

Towards a Dynamic Model of Learners' Ontologies in Physics

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Abstract: In a series of well-known papers, Chi and Slotta (Chi & Slotta, 1993; Chi, Slotta & de Leeuw, 1994; Chi, 2005; Slotta & Chi, 2006) have suggested that one reason for students' difficulties in learning physics is that they think about concepts in terms of 'things' rather than 'processes', and that there is a significant barrier between these two 'ontological categories'. We contest this work in two ways: (1) it reflects a misunderstanding of expert knowledge, and (2) reasoning by experts and novices often traverses ontological categories in both professional and everyday contexts. We cite examples from research articles as well as classroom discussions to illustrate that experts as well as novices hop across ontological boundaries to make sense of physical phenomenon. This suggests a dynamic context-dependent model of a person's ontological view. To promote one ontological description in physics instruction, as suggested by Slotta and Chi, could suppress an essential skill for the development of expertise.

Introduction

Development of expertise, including characterization of expert and novice states and models of transitioning from novice to expert, is a core issue of education and developmental research. With respect to science education, incorrect novice responses and resistance to science learning have been attributed to a variety of causes: students' alternative theories of science concepts (McCloskey, 1983), strongly held misconceptions (Carey, 1986), incoherent use of finer-grained knowledge resources (diSessa, 1993a).

In a series of papers (Chi & Slotta, 1993; Chi, Slotta & de Leeuw, 1994; Chi, 2005; Slotta & Chi, 2006), Chi et. al. have proposed an account of the differences between expert and novice understanding of science concepts as ontological, i.e. based in their view of the basic nature of the concept. Chi (2005) claims that novices tend to attribute matter-like properties to science concepts such as heat, light, or electric current while the true ontological nature of the concepts (also how experts think of them) is process-like. Misconceptions result due to this ontological mismatch and are resistant to instruction because of novices' strong commitment to their own ontological view and unfamiliarity with the target ontology.

In this paper, we challenge this attribution of a fixed ontology to expert description of a concept and the idea of novice commitment to a particular ontology for a science concept, arguing instead for the development of dynamic models of learners' ontologies. Using examples from peer-reviewed science journals, everyday speech, and student reasoning in classroom settings, we argue that a) expert reasoning is dynamic and context-dependent with respect to ontologies, and b) like experts, novices can and do reason across ontological categories in everyday as well as scientific contexts. Moreover, for experts and novices, resources associated with one ontological category are often marshaled productively for understanding concepts in another. Thus, teaching a particular ontology for physics concepts could undermine the very skills needed for development of expertise.

In the next section we present a brief overview of Chi's view of ontological nature of naïve and expert knowledge in physics. In Section III we discuss our counter arguments and counter-evidence. Section IV presents our concerns regarding the instructional implications forwarded by Chi and discusses our instructional goals. In section V we suggest future directions for research on expert and novice ontologies in physics.

Review of Chi's Ontological Framework:

Chi and Slotta present a domain general explanation for student misconceptions that are resistant to instruction. The proposed framework is based on the idea of an expert/novice divide in how they ontologically categorize scientific concepts. Chi (2005, pp. 163-164) defines ontological categories as the "basic categories of realities or the kinds of existent in the world, such as concrete objects, events and abstractions." One of the main features of this ontological scheme is the mutual exclusiveness of categories with respect to members and attributes that apply to these members. These ontological attributes were marked by adjectives or adjectival phrases that "a category member may plausibly have, but not characteristically nor necessarily has" (Chi, 2005, p. 164). In other words, although a possible ontological attribute may not apply to a particular member of that category, it becomes nonsensical if attached to the member of an ontologically distinct category.

In this ontology-framework a science concept has a single correct ontology and that science concepts such as heat, light, electric current, and evolution belong to the process category. As such it would be a category mistake to apply any matter-like attribute when describing them. Chi et. al. describe novice misconceptions as category mistakes that are entrenched because of novices' commitment to the incorrect ontology: "many robust misconceptions can be interpreted as a mismatch between conception and reality at an ontological level, rather than (and in addition to) at the concept-specific and theory-specific level. In this view, robust misconceptions are mis-categorizations across ontological boundaries in that a member of one ontological category is misrepresented as a member of another ontological category." (Chi, 2005, p. 164).

The experimental evidence for miscategorization of science concepts by students is based on the analysis of verbal predicates used by students when solving problems related to these concepts (Slotta, Chi & Joram, 1995; Slotta & Chi, 2006). The idea is that a person's ontological knowledge for a particular concept can be determined by the type of predicates that they use when talking about it. Slotta and Chi (2006, p. 265) explain this methodology as determining the ontological view "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". Consider another example of student response, on parallel bulbs in a circuit, (Slotta & Chi, 2006, p. 282): "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." The use of predicates such as *runs through*, *puts out a certain amount of electricity*, *gets spread out*, and *added up* were evidence for attributing a matter-like view of current to the student.

In this view, students' ideas about science concepts are difficult to change because students are committed to their own ontological view: "Misconceptions result from commitments to an inappropriate ontology. ... 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 ... Thus ontologically misattributed concepts would require an extraordinary process of conceptual change." (Slotta & Chi, 2006, p. 263).

This framework proposes the following solution to the instructional challenges of teaching topics such as light, heat, current or natural selection: "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." (Slotta & Chi, 2006, p. 287).

Challenges to Rigid Ontologies – Counter Evidence and Counter Arguments

We present evidence and arguments against Chi's and Slotta's analysis of student difficulties in science and the ontological nature of science concepts. Our arguments are divided into the following subsections: 1) examples of ontological metaphors from everyday speech; 2) data of students talking science ideas in an introductory physics class as evidence against the claim that novices are cognitively committed to an ontological categorization for a given concept; and 3) evidence from scientific literature against the idea of scientific concepts belonging to one particular ontological category. In the following analysis of the textual excerpts as well as video data, we use the methodology proposed by Slotta and Chi (2006), i.e. one's ontological commitment of a concept is determined by the kind of predicates they use while describing or discussing that concept.

Straddling Ontological Categories in Everyday Thinking

There are numerous examples from everyday reasoning that counter the idea of strict ontological categorization. Everyday thinking easily hops across categories or cuts across them. Adults as well as children, experts and novices alike use such language constructs without difficulty. Thus ontologically novel expressions such as 'World War II rolled through the town and crushed it' referring to World War II as a demolishing machine is not considered nonsensical. Of course, we do not always think of the World War II as a machine (matter-like ontology). The point here is that we can think of World War II as a process lasting a few years while at the same time visualize it as a 'demolishing machine.' Everyday thinking shows no resistance to such crossing of ontological categorization.

Various other ontologically ambiguous examples can be cited from everyday knowledge, such as "At the end, everyone meets death"; "Necessity is the mother of invention"; and, "Don't fall in love." The ease with which common people including children understand and use these examples of ambiguous/mixed ontology stands in contrast to the notion that concepts belong to single categories. Human cognition is flexible enough

that entities apparently on distinct ontological trees - specifically emotions, processes and objects based on the ontological tree drawn by Chi (1993) - can also share some characteristics. Thus activities can be bound in space like objects, events can be personified, and emotions can be objectified without any loss of meaning. These examples bring into question the idea of mutual exclusiveness of categories with respect to category membership.

Students Crossing Ontological Boundaries While Explaining Physics Concepts

The ease with which even novices straddle multiple ontological categories in making sense of everyday metaphors is also reflected in student reasoning about physics concepts. This is in contrast to one of the basic premises of Chi's and Slotta's framework that novices need to undergo an extraordinary process of conceptual change in order to alter or expand their ontological commitments from matter-like to process-like.

Here, we consider the example of electric current, a topic that has been specifically mentioned to be thought of as material substance-like by novices (Slotta, et. al., 1995; Slotta, 2006). The data comes from videotapes of an inquiry based physics course at a large public university. This was a 4-credit, lab course for elementary education majors, most of who had not taken high-school physics. The instructor for the course was a non-PER physics professor and the first author was the teaching assistant for the course. The course was divided into three units, each roughly 4 weeks long. The class was driven by student ideas and experimental observations, scaffolded by the instructor and TA. The particular example presented is typical of discussions during the unit on electric current. The class had developed a convention that current is "1" in a simple series circuit with one battery and one bulb and the measurement of current at a point in any circuit would be described based on that reference number. The class had been working with multiple batteries and multiple bulbs in series circuits, when the instructor asks if the current at one end of a series of 4 batteries is always '4'. Here is how one student, Kim, answers that question:

Kim: Well, am not sure if this is true but when we added more light bulbs you saw they got dimmer, so they're kind of *sharing* what the current for one light bulb would be. So *it got like divided* between bulbs. So maybe, current isn't measured by the number of batteries. Maybe it's measured by like the number of batteries and then *split up by what it's being used by*.

Less than an hour later, the class was discussing what the current would be at a point on the wire just outside the battery in a series circuit with two bulbs. The students had observed that both bulbs in a 1 battery-2 bulb series circuit are dimmer than a 1 battery-1 bulb circuit. The on-going class discussion was whether the current just outside the battery is "1" and then gets divided into 'half' for each bulb, or is it that same throughout the circuit. Kim argues for current being half throughout the circuit:

Kim: Maybe the electrons...I don't know. Don't hold me to this. But like think of them as a string of electrons; like, they are all connected. So, I guess, everything else is connected but its going, like, through, like, a tunnel through it. 'Cause, like, if it's a conductor it allows them to flow through. If you pull that string through the whole thing, they are all going to go at the same pace - it's not gonna slow down at one point and get fast, or else the string will actually break.

In the first discussion, Kim described electric current using verbal predicates, *sharing*, *got divided*, *split up* and *being used by*, which are attributes of matter category as defined by Slotta and Chi (Slotta, et. al., 1995). In this second instance, Kim reasons about current being measured by the *speed* of electrons (indication of "movement process" attribute) and that the current is the *same throughout* the circuit indicated in her support for 'the same pace' (a process predicate). Thus analysis of her verbal reasoning by the criterion used by Slotta and Chi (2006) would indicate that Kim has a process understanding of electric current. The variation in her reasoning at these instances were not mediated by any instructional attempt at conceptual change, but were generated by her based on the ongoing discussions in class.

There are also examples in physics education research literature of students arguing across ontological categories while learning physics concepts. In documenting how students reason about different wave phenomenon such as propagation velocity, superposition etc., Wittman (2002, p. 97) observed that "students approach the topic of wave physics using both event-like and object-like descriptions of wave pulses, but primarily focus on object properties in their reasoning". In one student interview (Wittman, 2002, p. 112), "a student (David) explicitly used most of the above described [waves as object] reasoning resources in an object-like fashion [when answering questions on wave physics] ... But, David also shows that this object is not quite like other objects. David explicitly and clearly used both object properties and superposition (i.e. the addition of displacement) when he described the interaction of two wavepulses ... David also answered many questions correctly when describing wave physics. Thus, he used the same reasoning resources in a variety of settings, sometimes object-like and sometimes event-like. In more advanced settings, using specially designed diagnostic test questions, we have found that students consistently use multiple types of explanations in their responses on a single test. " Although the authors speculate that one possible explanation of the incorrect responses might be resistance on part of students to adopting a completely reformed outlook of waves as processes, they also argue that "students are not only capable of holding multiple interpretations of single physics situations, they are also ca-

pable of switching between different interpretations at a high speed, while not judging the inconsistencies between their answers.” (Wittmann, 2002, p. 113).

In both sets of data, students do not reflect a strong adherence to either matter or process ontology (at least as reflected in use of predicates) as they try to make sense of a seemingly new concept. The flexibility of students’ reasoning in these examples argues against the ontological commitment that is the basis of Chi’s framework of ontological coherence of naïve physics. To be clear, we do not argue that substance-like reasoning cannot be dominant in student responses; we argue that novices are not *committed* to substance like reasoning as a rigid ontological categorization.

Context-Dependence of Expert Ontology of Science Concepts

There remains the issue of whether both common speech and naïve student reasoning somewhat differ ontologically from ‘correct’ expert reasoning. On the contrary, we find that experts can and do reason across ontological categories in professional discourse and in different contexts adopt ontologically distinct descriptions for the same scientific concept. In an early critique of Chi’s framework of expert ontologies, diSessa argues that experts productively apply material-substance resources to understand non-matter concepts in physics: “Conservation of field quantities is arguably the most central construct of [physics]. Everyone has heard of momentum and energy: most people have heard of ‘charm’ and other such quantities in accounts of modern particle physics. These are all matter equivalents in the sense that they are conserved things whose distribution and flow in time and space are critical parameters of describing interactions. Experts, even in the most exotic corners of the field, reuse with a vengeance many reasoning patterns learned for matter. Are physicists guilty of overuse of ideas such as conservation, originally learned in the context of matter? No.” (diSessa, 1993b, p. 275).

In the following paragraphs, we analyze excerpts from scientific literature using Slotta’s and Chi’s (2006) attributes from matter and process categories to argue that expert knowledge of a concept (optical pulse, in this case) cannot be described as confined to a single ontological category.

Optical Pulse as an object and as a process

Light is well understood by physicists as coupled oscillating electromagnetic waves – a process by which energy and momentum are transported through space following Maxwell’s equations. A pulse or wave packet is formed by the superposition (or spatial-temporal coexistence) of plain electromagnetic waves of different frequencies (J. D. Jackson, 1999, pp. 322-324). This description of the pulse is consistent with the claim that the scientific nature of light is process-like. However, when talking about propagation of a pulse of light, scientists often refer to the pulse as an object/thing with finite spatial extension and shape. Consider the following excerpt from a research article in a peer-reviewed journal on propagation of laser pulses: “A negative peak velocity occurs when the peak of the pulse emerges from the sample at an instant before the peak of the pulse enters the sample.... [T]he effect is due to a pulse reshaping, and the leading edge of the pulse is less attenuated than the trailing edge. The insidious aspect of the pulse shaping is that apart from an overall attenuation, the shape and width of the pulse can remain intact after it emerges from the sample.” (Chu & Wong, 1982, p. 738) By the methodology used by Slotta and Chi (2006), predicates such as *emerges*, *enters*— examples of the attribute *moves* of ontological category of matter (Slotta, et. al., 1995; Slotta, 2006) – and reference to the shape, width edge, and peak of the pulse would indicate an object-like visualization of the pulse.

The authors of another article talk about laser pulses interacting and coupling with matter: “The UV probe pulse was *sent through* an optical delay line and *copropagated* with the pump pulse through the cluster jet. The probe pulse transversely *overfilled* the pump region in its focal volume. The *pump was removed* from the beam by a 800 nm dielectric mirror after interaction with the jet, and *the probe was split* and imaged onto a CCD camera to measure absorption ...” (Kim, et. al., 2005, p. 011201) Once again, the use of predicates such as *overfilled*, *removed*, *split*, and *sent through* would indicate a matter-like visualization of the pump and probe pulses. However, the authors simultaneously also use the predicate *copropagated* which implies that the pump and probe pulses propagate through the same spatial region at the same time –not possible for a material object—and *propagate* is a process predicate (Slotta, et. al., 1995). In addition the article specifically deals with the issue of changes introduced in the relative amounts of the superposed frequency components of the pulse, thus clearly treating the pulse as a process.

More examples of multiple ontological representations of concepts can be found in almost all subfields of physics and would only belabor our point that physics concepts cannot be boxed in a single ontological category. Rather the expert use of these concepts is best described by multiple and mutually overlapping ontological views complementing each other to produce a richer and complex understanding of the physical phenomenon.

Slotta and Chi (2006) have drawn attention to experts sometimes using material-substance ontology to talk about physics concepts in everyday use. The examples we present, however, are of experts talking to experts and not of their everyday speech. These articles were published in scientific journals where the purpose is to communicate new scientific discoveries to peers (experts). So it cannot be said that the use of language is

tempered by the motivation to make the material accessible to the layman. Rather it supports our claim that multiple ontological descriptions characterize expertise in physics.

Instructional Implications

According to Chi and Slotta, their “view of learning physics suggests that it is not possible to refine or develop intuitive knowledge to the point that it becomes the veridical physics knowledge; entities on separate ontological trees cannot be merged, because they cannot inherit each other’s attributes. For example, the danger in using the analogy of flowing water to instruct about electrical current is that students will continue to assimilate newly taught information about electrical current into the ontological class of MATTER. If students assimilated new information about electric current into the Liquid subcategory, the concept might also inherit properties such as ‘has volume,’ ‘occupies space,’ and other ontological attributes of the MATTER category.” (Chi & Slotta, 1993, p. 256). More recently, they argued that “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.” (Slotta & Chi, 2006, p. 286)

The contention that teachers should work against students using substance-like resources, that it is not possible to “bridge the gap,” is counter-productive. As we have shown, reasoning across ontological categories is a core aspect of expertise in physics, such as with respect to understanding conserved quantities, as diSessa (1993b) emphasized. In this light, an instructional model that conceives of novice and expert ontologies as static (or inflexible, context-independent) and aims to replace the former with the latter would actually hinder the development of what in our view constitutes an important aspect of physics expertise. So, strictly placing optical pulses in a process category might introduce barriers to thinking about reshaping the pulse, pulse distortion and pulse absorption that our quoted experts talk about. Moreover, an instructional strategy focused on ontological change might mean that we would fail to harness the resources that students bring to the table. For example, forcibly divorcing the concept of current from the matter category could undermine students’ marshalling productive resources for understanding Kirchoff’s law of addition of currents in a circuit – the beginnings of which can be seen in C2’s response above – or for understanding conservation of energy in a circuit.

The context-dependence of expert and novice ontological views indicates that the road to expertise lies in encouraging students to develop multiple ways of thinking about a concept, and an instructional strategy that draws their attention to these different descriptions and discussions on when some description is appropriate and when it is not. It is more important for students to be aware of the productiveness and limitations of the descriptions and metaphors they use rather than learning the ‘true’ scientific ontology of a few concepts.

Discussion

Paying attention to the ontological view of students can help us diagnose student difficulties and help instructors to more carefully clarify the boundaries/limitations of ontological metaphors that they use. But instead of trying to alter students’ ontological commitments, instruction should be geared towards tapping students’ productive ontological resources. In this paper, we argue against a unitary or fixed ontology for physics concepts. Our analysis of verbal predicates following Slotta’s and Chi’s (2006) methods shows that both experts and novices moving across ontological categories for the same concept. Our evidence points towards a more dynamic picture where our ontological knowledge is flexible and ideas in the world and ontological categories are multiply connected. However, there are also many questions not answered by the present research: How accurately does the predicate analysis of a small portion of someone’s speech reflect their ontological view of that topic? Can there be a mismatch between a person’s lexical ontology and their ontological view? What is a proper framework for understanding and analyzing a person’s ontological view of a concept in a given context? Detailed case studies of expert discourse and from student discussions can provide an insight into these questions. We plan to address these questions in future work.

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