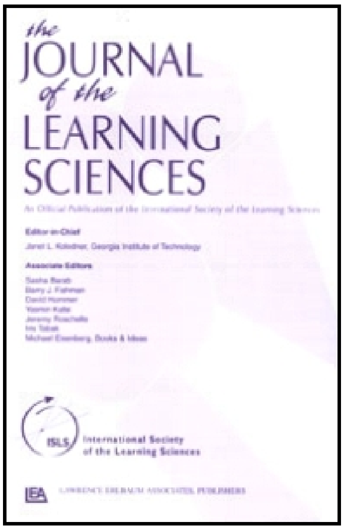

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In Defense of Chi's Ontological Incompatibility Hypothesis

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COMMENTARY

In Defense of Chi's Ontological Incompatibility Hypothesis

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This article responds to an article by A. Gupta, D. Hammer, and E. F. Redish (2010) that asserts that M. T. H. Chi's (1992, 2005) hypothesis of an "ontological commitment" in conceptual development is fundamentally flawed. In this article, I argue that Chi's theoretical perspective is still very much intact and that the critique offered by Gupta et al. is itself based on a flawed interpretation of Chi's theory. The purpose of this article is to address that misconception of Chi's work and to clarify her overall theoretical perspective. I begin by reviewing Chi's theory of ontological commitments, making an important comment about her position on the nature of expert conceptualizations. I review the methodological approaches used by J. D. Slotta and M. T. H. Chi (2006) to measure ontological commitments and comment on the instructional implications of Chi's theory. I then address the misconception held by Gupta et al. about Chi's work and call for more empirical research to tease apart the differences between Chi's view of "parallel ontologies" and Gupta et al.'s view of "flexible ontologies."

This article responds to an article by Gupta, Hammer, and Redish (2010) that asserts that Chi's (1992, 2005) hypothesis of an "ontological commitment" in conceptual development is fundamentally flawed. In this article, I argue that Chi's theoretical perspective is still very much intact and that the critique offered by Gupta et al. is itself based on a flawed interpretation of Chi's theory. The purpose of this article is to address that misconception of Chi's work and not to provide any further critique of the research described by Gupta et al. This is in

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part because I am most familiar with the work of Chi and her colleagues; but it is also because I want to keep this article focused strictly (as reflected in the title) on the matter of clarifying and reasserting Chi's position. The article should make it clear that there is no apparent conflict at the psychological level of description between Chi's hypothesis of ontological commitments and any of the observations described by Gupta et al. This is not to say that there are no differences between the two views—only that a more nuanced interpretation of the differences will be required, based on a correct interpretation of Chi's position. I hope that this will serve to advance the overall theoretical discussion of ontological attributions, which has seen renewed interest within the learning sciences (e.g., the recent work of Gupta et al., 2010, as well as new research from the domain of engineering education by Yang et al., 2010).

I begin by reviewing Chi's theory of ontological commitments, making an important comment about her position on the nature of expert conceptualizations. I then address a misconception held by Gupta et al. about Chi's work and call for more empirical research to tease apart the differences between what could more accurately be described as Chi's view of "parallel ontologies" and Gupta et al.'s view of "flexible ontologies."

ONTOLOGICAL COMMITMENTS AND CHI'S THEORY OF CONCEPTUAL CHANGE

A large body of research has applied the ideas of similarity and categorical attribution to account for processes of conceptual development in children as well as conceptual change in adults and the development of expertise (Carey, 1982, 1985; Chi, 1992; diSessa, 1993; Keil, 1987, 1989; Medin & Smith, 1984; Rosch, 1978). In one of the more recent applications of these ideas, Chi (1992, 2005; Slotta & Chi, 2006) hypothesized that some differences between novice and expert conceptualizations of science topics could be seen as a matter of categorical inheritance and category commitment. This section provides a brief review of that work.

In reviewing prior research on students' alternative conceptualizations, Reiner, Chi, and Resnick (1988) recognized a propensity among physics novices to conceptualize topics of light, heat, electric current, and force as material substances, as properties of material substances, or as simple processes involving material substances. In further support of this idea, Reiner, Slotta, Chi, and Resnick (2000) published a comprehensive review of the research literature concerning alternative conceptualizations of these four topics. For example, several early studies of students' alternative conceptualizations of heat had documented a sort of "caloric" view (e.g., Erickson, 1980; Fuchs, 1987). Similarly, several studies found that students conceive of light as a kind of fluid (e.g., Guesne, 1980, 1985) and electric current as a fluid-like substance that can be stored and consumed (Duit, 1986; Gott, 1985; Joshua & Dupin, 1987).

This review led Chi and her colleagues to question *why* such a pattern would exist across multiple, distinct concepts in the physical sciences. Perhaps there is a linguistic propensity in how people talk about such concepts that would bias children toward such materialistic interpretations (e.g., "shut the door, you're letting all the heat out," "throw a little more light on it")? Are there materialistic analogies that promote a certain way of thinking about such topics (e.g., "the juice is running around the circuit")? Reiner et al. (1988, 2000) presented evidence that (a) physics novices think about and speak about such concepts in materialistic terms, and (b) they are reticent to abandon such conceptualizations. This identification of a crosscutting commitment to "substance-based" conceptualizations offered Chi a source of insight into a possible mechanism underlying conceptual reasoning and conceptual change.

Building on Carey's (1985) notions of strong versus weak conceptual change and theory-like knowledge, as well as Keil's (1987, 1989) notions of ontological categories, Chi developed her own hypothesis about ontological commitments during the process of conceptual development (Chi, 1992; Chi & Slotta 1993). This hypothesis begins with the accepted notion (e.g., Keil, 1989) that whenever people encounter an unfamiliar concept, they look for clues about what *kind* of concept it may be, using whatever information is available: context of use, patterns of linguistic predication, co-occurrence with other concepts, and so on. Certain clues about the concept would reveal its most basic or "ontological" nature: Is it a process? A substance? A historical event? Then, once the learner has made a commitment to a particular ontological category for a concept (i.e., decides upon its ontological nature), he or she will automatically think of that concept as having the fundamental properties or attributes of that category. For example, all substances have mass and volume. So if a concept is categorized as a substance, the concept will "inherit" the attributes of material substances (e.g., that they have mass and volume, can be stored, can be contained).

Chi's (1992) original insight was to apply this notion to account for the pattern of robust misconceptions identified by Reiner et al. (1988). The learner will remain committed to his or her original ontological assignment unless some evidence is encountered that challenges that commitment (e.g., the person hears someone speak of the concept in a way that is not consistent with his or her initial categorization). Indeed, even in the face of counter-evidence, it will be difficult or impossible for the person to simply suspend his or her ontological attribution of the concept if he or she does not possess another more suitable target ontology. This interpretation is consistent with other reported findings that students tend to cling to their alternative conceptualizations, even in the face of counter-evidence (Brewer & Samarapungavan, 1991).

Chi hypothesized that the materialistic bias noted by Reiner et al. (1988) is caused by physics novices associating those concepts with a material substance ontology when the concepts should more appropriately (i.e., according to the scientific theory) be categorized as "constraint-based interactions" (Chi, Slotta, & deLeeuw, 1994) or "emergent processes" (Chi, 2005; Slotta & Chi, 2006). Because students have had very little experience with or exposure to the latter category, they will have little or no psychological representation of that ontology, and hence they will be unable to ascribe that ontology to any newly encountered concept. Thus, novices' materialistic conceptualizations are robust, even in the face of targeted instruction:

> 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, which implies the attribute "occurs over time", since this is a common characteristic of all processes. Misconceptions result from commitments to an inappropriate ontology. (Slotta & Chi, 2006, p. 262)

In learning about the concept of "heat," for example, children tend to assume a *substance*-oriented ontology,[1] 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 actually associated with an *emergent process* ontology, as it involves the transfer of kinetic energy between molecules in motion (Slotta, Chi, & Joram, 1995). Once an ontological commitment has been made with respect to the concept of heat, it is difficult to change this conceptualization into one with an *emergent process* ontology, particularly because the latter ontological category is most likely poorly held or even absent for most people (Chi & Roscoe, 2002).

Chi hypothesizes that concepts that are initially attributed with the one ontology would require "radical conceptual change" in order to shift their ontological

[1] In recent work, Chi (e.g., 2005) has shifted her description of the *substance* ontology to one of "direct processes" and, more recently, "sequential processes" (Chi, Roscoe, Slotta, Roy, & Chase, under review) in order to clarify that although novices think of concepts like heat and light as actual substances, their conception of heat transfer is a very simple process involving the movement of substances. In the case of electric current, for example, novices may not say that current itself is a kind of "stuff" but rather that it is a process whereby the "stuff" moves around in the wires. Such direct processes are ontologically distinct from "emergent process," in which a characteristic pattern or overall effect emerges as a consequence of the interactions of elements within the system. In the case of electric current, for example, the emergent process entails a net statistical migration of electric charge through the circuit in the presence of an electric field.

attribution.[2] In such cases, there is no process by which a person could gradually change his or her conceptualization through any stages of mental transformation.[3] It follows that the only way that science novices—who, for example, almost certainly possess some conceptualization of heat—can develop a scientifically normative view of that concept is by ignoring their initial conceptualization and developing a second conceptualization with new ontological attributions. However, this process will be quite difficult if the new target ontology is poorly established, as would likely be the case with the ontology of *emergent processes*. Chi initially referred to her core idea as an "incompatibility hypothesis" (e.g., Chi, 1992; Chi, Slotta, & deLeeuw, 1994), which ultimately became an integral part of a more comprehensive theory of conceptual change (Chi, 2005).

Slotta and Chi (1996, 2006)[4] offered empirical support for the incompatibility hypothesis, noting that it should be possible to facilitate conceptual change in physics topics like heat or electric current by first helping novices establish the appropriate ontological category, then providing physics instruction. They developed an "ontology training module" that included substantive textual treatment, rich examples, simulations, and reflection prompts to help physics novices (in a laboratory setting) develop a deeper understanding of the ontology of "constraint-based interactions." The training module developed a set of "ontological attributes" that characterized concepts in this ontology and examined multiple examples according to those attributes in order to help firmly establish the new ontology. The examples used in their treatment were distal from electric current, including predator–prey populations, garbage building up on the side of a highway, and gas piston systems. By the time experimental subjects had completed the training activity, they had developed a familiarity with the ontological category as determined by a training posttest. A control group was given a separate set of training materials that engaged them in reasoning about meteorological science, balanced for length and media content but with no explicit treatment of the target ontology. Next the experimental and control groups were both presented with a

[2]Chi (1992) notes that some ontological categories are more proximal than others and that "radical conceptual change" is change that requires a shift between quite distinct ontologies (e.g., from *substance* to *process*), whereas "gradual conceptual change" is change that requires only a shift within a major ontological category (i.e., from one kind of process, like an *event*, to another, like a *procedure*). Although the strict interpretations of conceptual ontologies as categories within "branches of a tree" has not generally been productive, they do serve to illustrate the notions of proximal versus distal ontologies.

[3]It is important to note that once the new ontological attribution has been achieved (i.e., a new category has been established and the concept in question attributed to that nascent category), then the normal processes of gradual conceptual change can occur, whereby more nuanced understandings are developed "within category."

[4]These two citations refer to the same body of empirical research, which was my dissertation study.

"physics training" phase in which the topic of electric current was presented by a popular conceptual textbook: Paul Hewitt's (2002) *Conceptual Physics*. Even though no explicit reference was made to the target ontology during the physics instruction phase (i.e., the experimental group were not encouraged to think of electric current as an emergent process), the experimental group showed a positive impact of the ontology training.

Measuring such ontological commitments is a challenging endeavor, and Slotta and Chi thought of two ways to do it. First, following McDermott and van Zee (1984), Gott (1985), and others, they "trapped" physics novices into reasoning errors that would be predicted for someone who held a *substance-based* conceptualization (e.g., in qualitative electric circuits problems, getting novices to predict that when many light bulbs are connected in series to a battery, the ones nearer to the battery illuminate earlier or burn more brightly). Second, they could detect ontological commitments through patterns of verbal predication in subjects' explanation data. Slotta and Chi (1996, 2006) used both of these approaches to get a bearing on the ontological commitments of their research subjects. They found that experimental subjects revealed improvements on the characteristic misconceptions in terms of their performance on diagnostic qualitative physics problems. In addition, they found that experimental subjects changed their patterns of verbal predication when describing electric current, suggesting an ontological shift in their conceptualizations. Although this study was the first source of empirical evidence for the ontological compatibility hypothesis, it has now been replicated by Chi (e.g., Chi, 2005; Chi et al., in press) and by researchers in other domains (Charles & d'Apollonia, 2004; Yang et al., 2010).

WHAT BECOMES OF PHYSICISTS' PREVIOUS CONCEPTIONS?

Chi has not yet studied or offered a detailed theoretical account of the knowledge of physics experts who, after all, do manage to achieve conceptual change. What happens to their initial conceptualizations, which presumably were of the same materialistic ontology that characterizes all physics novices? This important question is at the heart of the objections made by Gupta et al. (2010), who have labeled Chi's hypothesis as one of a "static ontology" whereby a person can only hold a single conceptualization of any topic. Thus, in the view of Gupta et al., Chi would propose that physicists must somehow change their initial substance-based conceptualizations *into* emergent process ones, leaving behind any capacity to reason in substance-based ways.

But Chi has never suggested this, nor would it make any sense for her to do so. For one thing, it is *not possible* under Chi's theory for anyone to gradually change a conceptualization from one ontological category to another. This is at the very heart of the definition of ontological categories: What makes them ontologically distinct is that one cannot gradually or radically change a concept's ontological attribution from one category to another. The only way to change the ontology of a conceptualization is to develop a completely new conceptualization (*not* to transform or transfer the initial one). Thus, the initial conceptualization *must* remain intact, even if it comes to be suppressed by lack of use or some other explicit conceptual mechanism. Chi has not addressed the fate of experts' initial conceptualizations explicitly in her empirical work but has spoken about it when explaining how experts obviously retain access to their lay interpretations of light, heat, and electric current (e.g., when they are working on a home wiring project and talk about the "juice flowing in the wires").

Indeed, Chi's theoretical position not only allows naïve conceptualizations to persist but explicitly requires them to persist in the process of radical conceptual change. In a article cited widely by Gupta et al. (2010), Slotta and Chi (2006, p. 266) stated explicitly that physics experts retain their earlier conceptualizations:

> Indeed, there is some evidence . . . 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. 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.

This quote is an unambiguous statement of Chi's position that experts can hold multiple, ontologically distinct conceptualizations (i.e., parallel ontologies) of some topics. Experts can still think of electric current as "juice" squirting through a wire but would quickly acknowledge that such a substance does not actually exist. Moreover, Slotta and Chi (2006) make an important point here that expertise in physics may be marked by a flexibility in the use of multiple ontological attributions for some concepts. Although Gupta et al. (2010) cite Slotta and Chi's article widely, they seem to have ignored this aspect of Chi's theory, which is completely at odds with their characterization of static ontologies. Indeed, it is unclear how Chi's notion of parallel ontologies is different from the "flexible ontology" proposed by Gupta et al.

Slotta and Chi (2006) suggested a possible implication of the incompatibility hypothesis for physics instruction: that it may actually be better to avoid the use of materialistic analogies—much as instructors may love them—during instruction of topics like electric current. Although a water analogy for electric current may be productive in helping students learn how to solve circuits problems, it could actually serve to reinforce students' deeper conceptual commitment to a notion of electricity as a "stuff" that is stored in batteries, comes out when the switch is thrown, gets used up, and so on. Gupta et al. have offered no evidence that the use of material analogies is not reinforcing such commitments. Certainly there is a history in physics of first pursuing and then abandoning certain pedagogical devices (e.g., the Bohr atom) after their impedance of deeper understanding is revealed.

Slotta and Chi (2006) applied an alternative approach of offering students first explicit instruction in the target ontology (i.e., emergent processes) followed by instruction that intentionally avoids any reference to the substance-based conceptualization (all references to the famous water analogy for electric current were removed from the physics training materials used in their study). Inspired by the early success of this approach, Ron Miller of the Colorado School of Mines Department of Chemical Engineering and Ruth Streveler of Purdue University's School of Engineering Education have been studying such an instructional approach for use with engineering undergraduates. These scholars found that despite intensive instruction, advanced engineering students repeatedly demonstrated persistent misconceptions of heat transfer and fluid mechanics—particularly at microscopic levels at which fluid and thermal systems behave in nonclassical ways. After extending the materials and approaches of Slotta and Chi to address a new scientific domain, they were able to demonstrate a positive benefit of the ontology training approach for undergraduate engineering students (Yang et al., 2010).

DISCUSSION

The notion of category attributions in conceptual development has enjoyed decades of support (Chi, 1992; Keil, 1987, 1989; Medin & Smith, 1984; Rosch, 1978; Wattenmaker, Nakamura, & Medin, 1988). Patterns of misconceptions in science—particularly those that resist instruction—have also been a pervasive topic of research (Pfundt & Duit, 2004). Chi's contribution was to connect the notion of radical conceptual change (Carey, 1985) to that of ontological reclassification, suggesting that radical change can be defined as that requiring an ontological shift. This contribution has allowed a fruitful and engaging discussion about *why* some conceptualizations of science topics are robust in the face of instruction and *how* experts might address them.

Chi's theory has interesting implications for science educators in terms of the approaches they adopt for the instruction of certain topics. Most notably, it may be advantageous to avoid any form of instruction that could reinforce novices' existing ontological commitments. The theory suggests that instructors should first help students establish the target ontology, then explicitly link any instruction of the concept to that target ontology while explicitly avoiding the original ontology. This is an intriguing notion with some empirical support (Charles & d'Appolonia, 2004; Slotta & Chi, 2006; Yang et al., 2010).

Gupta et al. (2010) have asserted an erroneous version of Chi's hypothesis that they then strenuously refute with "counter-evidence" drawn from observations about student reasoning within the first author's physics class. Although I have written this article mainly to redress that error and clarify Chi's hypothesis, it is important to note that the interests expressed by Gupta et al. are well intended. Moreover, it is exciting to see this level of interest, suggesting that there may be further progress or debate concerning the role of ontological commitments in conceptual change. For example, the present exchange could bring greater attention to the aspect of Chi's theory that experts must retain their previous ontological attributions (an aspect that is apparently not well publicized or explained).

Essentially, Gupta et al. suggest that physics conceptualizations may be more complex than what is allowed by Chi's theoretical perspective, requiring the flexible attribution of ontologies in accordance with the person's immediate conceptual needs. It seems possible that there are "degrees of flexibility" (i.e., where Chi's theoretical position of parallel ontologies could still be too rigid to allow for the conceptual dexterity being argued by Gupta et al.). However, it is not possible to tell from the illustrations offered by Gupta et al. how flexible the switching was in students' reasoning. Nor was it possible to tell whether students switched back and forth to the *emergent process* ontology, which is the only ontology that would be of any relevance to this discussion (because presumably the novices would not initially possess it). It is also not clear what differences in flexibility, if any, are predicted by Gupta et al. between physics novices and experts. As no empirical study has yet been performed, it is not possible to make any strong connection between Chi's position and the notions of flexibility described by Gupta et al.

It may be that the perspectives of Gupta and Chi are actually consistent with one another, as they both recognize the importance of traversing distinct ontological conceptualizations. Although Chi has always held that experts maintain access to their materialistic preconceptions, using them whenever it is convenient or desirable, she has not made any explicit statements about the nature of expert conceptualizations (e.g., how and when experts shift across ontologies). To date, Chi has focused on the fact that fundamental characteristics of some science concepts make these concepts inaccessible to novices. It is possible that further theoretical and empirical work concerned with expert reasoning could reveal a greater flexibility and cognitive economy in shifting across ontological characteristics. There may also be some topics in physics—particularly in modern physics—that defy any single ontological attribution. Light, for example, is famous under the physics theory for its ontological duality. Even particles—the seeming epitome of a substance-based ontology—can sometimes appear as emergent processes (i.e., as in Brown's famous double slit experiment).

There may also be real differences between Chi's notion of parallel ontologies and the flexible ontologies proposed by Gupta et al. Chi has suggested that it is not possible to develop the *emergent process* view of concepts like electric current in any continuous transformation of the material substance or direct process view. This assertion is consistent with the literature on gradual versus radical conceptual change and offers a cognitive explanation for those phenomena. Perhaps Gupta et al. feel that they can, through the use of bridging analogies or some other instructional technique, build on students' materialistic preconceptions to develop an emergent process view of electric current. If so, this suggests a possible empirical study that could distinguish the two perspectives.

A source of productive contrast between the two perspectives may be found in the phenomena that the two views are able to explain. Chi's theory accounts for why certain misconceptions—and not others—are particularly robust to instruction. Gupta et al. have not yet provided enough detail for their flexible ontology position to explain how they can account for this well-established pattern of results from the literature on alternative conceptions in science (e.g., Reiner et al., 2000). However, Gupta et al. have provided a rich set of examples and a discussion about the flexibility of conceptual reasoning performed by novices and experts that suggests a rapid switching between ontological attribution. Perhaps there are some phenomena in their article that Chi would have difficulty accounting for, even with her notion of parallel ontologies. Thus, there is potential for ongoing discussion and research (i.e., of expert reasoning or carefully designed instructional approaches), and I hope that Gupta and his colleagues will design and implement such research.

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