amount of electricity put into it.

Subject C-12:

> All the bulbs would illuminate at exactly the same time, because they're separate. They're like by themselves. Whatever comes out of there - the volts from the battery? The CHARGE from the battery doesn't have to go through every one, every bulb. It doesn't have to go through like the first one to make the second one come on. It just goes through, I would say the top wire, and then each bulb gets its charge from there.

Figure Captions

Figure 1. Results from Slotta, Chi and Joram (1995). The mean frequency with which novices (solid lines) and experts (dotted lines) used *substance* and *process* predicates for physics concept and material substance isomorph problems.

Figure 2. A sample pre-post problem, derived from the materials of Slotta et al. (1995).

Figure 3. The interface of the Training Module, showing a running simulation of air pressure, the text screen, and user interface.

Figure 4. Subjects in ontology training condition showed improved performance on conceptual problems in electricity from pre- to post-test.

Figure 5. Experimental subjects who scored well on the training post-test achieved greater gains on the electricity post-test than Experimental subjects who scored low on the training post-test. Both groups outperformed Control subjects.

Figure 6. Experimental subjects show a reduction in *substance* predication from pre- to post-test, and a corresponding increase in *process* predication. Control subjects remain essentially unchanged in their use of both types of predicates.

Figure 7. Experimental subjects who scored higher than the median on the training post-test showed greater use of *Emergent Process* predicates than their low-scoring counterparts, who resembled the control group in their use of predicates.

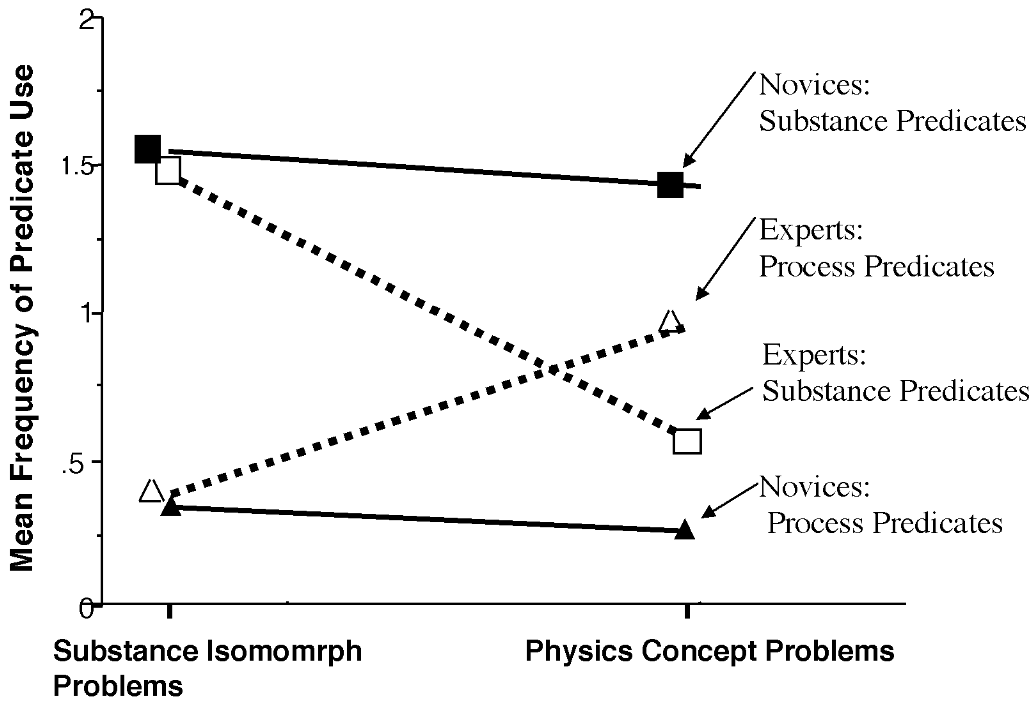
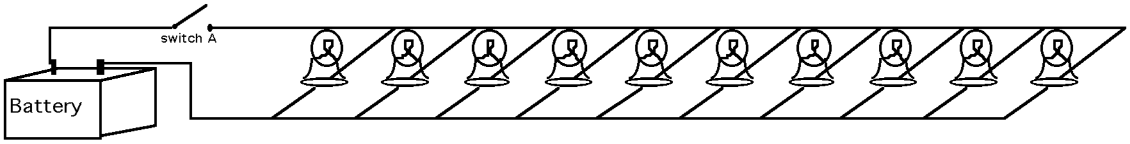

2
1.5
1
.5
0
Mean Frequency of Predicate Use
Novices: Substance Predicates
Experts: Process Predicates
Experts: Substance Predicates
Novices: Process Predicates
Substance Isomomrph Problems
Physics Concept Problems

Figure 1..



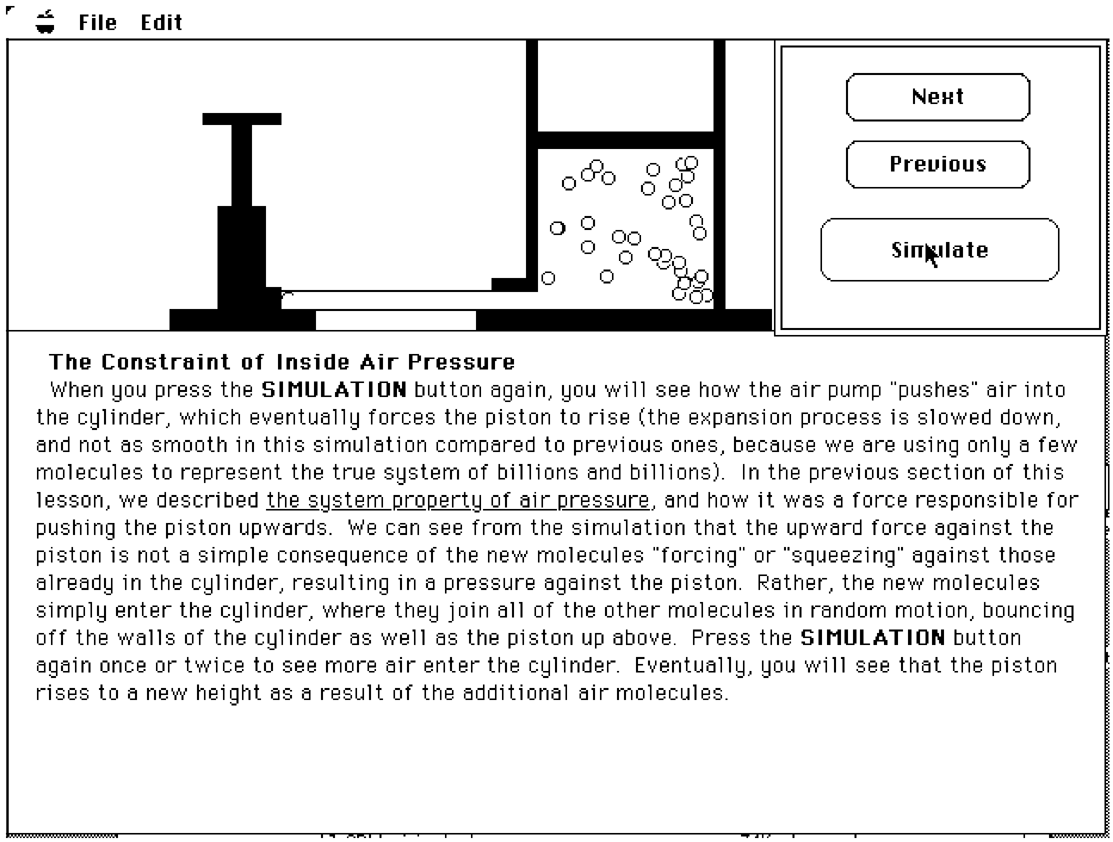
When the switch in this electric circuit is closed, what can we say of the ten light bulbs?

a) The light bulbs that are closer to the battery will illuminate slightly before those farther away.

b) The light bulbs farther away from the battery will illuminate slightly before those that are closer.

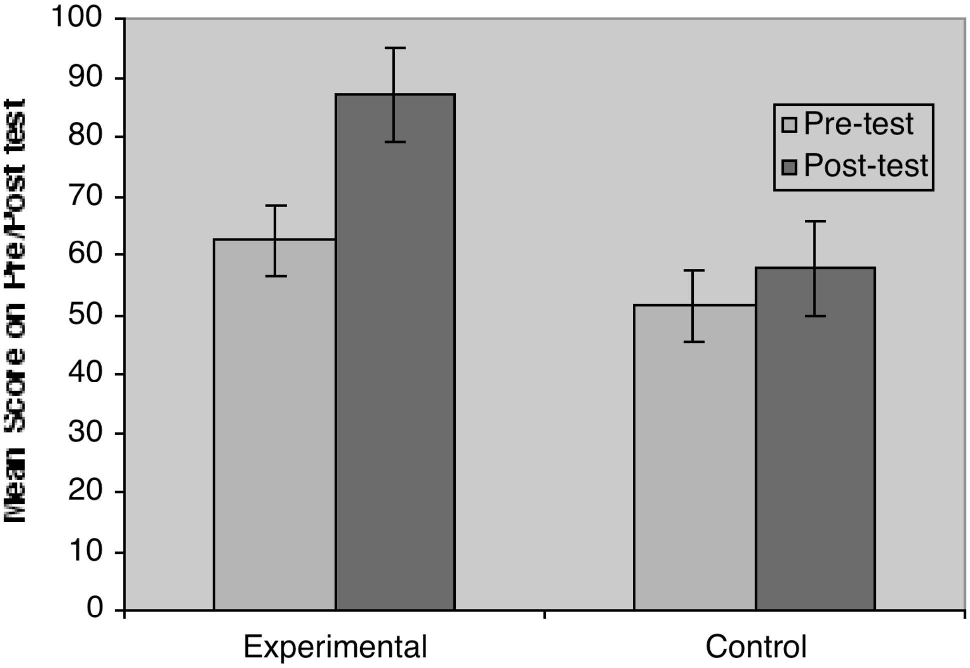
c) all of the light bulbs will illuminate at exactly the same time.

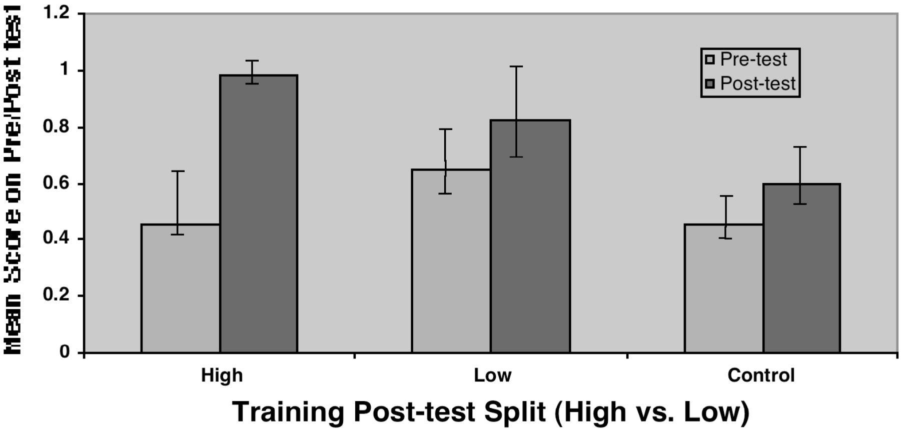
Explain your answer

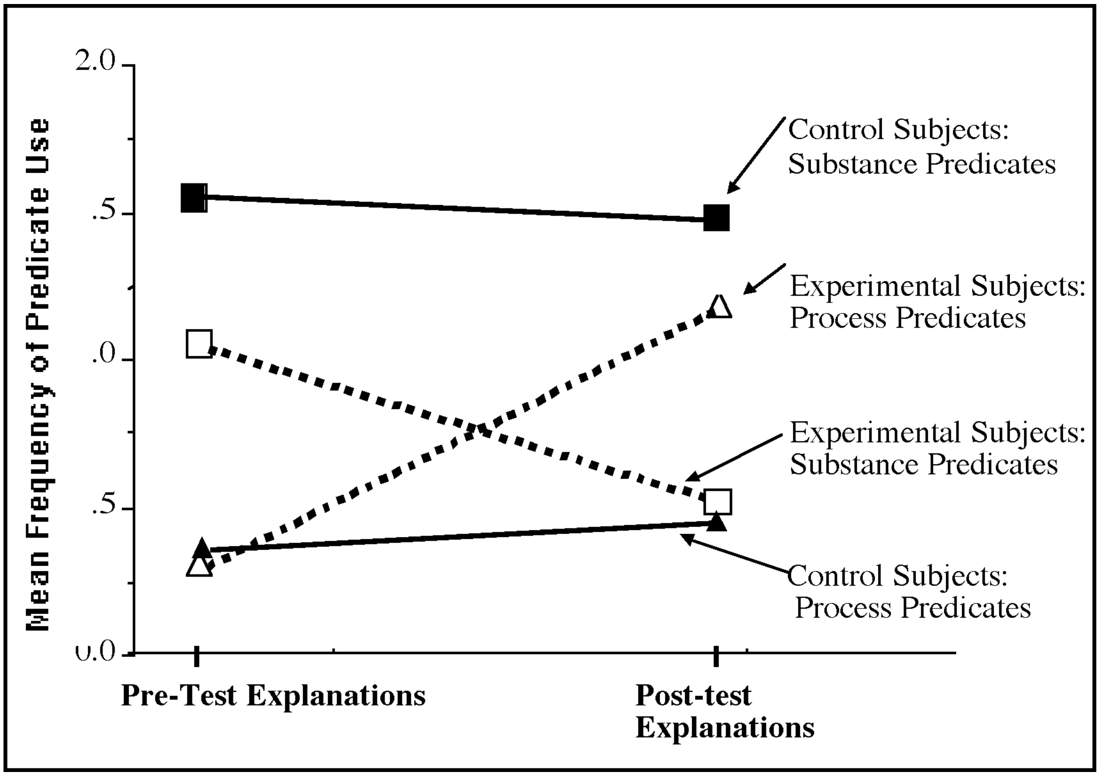


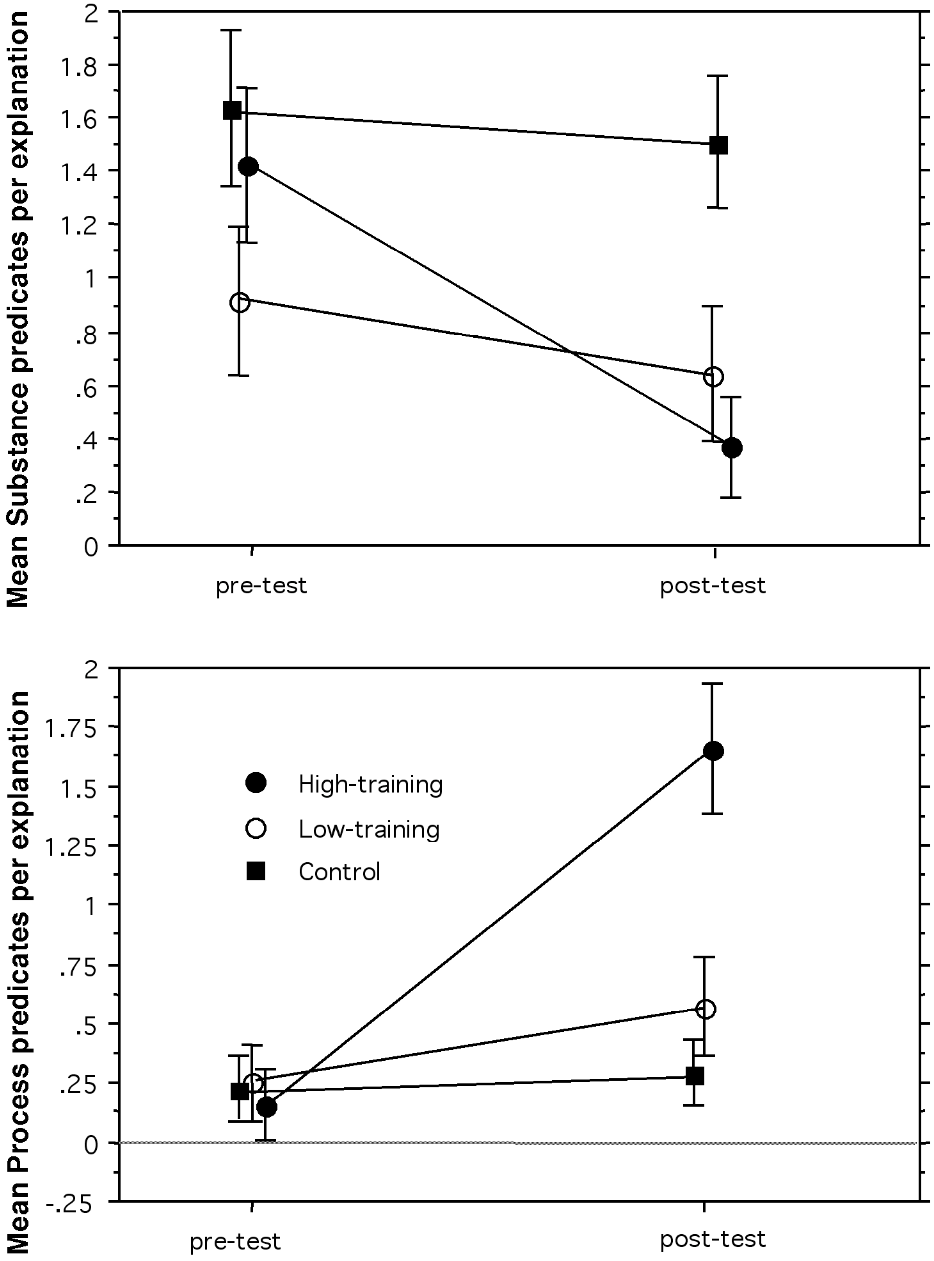
The Constraint of Inside Air Pressure

When you press the **SIMULATION** button again, you will see how the air pump "pushes" air into the cylinder, which eventually forces the piston to rise (the expansion process is slowed down, and not as smooth in this simulation compared to previous ones, because we are using only a few molecules to represent the true system of billions and billions). In the previous section of this lesson, we described the system property of air pressure, and how it was a force responsible for pushing the piston upwards. We can see from the simulation that the upward force against the piston is not a simple consequence of the new molecules "forcing" or "squeezing" against those already in the cylinder, resulting in a pressure against the piston. Rather, the new molecules simply enter the cylinder, where they join all of the other molecules in random motion, bouncing off the walls of the cylinder as well as the piston up above. Press the **SIMULATION** button again once or twice to see more air enter the cylinder. Eventually, you will see that the piston rises to a new height as a result of the additional air molecules.


100
90
80
70
60
50
40
30
20
10
0
Mean Score on Pre/Post test
Pre-test
Post-test
Experimental
Control


Mean Score on Pre/Post test
1.2
1
0.8
0.6
0.4
0.2
0
Pre-test
Post-test
High
Low
Control
Training Post-test Split (High vs. Low)


2.0
.5
.0
.5
0.0
Mean Frequency of Predicate Use
Control Subjects:
Substance Predicates
Experimental Subjects:
Process Predicates
Experimental Subjects:
Substance Predicates
Control Subjects:
Process Predicates
Pre-Test Explanations
Post-test Explanations


Mean Substance predicates per explanation
2
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
pre-test
post-test
Mean Process predicates per explanation
2
1.75
1.5
1.25
1
.75
.5
.25
0
-.25
● High-training
○ Low-training
■ Control
pre-test
post-test