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Helping Students Understand Challenging Topics in Science Through Ontology Training

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Chi (2005) proposed that students experience difficulty in learning about physics concepts such as light, heat, or electric current because they attribute to these concepts 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 whereby participants learned about emergent processes. Control participants 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 posttest. Verbal explanations and qualitative problem solutions revealed that experimental students gained a deeper understanding of electric current.

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., Doran, 1972; King, 1961; Kuethe,

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1963; Minstrell, 1982; Shipstone, 1984; Viennot, 1979) 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 6,000 published studies of students' misconceptions and instructional attempts at their removal (Duit, 2004; Pfundt & Duit, 1988).

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 materialistic properties to difficult concepts. 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. 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 on 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. 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. 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) 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 (cf. Keil, 1981), such as *processes, ideas,* and *material substances* to name a few. (Throughout the article, ontological categories are 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," as 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 one's 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 that should be attributed to certain concepts. Chi (2005) proposed that many concepts of this nature are not only *processes* (as opposed to *substances*), but are actually a specific kind of *process* that she called *emergent* (as opposed to *direct*), which is particularly challenging 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 relations 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, although this appears to be a *direct process* where blue liquid flows from one side of the beaker to the other, it is 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) identified such processes as *emergent* (as opposed to *direct*) ones, because their observable, "macrolevel" patterns are seen to emerge from the lower, or "microlevel," 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) explained that *emergent processes* are particularly troublesome for students to understand because they misattribute the concept's ontological nature,

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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).

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 & Findley, 1996), light (Slotta et al., 1995), traffic jams (Resnick, 1996), heat and temperature (Wiser, 1995; Wiser & Carey, 1983), and electric current (Joshua & Dupin, 1987; McDermott & Shaffer, 1992; Slotta et al., 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. 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 et al. (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," and so forth.

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 participants 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 participants 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 participant's ontological commitments based on the presence of particular verbal predicates in his or her explanation. For example, if a participant 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 (italicized) predicates were taken as evidence that participants conceptualized current as a *substance-like* entity with attributes of (a) "moving," (b) "can be consumed," (c) "can be quantified," and (d) "moves," respectively. By measuring the degree to which participants 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,

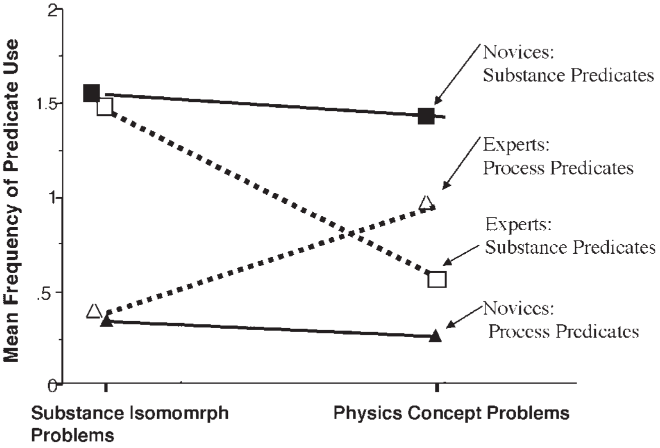

FIGURE 1 Results from Slotta, Chi, and Joram (1995). The mean frequency with which novices (solid lines) and experts (dotted lines) used *substance* and *process* predicates for physics concept and material substance isomorph problems.

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, whereas expert conceptualizations of the same topics show no sign of a *substance-like* ontology but rather appear to be consistent with a *process* ontology.

TESTABLE PREDICATIONS ABOUT INSTRUCTION FOR CONCEPTUAL CHANGE

Chi's (1995) 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. However, 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 concept, 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, 1984; Slotta et al., 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 et al., 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 preexisting *substance-like* conceptualizations?

This article assumes that physics novices possess *substance-based* conceptualizations of electricity, based on prior research by Slotta et al. (1995) and Reiner et al. (2000). We hypothesized 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

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. Participants' conceptualizations of electric current were measured by a pre–posttest consisting of eight qualitative physics problems concerned with electric current, for which participants selected a response from multiple choices, then verbally explained their reasoning in an interview format. Participants' choice of response to these problems, as well as their verbal explanations, provided measures of their ontological commitments at pre- and posttest, 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 or 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 participants' commitment to a either a *material substance* or an *emergent process* ontology, respectively. Thus, if a participant 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* was taken to reflect the presence of an *emergent process* association. It was predicted that the experimental group would show a transition from the pretest, where they explained problems in terms of a *substance* ontology, to the posttest, where they drew upon *emergent process* predicates in their explanations. In addition to this analysis of ontological commitment, the pre- and posttests were also scored for accuracy of responses, as the tests consisted of qualitative physics problems that were designed to be sensitive to the existence (or removal) of substance-based misconceptions of electric current.

METHOD

Participants

Participants were 24 university undergraduate students (15 women, 9 men) recruited from the University of Pittsburgh and paid for their participation. Participants had no university-level science background or any other formal training in electricity. Table 1 provides a profile of the mean SAT scores and grade point averages for participants in the experimental and control conditions. The table is not complete, because these figures were determined from an exit survey that some participants could not accurately complete. The *n* value listed for each figure in the table represents the number of participants who responded confidently to that item, from which these means were computed (out of a possible total of 12). Although these figures were obtained informally, they provide a qualitative sense of the participants who took part in the study. Note that the participants in the control group had slightly higher scores on four of the five measures.

Materials

Materials used in this study included pre- and posttests of electricity concepts, the *emergent process* ontology training module (interface, simulations, and training module text), the control module, the training module posttest, the control module posttest, the physics learning text (in topics of electricity), and the physics learning posttest.

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

TABLE 1
Participant Data From Exit Survey Used to Construct a Quantitative Ranking Score for Each Participant

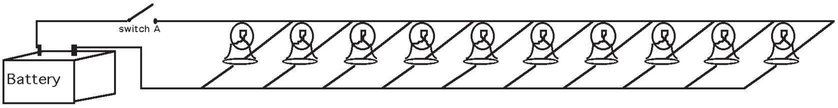
		Standardized Test Score (SAT Verbal)		*Standardized Test Score (SAT Math)*		*High School GPA*		*University GPA*		*Years in University*	
Group	*N*	*M*	*n*	*M*	*n*	*M*	*n*	*M*	*n*	*M*	*n*
Experimental	12	495	10	485	10	3.26	10	2.53	12	2.2	12
Control	12	537	8	506	8	3.01	11	2.94	11	2.4	11

Pretest (and posttest). Pretest and posttest 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 the question shown in Figure 2, the participants 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, participants were asked to verbally explain the behavior of the circuit to justify their choices.

The test items were designed so that different responses corresponded to 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).

Although using the same items in the posttests as used in the pretest did introduce an aspect of familiarity with the posttest items, participants were observed to carefully deliberate their responses to each item in the posttest, even if they recognized it from the pretest. 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 posttest problems. If a participant uses different patterns of verbal predication in explaining the same problem two different times, we can infer more strongly that the participant'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



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

FIGURE 2 A sample pre–post problem, derived from the materials of Slotta, Chi, and Joram (1995).

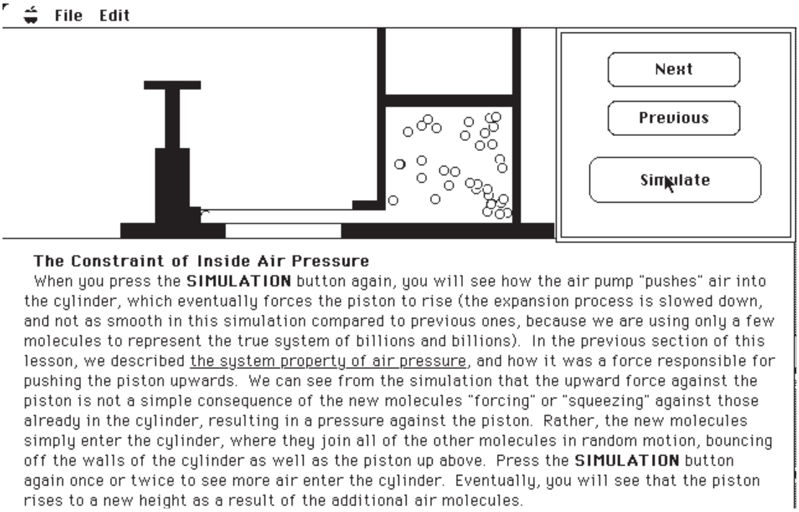
student at his or her own pace, where this textual material periodically referred to one of several running simulations on the top portion of the screen. Figure 3 displays a screen capture of the interface used in the training module. Notice the buttons that can be selected with the mouse to move between pages of text, as well as to interact with the simulations. The "Simulation" button was not selectable if the participant 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 later), 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 participant with a sense of the ongoing nature of *emergent process*.

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 participants 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 participants 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 as follows:

1. *System-wide:* Emergent Processes have no clear cause-and-effect explanation.
2. *Equilibrium-seeking:* Emergent Processes involve a system of interacting components seeking equilibrium amongst several constraints.
3. *Simultaneous and independent:* 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. *Ongoing:* 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,



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.

FIGURE 3 The interface of the training module, showing a running simulation of air pressure, the text screen, and user interface.

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 participants 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 participants with two distinct instances of the *emergent process* ontological category.

For the concept of air expansion, the simulation (see 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, participants 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 the participant 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, because prompting participants to explain has been shown to be beneficial to understanding (Chi, de Leeuw, Chiu, & LaVancher, 1994).

Training posttest. Experimental participants 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 participants 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. Participants 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 posttest served to measure how well participants had understood the training module content. This was important, because one would not predict any positive effect from a training session in which the participant did not comprehend the training content. Indeed, the results of this training posttest allowed a contrast between those experimental participants who understood the training material and those who did not.

Control module. Control participants 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 textbook (Towle, 1989) for the pages relating to liquid diffusion.

Control text explanation prompts. Throughout the control task, participants 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 participants 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 provided several "Questions" highlighted within the text and at the end of the chapter.

Control text posttest. Control participants 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 participants 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* (chap. 33–35). By removing several tangential sections (e.g., one concerning Van de Graf generators and one concerning the difference between alternating current and direct current), as well as the questions and answers provided within the chapters, it was possible to condense the text into approximately 15 full-length pages that covered the basic theory of voltages, current, resistance, and simple resistive circuits. This length of text was manageable for participants in a single 60- to 90-min 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% of the overall text) were removed. The resulting electricity text was read by the participants in the form of photocopied paper, in a three-ring binder, with approximately one paragraph of text per page.

Electricity text explanation prompts. Throughout the electricity text, participants 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 talked about the actual speed of an electron through the wire as being "slower than a snail's pace," and explained 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 participant to explain this in his or her own words.

Design

Twenty-four participants were assigned randomly between the experimental and control groups. There were both within-subject and between-subjects aspects to this design. Within-subject aspects were concerned with pre–posttest differences, and between-subjects aspects were concerned with experimental–control differences. Two sorts of dependent measures were obtained from the data: pre–posttest gains and verbal predication measures. The study consisted of two sessions (see Table 2), each lasting between 1 and 2 hr (participants were self-paced and varied in reading speed).

Procedure

Session 1. All participants began Session 1 by receiving instructions about the general course of the two-session study. They were then given the pretest 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 pretest, they were left alone at the computer to pro-

TABLE 2
Overview of Experimental Design

Control	*Experimental*
Session 1	
Pretest: Participants 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 (≈1 hr)
Training posttest: To assess training module (≈20 min)	Control posttest: To assess control module (≈20 min)
Session 2	
Learning module ("electricity text"): Participants read roughly 25 pages of text from Hewitt (1987), covering topics in electricity (≈1.25 hr)	
Posttest: Identical to pretest (same eight problems and procedure)	

Note. Two groups of participants (experimental and control) participated in two sessions, each lasting approximately 2 hr. The second session was identical for the two groups.

ceed through either the training module or the control module. Throughout the training module, participants were occasionally interrupted by computer-presented explanation prompts that were meant to ensure that some level of attention was paid to the content. All sessions were audio recorded 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. Participants were also informed that a posttest would be administered after the session, covering the content material. This training posttest helped ensure attention to content but, most important, provided a means of determining which participants comprehended the training and which did not.

Control participants 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, participants were occasionally interrupted by computer-presented explanation prompts. At the end of the session, all control participants received the control posttest, which consisted of qualitative questions concerning the definition and properties of the material described in the control text. Participants were informed that they would be given this test, ensuring some motivation for them to attend to the material. In addition, it provided some means of assessing the extent to which participants were able to learn the material in the control text.

Session 2. Experimental and control participants received identical materials and procedure in Session 2, consisting of the electricity text and electricity posttest. Participants were instructed to try to apply what they had 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, participants encountered occasional explanation prompts, which helped them reflect on their understanding and ensured that attention was paid to the content. After completing the electricity text, all participants received the posttest, which was identical to the pretest. Finally, participants 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 posttest 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 posttest 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 posttest scores revealed significant improvement for the experimental group (see Figure 4). Experimental participants showed pre–posttest gains of 29% compared with the control group's gain of only 9%. This difference was significant, $F(1, 22) = 6.765$, $p = .0163$. The difference in pretest scores suggested by the figure is not significant, and the conditions of administering the pretest were identical between experimental and control groups.

Of interest, experimental participants' improvement on the posttest depended on how well they understood the training materials. The training materials were challenging for participants, requiring them to learn general principles about a new type of concept, as well as specific examples of systems that seek equilibrium among constraints. The training posttest was also quite difficult, requiring participants to transfer what they had learned to a new example of *emergent processes* (predator–prey populations). We split the training group into high and low scorers on the training posttest (which measured how well they remembered and applied the training), and Figure 5 shows a breakdown of the Figure 4 results into three

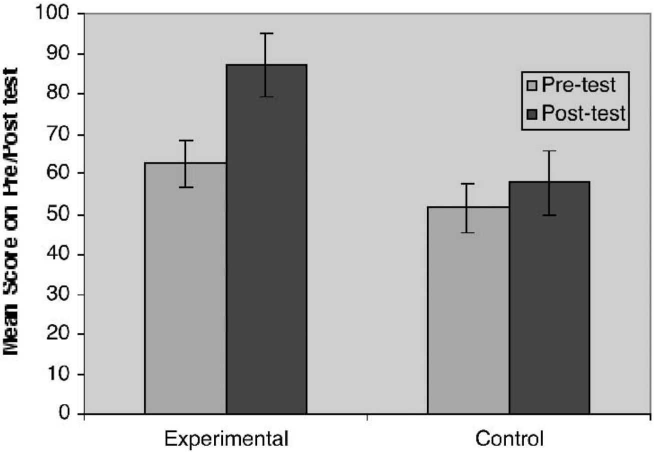


FIGURE 4 Participants in ontology training condition showed improved performance on conceptual problems in electricity from pre- to posttest.

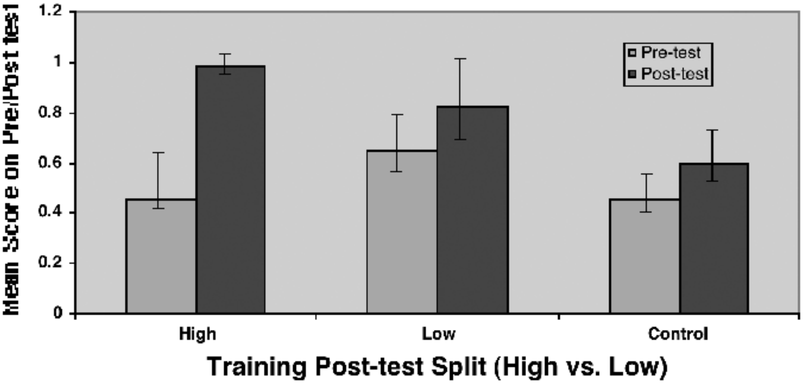


FIGURE 5 Experimental participants who scored well on the training posttest achieved greater gains on the electricity posttest than experimental participants who scored low on the training posttest. Both groups outperformed control participants.

groups: high-training, low-training, and controls. Those participants who scored the highest on the training posttest achieved greater gains during the second session of the study. The interaction of test score with training group was significant, with $F(2, 21) = 13.847$, $p = .0001$.

The greater gains made by the "high-training" portion of experimental group are not simply due to those participants' 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] Although most of the high-ranking experimental participants did become part of the high-training group (i.e., the group who scored best on the training posttest), there were some exceptions. Ranking alone was not as successful in predicting improved test scores as was the training posttest; this interaction is not as great as that shown in Figure 5, $F(2, 21) = 3.457, p = .05$. Thus, comprehension of the training module content was a better predictor of pre–post improvement than student ranking.

Verbal Predication in Pretest and Posttest Explanations

The qualitative reasoning gains described earlier 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 participants' ontological commitments. Participants' explanations were therefore analyzed for patterns of verbal predication. Each explanation was coded for the presence of six 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.

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[3] This score was obtained from incomplete data on all measures listed. For each measure (e.g., Verbal SAT), all participants who provided that measure were rank ordered. Thus, if 9 out of the 12 experimental participants had provided their verbal SAT scores, they would be ranked as 1/9, 2/9, and so on. Such numerical rankings were obtained for each of the four measures and were then averaged for each participant 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 he or she provided). Seventeen participants provided all four measures; 3 participants provided only three measures; 3 participants provided only two measures, and 1 participant 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 participants with respect to one another, based on four separate measures, and tolerating incompleteness in the survey data.

A complete coding was performed of all participants' explanations for the presence of the six predicates from each of the two sets. This coding provided a measure of the extent to which participants 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, and so forth. Slotta et al. (1995) provided 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 used by the participant, resulting in a maximum score of 6 for each of the two ontological sets. Although multiple occurrences of any attribute were ignored in this measure, Slotta (1997) explored 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 used. The present measure of simply tallying which of the six measures were used by a participant within each explanation was the most parsimonious and therefore was selected for the present article. Slotta et al. (1995) also presented 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 min) concerning the six attributes from each of the two basis sets (12 coding items in all). This second rater coded two complete participant protocols (pre- and posttest explanations, amounting to 16 problem explanations for each participant), and was given feedback on her coding. At this point, she was provided with four complete participants: 2 control and 2 experimental participants, with no knowledge of either the participant's group (control or experimental) or condition (pre- or posttest). 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% 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 participants, resulting in a total of 12 participants, or 50% of all protocol data. These 16 participant protocols (pre- and posttests for each of the 8 participants) were again coded blind to condition and group. This second trial found greater than 95% agreement in codes; thus, the remainder of all coded participant protocols was judged to have been coded reliably.

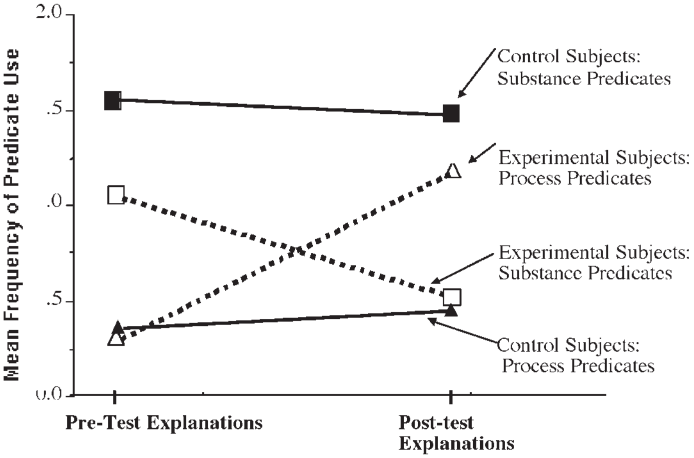

FIGURE 6 Experimental participants showed a reduction in *substance* predication from pre- to posttest, and a corresponding increase in *process* predication. Control participants remained essentially unchanged in their use of both types of predicates.

Comparisons of Pretest to Posttest Explanations

When the verbal explanations were coded for the presence of all attributes in both representative sets, the pattern of results (see 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 Figure 6) in explaining their pretest solutions. Second, like the novices in Figure 1, the control participants (the solid lines) showed little change from pretest to posttest in either their predominant use of *substance* predicates or their scarce use of *process* predicates. Finally, like the experts in Figure 1, the experimental participants (the dotted lines) discriminately used more *substance* predicates in the pretest and more *process* predicates in the posttest.

Statistical comparison of the predicate use within posttest 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, $F(1, 10) = 31.04$, $p = .0002$, and the decrease in *substance* predication, $F(1, 10) = 20.17$, $p = .0012$, were significant. Control participants showed no such transition in their preference for conceptual attributes, with no significant differences in level of *process* or *substance* predication.

Pretest explanations. The experimental and control participants relied almost exclusively on substance predicates in their pretest 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. Pretest 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 participants and two from controls) that closely resembled the novice explanations reported by Slotta et al. (1995).

Posttest explanations. Participants in the training condition showed significant changes in the way they explained posttest problems such as that of Figure 2. These changes were consistent with the hypothesized conceptual change: away from a *substance*-based and toward a *process* view. Table 4 provides four representative explanations of the 10-bulbs problem of Figure 1, taken from the same 4 participants displayed in Table 3. The explanations of the experimental participants now refer to a system-wide process occurring throughout the circuit and involving simultaneous activity at all 10 bulbs. The control participants often answered this problem correctly, because it was treated explicitly within the physics text. How-

TABLE 3
Representative Pretest Explanations of the "10 Bulbs" Problem
Shown in Figure 1

Participant	*Explanation*
E8	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 farther away.
E11	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.
C2	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.
C12	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).

Note. Experimental participants E8 and E11 resemble control participants C2 and C12, as both describe a substance-like conception of "electricity" that flows in wires.

TABLE 4
Representative Posttest Explanations of the "10 Bulbs" Problem for the Same 4 Participants Shown in Table 3

Participant	*Explanation*
E8	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.
E11	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.
C2	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.
C12	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.

Note. All participants managed to answer correctly, but experimental and control explanations differ markedly.

ever, the fact that control participants can sometimes know the correct response to qualitative problems only highlights the importance of appropriate assessment of participants' underlying conceptions, such as performed in the aforementioned analysis of verbal predications. Control participant explanations typically retained their substance-based flavor, even though they often become more sophisticated and logically sound, as in the case of Participant C12 (shown in Table 4).

Just as the high-trained experimental participants (those who scored higher than the median on the training posttest) showed more gains in the problem-solving measure than did 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 participants responsible for nearly all the gains of the experimental group. The upper panel of Figure 7 shows the decrease in participants' use of *substance* attributes, and 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—was significant, $F(2, 21) = 7.57$, $p = .003$, as was the interaction between Training split and increase in *process* predication, $F(2, 20) = 35.89$, $p = .0001$. The low-training experimental group did show a reduction in *substance* predication and an increase in *process* predication compared with 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 participant did on the training posttest) and the conceptual change resulting from the electricity text.

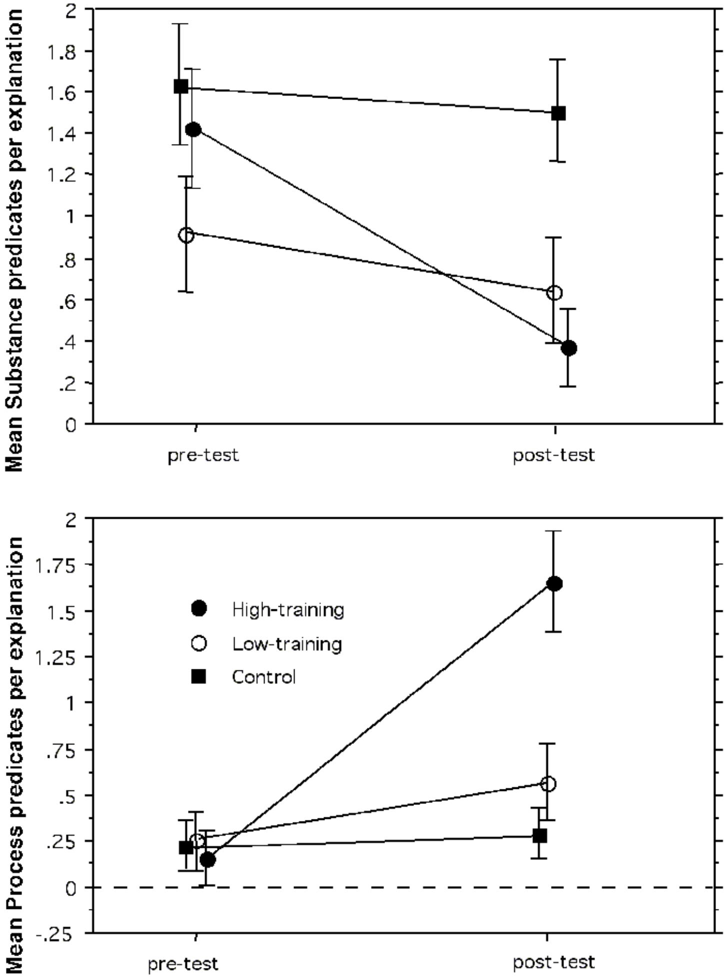

FIGURE 7 Experimental participants who scored higher than the median on the training posttest showed greater use of *Emergent Process* predicates than their low-scoring counterparts, who resembled the control group in their use of predicates.

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 (1992, 1993, 1997, 2005) argued 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 toward 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 & Koeske, 1983; Gobbo & Chi, 1986) showed that children's development of expertise closely resembles that of novices. Thus, it is 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 in which the learner had been unfamiliar with the target ontology or was 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. This study demonstrated this approach, as experimental participants were observed to talk and think about electric current in fundamentally different terms than control participants—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 here suggest that it 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 participants 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 participants' ability to shift their conceptualizations, however. Those participants who received and understood the training (the high-training subgroup) showed greater gains in their problem solving (see Figure 5) as well as their explanation data (see Figure 7). This finding is not likely a simple result of differences within the experimental participants' ability, because 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 subgroups. Moreover, the low-training subgroup slightly outperformed the high-training subgroup on pretest measures.

Our analysis of pretest 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. Although 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). Although 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 was actually observed to change (i.e., within a single participant, 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; shown in Figure 1). Finally, the comparison of explanations offered by high- and low-training subgroups (see 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 in some conceptual domains learning may require specific attention to ontological issues, whereas in others the learning may be straightforward in terms of ontological attributions. Before designing instruction for a specific science topic, educators 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, 2000b, 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, as 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, 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

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[4] Note that the flow of blood in veins is a substance-based concept, as compared with the flow of electrons in wires—which is the very misconception that we are reporting about in this article. 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 teach. The contribution of our article is that ontological commitments provide an account for why these two concepts differ in their level of difficulty for students and teachers. Chi (2005) provided much more detailed descriptions of the subtle differences between the different ontological classes.

[5] Note that 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, 2000b).

phenomena that might otherwise reinforce the *substance-based* view. In addition, 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, and so forth. 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). 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 that specifically addresses the ontological nature of the concept and (more important) avoids any reinforcement of the inappropriate ontology.

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