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Conceptual Metaphor Meets Conceptual Change

Tamer G. Amin

American University of Beirut, Beirut, Lebanon

Key Words

Concept of energy · Conceptual change · Conceptual metaphor · Language in cognitive development · Science education

Abstract

This paper argues that the metaphorical representation of concepts and the appropriation of language-based construals can be hypothesized as additional sources of conceptual change alongside those previously proposed. Analyses of construals implicit in the lay and scientific use of the noun *energy* from the perspective of the theory of conceptual metaphor are summarized. The experientially grounded metaphorical construals identified in both uses help conceptualize the shift from the concrete, naïve to the abstract, scientific understanding of energy. The case of the concept of energy motivates the more general hypothesis that an important part of learning a highly abstract (even mathematical) concept is the appropriation of experientially grounded metaphorical construals implicit in scientific discourse. Pedagogical implications of this proposal are discussed.

A large body of research, carried out from cognitive-developmental and science education perspectives, has demonstrated that a range of factors play a role in the process of concept learning: the content of prior conceptions, metaconceptual understanding, domain-general information processing, cognitive conflict and other influences on motivation, and the identity implications of changing ideas [Carey, 1985, 1999; Limón & Mason, 2002; Schnotz, Vosniadou, & Carretero, 1999; Sinatra & Pintrich, 2003]. These factors can help explain preference for one belief over another, but they all assume that two or more beliefs or hypotheses can be intelligibly entertained and their plausibility evaluated. A key challenge to research in conceptual development and learning is to understand what has come to be referred to as *conceptual change*. While the phrase is sometimes used rather loosely to refer to any

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Tamer G. Amin, Department of Education
American University of Beirut
PO Box 11-236, Beirut (Lebanon)
Tel. +961 70 945 931, Fax +961 1 744 461
E-Mail tamer.amin@aub.edu.lb

change in conceptual understanding, Carey [1999] has pointed out that it is important to understand this idea much more narrowly to appreciate the challenge to researchers trying to understand the process of conceptual change and also to children expected to undergo it. It is relatively straightforward to change a child's belief – for example, from 'a whale is a fish' to 'a whale is a mammal' – if the concepts over which these beliefs are defined are already possessed by the child. It is something else entirely to change the concepts themselves that constitute beliefs.

Research in both the cognitive-developmental and science education traditions have made important contributions to both the theoretical challenge of identifying sources of conceptual change, in this narrow sense, and the pedagogical challenge of inducing it. In this paper, literature on the metaphorical representation of concepts and the role of language in cognitive development are reviewed and two additional, related sources of conceptual change are hypothesized. It is suggested that the appropriation of construals implicit in language and the metaphorical nature of our understanding of many concepts pervasively reflected in language, together, are likely to constitute important sources of conceptual change. The case of learning and teaching the scientific concept of energy is discussed as a test case to lend plausibility to this hypothesis.

The Search for Sources of Conceptual Change

Two prominent lines of research – theory change and knowledge-in-pieces approaches – carried out within the perspectives of cognitive-developmental psychology and science education, respectively, have tackled the difficult problem of conceptual change. An influential approach to conceptual change in cognitive-developmental psychology is grounded in a view of concepts as embedded in theories, cognitive structures that represent a range of phenomena and the causal principles that explain them [e.g., Carey, 1985; 1999; Carey & Spelke, 1994; Smith, Maclin, Grosslight, & Davis, 1997; Wiser, 1995]. While theory change can involve the gradual change in beliefs formulated in terms of the same concepts, sometimes concepts in successive theories may themselves differ [Carey, 1992, 1999; Carey & Spelke, 1994]. The latter is a deeper kind of change in which previously unthinkable thoughts become thinkable. Carey and colleagues have argued that this sort of knowledge change occurs in development, with prominent examples including differentiating weight and density [Smith et al., 1997], heat and temperature [Wiser, 1995] and developing the adult concept of alive [Carey, 1985, 1999].

Carey [1999] dismissed three mechanisms as inadequate to account for this kind of change: adults providing information to children through language; triggering conflict among children's ideas which may motivate attempts to revise understanding; and increasing information processing ability and/or increased metaconceptual or epistemological understanding which can help in the process of constructing new and more complex theories. None of these, Carey argues, can be the source of the specific novel conceptual content of a new theory. One has to look elsewhere for sources of conceptual change. Carey's proposal is to look to existing domain-general and domain-specific conceptual resources as well as to a variety of bootstrapping processes. Domain-general resources come in the form of abstract causal schemas available early and are possibly innate (e.g., essentialist assumptions about invisible causes of visible properties, as well as teleological, efficient, and material causal schemas). Other resources are domain-specific. Particularly important are the core conceptual frameworks that are present very early in life, and that may also be innate: the core domains of intuitive understanding of mechanics, psychology, number, and space [Carey & Spelke, 1994; Spelke & Kinzler, 2007].

Carey [1999] also described two forms of bootstrapping: analogical mapping between domains of knowledge, and restructuring that makes use of knowledge within the domain itself. Bootstrapping is a construction process that makes use of material structured in one way, producing a structure very different from the one that grounded the process in the first place. Analogical mapping is the more familiar example of such a process [Gentner, 1989; Vosniadou, 1995]. Rudimentary understanding in some domain of knowledge forms the basis for establishing a mapping between that domain and another more familiar. Once this mapping has been established, knowledge can be transferred from the more familiar to the less familiar domain, restructuring understanding of the latter. Examples from the conceptual change literature include differentiating heat and temperature [Wiser, 1995; Wiser & Amin, 2001, 2002] as well as weight and density [Smith, 2007; Smith et al., 1997; Smith, Snir, & Grosslight, 1992], using visual models that embody the extensive/intensive distinctions in both cases.

Within-domain bootstrapping is less familiar. Carey [1999] suggested that such a process is likely to be implicated in developing a biological understanding of living things. Initially, young children have an undifferentiated notion (combining *alive, existent, real,* and *active*) uniting people, nonhuman animals, and moving artifacts within the same category of alive, excluding plants. Carey provided a within-domain bootstrapping account of the change in the concept of alive grounded in concepts from children's nonbiological theory. Specifically, Carey claimed that children readily learn simple causal facts such as 'people need food and water to grow and stay healthy;' 'without food and water people don't grow properly and can die.' In parallel, children learn an analogous set of facts about plants. No such facts are learned about other things that display activity such as moving artifacts. This supports a differentiation of the concept living thing, uniting animals and plants, from existent, real, and active.

A second account of conceptual change comes from the science education literature. This *knowledge-in-pieces* or *knowledge systems* view shifts attention to a subconceptual level of knowledge representation at which continuity between the novice and the expert can be identified [diSessa, 1983, 1988, 1993, 2002; diSessa, Elby, & Hammer, 2003; diSessa & Sherin, 1998; diSessa & Wagner, 2005; Sherin, 2001; Smith, diSessa, & Roschelle, 1993]. The central knowledge-in-pieces claim is that the same, small knowledge structures play functional (albeit different) roles in the knowledge and reasoning of both the expert and the novice. diSessa [1983, 1993] called these knowledge structures *phenomenological primitives* (or p-prims), emphasizing that they are often abstractions from sensorimotor experiences.

An example is Ohm's p-prim, a knowledge structure that abstracts invariants from the sensorimotor experiences involving the grasping, pushing, and pulling of objects of different sizes and weights. The resulting knowledge structure in this case can be described as follows: 'an *agent* that is the locus of an *impetus* that acts against a *resistance* to produce some sort of *result*' [diSessa, 1993, p. 126]. P-prims are largely unarticulated knowledge structures occupying an intermediate level of abstraction between rich sensory images and named concepts. diSessa insisted that many p-prims are likely to be required to fully characterize lay and expert understanding of physical situations. It is expected that any given p-prim has a limited scope of application and is automatically triggered to guide local reasoning in a physical situation. The difference between the naïve and expert understanding is seen as primarily a matter of changes in the situational cues that trigger the application of p-prims.

Recently, diSessa and colleagues [diSessa, 2002; diSessa & Sherin, 1998; diSessa & Wagner, 2005] have begun to develop an account of concepts as complex knowledge systems, with p-prims as constituents of these systems. Moreover, similar assumptions regarding the nature and role of intuitive knowledge in scientific understanding have grounded instructional strategies that strategically trigger intuitive subconceptual elements of knowledge using computer-based visual models [White, 1993, 1995], bridging analogies [Brown & Clement, 1989; Clement, 1982, 1993], and extreme case reasoning [Zietsman & Clement, 1997].

The theory change and the knowledge-in-pieces views of conceptual change appeal to somewhat different bootstrapping accounts. While both acknowledge that the process of conceptual change takes time, the theory change account treats conceptual change as a gestalt shift with a great deal of coherence and consistency attributed to both the naïve and expert theory. In contrast, the knowledge-in-pieces view expects that naïve understanding is highly sensitive to context with predictions and explanations depending in subtle ways on which particular knowledge elements happen to be triggered in particular reasoning situations. Conceptual change on this account involves a gradual increase in coherence. These contrasting views have led to an interesting debate in the literature with the extent of coherence of naïve knowledge explored in a variety of domains with varying results [see e.g., contrasting positions in diSessa, 1993; diSessa, Gillespie, & Esterly, 2004, on the one hand, and in Chi & Slotta, 1993; Ioannides & Vosniadou, 2002; Smith et al., 1997; Vosniadou, 2002; Wiser, 1995, on the other]. I return to this debate briefly in a later section to situate the view advocated here with respect to these other positions.

For the purposes of this paper, two particular features of this work on conceptual change need to be highlighted and discussed: the roles of cross-domain mapping, and of language in the process of conceptual change. With regard to the first feature, as noted above, analogical mapping between domains of knowledge has been considered an important source of conceptual change in the narrow sense. Transfer of relational structure from a familiar and elaborated domain of knowledge to one less familiar and elaborated has been seen as a powerful source of new concepts. Indeed, analogical reasoning has been appealed to by both theory change and knowledge-in-pieces approaches to conceptual change. The contributions of this literature have been very important in increasing our understanding of how existing knowledge in a learner's repertoire can be harnessed through explicit instruction to engage in analogical reasoning drawing on strategically chosen, familiar, analog situations. However, a more general claim has been made by Gentner [2003] that literal similarity comparisons and higher-order relational mapping between distant domains are a key distinguishing characteristic of human learning and development, often occurring implicitly, not just in the context of explicit analogical reasoning. Moreover, when viewed from the perspective of the cognitive linguistic theory of conceptual metaphor (to be reviewed below), cross-domain mapping can be seen as a phenomenon that pervades human conceptualization. Indeed, it has been suggested that much of human conceptualization involves implicit metaphorical projection from one domain of understanding to another [Johnson, 1987; Lakoff, 1990, 1993; Lakoff & Johnson, 1980, 1999]. Given the extent of cross-domain mapping in the representation of concepts, its acknowledged importance as a source of learning and development, in general, and conceptual change in its narrow sense, in particular, it is hypothesized here that implicit metaphorical projection can be added to the list of possible sources of conceptual change alongside strategically triggered analogical reasoning.

The second feature of research on conceptual change that requires particular attention here is the role of language in the process. Various researchers have identified ways in which language is implicated in the process of conceptual change. A number of points have been made regarding language-related difficulties that students face. It is often noted by researchers adopting diverse perspectives that students demonstrate confusion between the meanings of related terms in an area of science – for example, *heat* and *temperature* [Wiser, 1995]; *force, energy,* and *momentum* [diSessa et al., 2003; Ionnides & Vosniadou, 2002]. Moreover, everyday use of the same term that designates a scientific concept (e.g., *energy, force, heat, temperature, weight*) with a related but subtly different meaning has been noted as a source of misconceptions that need to be addressed in instruction [e.g., Carey, 1992, 1999; Ioannides & Vosniadou, 2002; Lijnse, 1990; Wiser & Amin, 2001]. Ioannides and Vosniadou [2002] have also noted that distinct problems may arise for speakers of different languages, for example, where a number of senses are associated with a single term in one language but are labeled distinctly in another. In an in-depth case study with a single student conducted from a knowledge systems perspective, diSessa, Elby, and Hammer [2003] noted ways in which the student's metalinguistic assumptions can stand in the way of successful conceptual change. For example, the student used technical terms loosely in a way that resembled everyday language use: a term such as *force* was used as if it had multiple senses and terms such as *force, momentum,* and *velocity* that to an expert have precisely distinct meanings were used interchangeably by the student. Solomon [1983b] also noted this parallel in students' use of scientific terms as if they had multiple senses with everyday language use. In addition, diSessa and Sherin [1998], and diSessa, Elby, and Hammer [2003] have suggested that an absence of an adequate commitment to the generality of verbal principles and theory central equations constitute an obstacle to successful conceptual change.

It has also been proposed that language, or propositional structures generally, can play a positive role in aiding conceptual change. diSessa [1993] mentioned the possibility that understanding of formulae and propositions are based on a distributed assembly of p-prims, speculating that initial rote learning of these formulae or propositions may provide a source of top-down coherence, supporting the productive assembly of p-prims. Using coordination class theory, Levrini and diSessa [2008] described how teacher-introduced definitions supported high-school students' application of their developing understanding of the concept of proper time (itself a complex knowledge system) across a wider range of problem contexts while they studied the topic of special relativity.

Absent from all of these suggestions has been an acknowledgement of a role for specific conceptual content coded in language in the process of conceptual change.

In contrast, Carey [2004] has provided an account of preschoolers' development of the concept of number in terms of bootstrapping relying on number names in the counting sequence. And in the context of a discussion of development in children's understanding of matter, Wiser and Smith [2008] have hypothesized that linguistic input as young children interact with objects supports the extraction of common properties of material kind. They suggested that exposure to statements like *This is a plastic spoon* or *This spoon is made of plastic* might invite children to make generalizations over different plastic objects. These are important and interesting specific proposals regarding the facilitating role of language in conceptual change. However, there are good reasons to formulate more general hypotheses regarding the role of language in conceptual development and learning, including conceptual change in its narrow sense. Influential theoretical proposals have been made regarding the importance of the appropriation of language-based construals, including metaphorical construals, in cognitive development. These proposals (to be reviewed below) suggest that classes of language-based construals, in particular verbal metaphor, might also be added to the list of sources of conceptual change.

Two Additional Sources of Conceptual Change

Research on conceptual metaphor has suggested that many abstract concepts are represented metaphorically in terms of other more familiar experiential domains of knowledge, with this metaphorical understanding reflected in vast sets of verbal metaphorical expressions that can be readily identified and organized. Moreover, a number of influential comprehensive accounts of cognitive development have closely examined the role of language in development suggesting that more extensive attention to language as a tool for conceptual change is warranted. These two areas of research will be reviewed in this section and two additional sources of conceptual change hypothesized.

The Metaphorical Representation of Concepts and the Invariance Hypothesis

That many human concepts are represented metaphorically has been *the* central claim emerging from research on conceptual metaphor, a strand of research in cognitive linguistics [see e.g., Fauconnier & Turner, 2002; Lakoff, 1987, 1990, 1993; Lakoff & Johnson, 1980, 1999; Langacker, 1987, 1991]. Broadly, cognitive linguists are interested in identifying how lexical and grammatical options in language are associated with subtle variations in the construal of experience such as differences in attention allocation, figure/ground orientations, generalization, imagistic simulation, and metaphorical mapping. An important empirical finding emerging from linguistic [Lakoff, 1987, 1990, 1993; Lakoff & Johnson, 1980, 1999; Lakoff & Turner, 1989], psycholinguistic [Boroditsky, 2000; Gibbs, 1994, 2006; Gibbs & Colston, 1995; Wilson & Gibbs, 2007], and gesture studies [Casasanto & Lozano, 2006; Roth & Lawless, 2002] is that many concepts might not be understood literally but metaphorically in terms of another domain of knowledge. An important related proposal is that metaphorical understanding is ultimately grounded in embodied experience [Johnson, 1987; Lakoff, 1990, 1993; Lakoff & Johnson, 1999]. This was expressed by Lakoff

[1990] as the *invariance hypothesis:* the claim that the understanding of abstract concepts is ultimately grounded in experiential image schemas.

In their classic book, *Metaphors We Live By,* Lakoff and Johnson [1980] identified what they called structural metaphors, implicit in the organization of a vast number of English sentences. Many conceptual domains seemed to be understood in terms of other domains. An example is the Argument Is War structural metaphor[1], which is implicit in the following sentences listed (among many others) by Lakoff and Johnson:

- Your claims are *indefensible.*
- He *attacked* every weak point in my argument.
- If you use that *strategy,* he'll *wipe you out.*

Rather than view such sentences as simply a matter of isolated instances of figurative language, Lakoff and Johnson pointed out that they reflect a systematic way in which arguments are conceptualized in terms of our understanding of physical conflict – attacking and defending, the success or failure of which will result in gaining ground or retreating, winning or losing and so forth. The claim is that our understanding of physical conflict organizes how we talk about and orient actions regarding arguments. Some examples of the many other structural metaphors identified include Love Is a Journey, Time Is Money, The Mind Is a Machine.

Lakoff and Johnson [1980] went on to argue that what explains the gestalt-like coherence of the source domains and constrains the kinds of mappings between domains of knowledge is generic multidimensional experiential gestalts, later referred to by Lakoff as 'event structure' [1990, p. 57]: their causal structure, temporal structure, event shape, purpose structure, modal structure, and linear scales. Reinforcing Lakoff and Johnson's [1980] conclusions, Lakoff and Turner [1989] found that all of the proverbs and novel poetic metaphors that they studied were organized in terms of this same generic level event structure – that is, causes map onto causes, purposes onto purposes, changes onto changes and so on. In turn, Lakoff [1990] argued that the basic concepts implicated in event structure (e.g., time, cause, change, state, purpose) are themselves understood metaphorically in terms of image-schematic structures. Lakoff followed Johnson [1987] in treating image schemas as gestalt structures that emerge as abstractions from experience, in particular, bodily experience implicating space, motion, and force. In Johnson's words 'image schemata operate at a level of mental organization that falls between abstract propositional structures, on the one side, and particular concrete images, on the other' [1987, p. 28].

Lakoff and Johnson [Lakoff, 1990; Lakoff & Johnson, 1999] presented a rich survey of the basis of our understanding of time, causality, events, self, and mind. They listed a large number of metaphors that reflect the grounding of understanding of basic event structure concepts in the notions of space, motion, and force. These are 'ontological metaphors,' where a type of thing is conceived in terms of a fundamentally different type of thing. Some examples include:

[1] I follow here the convention in the cognitive linguistics literature to refer to conceptual metaphors using capitalized X Is Y statements. This convention indicates that components of the domain X are understood in terms of elements in the domain Y. X Is Y is shorthand for the complex mapping from one domain to the other.

- Attributes Are Possessions (e.g., He *has* a lively spirit)
- States Are Bounded Regions in Space (e.g., I'm *in* love; He's *in* a depression)
- Changes Are Movements into or out of Bounded Regions (e.g., She *fell in* love; He *emerged from* his depression)
- Causes Are Forces (e.g., I was *pushed into* taking the job; He *brought* the water *to* the boil)

In sum, the theory of conceptual metaphor includes the claim that based on a chain of mappings, understanding many abstract concepts relies on image schemas: mappings between propositional knowledge structures (e.g., Argument Is War) where event structure is preserved; then mappings in which the concepts of cause, purpose, time, and so forth that make up event structures are construed in terms of image schemas. This led to the invariance hypothesis: that ultimately, the relational structure of abstract domains derives from the relational structure constituting image-schematic gestalts involving basic nonpropositional experientially based notions of force, space, and motion [Lakoff, 1990]. Thus, a knowledge structure such as War is propositional in the sense that its constituent beliefs are formulated in terms of propositions – for example, 'generals lead their troops to victory.' Grounding an understanding of this belief is the PATH image schema which structures understanding of achieving a purpose in terms of movement along a path.

While linguistic evidence has been dominant in research on conceptual metaphor, what is at stake is an account of concept representation and reasoning. From the beginning, Lakoff and Johnson [1980] presented their work as an analysis of 'general principles of understanding' [1980, p. 116], making the specific claim that 'all of the resources that are used in direct, immediate understanding are pressed into service in indirect understanding via metaphor' [Lakoff & Johnson, 1980, p. 178]. Thus, we find Johnson's [1987] discussion of the image-schematic grounding of logical inference. He has argued, for example, that patterns of logical inference are grounded in the experientially based inferential patterns of 'containment.' For example, the *law of the excluded middle,* that everything is either P or not-P, with no third possibility, derives from our understanding of categories as containers. That is, our intuitive understanding that an object is either *in* or *outside of* a container, with no third possibility, constitutes the basis for the law of the excluded middle. As a theory of concept representation and reasoning, the theory of conceptual metaphor has served as a framework for the investigation of technical understanding in a variety of domains. Examples include mathematics [Lakoff & Núñez, 2000], scientific theories of attention [Fernandez-Duque & Johnson, 1999, 2002], Darwin's theory of natural selection [Al-Zahrani, 2008], and quantum mechanics [Brookes & Etkina, 2007].

Language-Based Construal in Cognitive Development

In the last couple of decades, there have been increasingly forceful claims that language should be seen as a tool for the developing child (or learner, more generally), and not just a tool for the researcher to infer the characteristics of underlying cognitive structures and processes [Budwig, 1999, 2003]. Of course, this idea can be traced at least to the works of Vygotsky [1978, 1986] and Bruner [1964]. Moreover, recent empirical work has provided more support for Vygotsky's claim that language, in the form of inner speech, should be understood as a tool for self-regulation and control over cognitive processes [Berk, 1994; Berk & Garvin, 1984; Bivens & Berk, 1990]. In addition, recent theoretical extensions of Vygotsky's theory have treated the appropriation of patterns of language use (e.g., genres and registers) as an important part of developing culturally valued cognitive skills [Bruner, 1986; Cole, 1996; Rogoff, 2003; Wertsch, 1991], including developing a scientific mode of thought [Bruner, 1986; Mortimer & Wertsch, 2003; Wells, 1999]. However, these extensions do not address the specific challenge of understanding the development of *specific* concepts [see also Gentner, 2003 for a similar point].

A number of other theoretical accounts are more directly relevant [Gentner, 2003; Gentner & Loewenstein, 2002; Nelson, 1996, 2002; Tomasello, 1999]. These views foreground different aspects of the role of language in development, but they all share a commitment to the significance of viewing human ontogeny as embedded within human culture. They emphasize that all human societies have evolved, over historical time, rich and varied ways of construing their experience which they encode in natural languages (as well as other artifacts), and that much of cognitive development needs to be understood as the process, and effects, of appropriating these language-embedded construals.

Drawing on research in cognitive linguistics, Tomasello [1999] drew attention to the vast array of options for the construal of experience embedded in language used to direct attention for particular communicative purposes: language partitions experience into events and participants in them, segmenting the flow of experience into discrete conceptual units; it imposes particular perspectives on these events and participants (e.g., a participant can be construed as *man, father,* or *doctor;* the same event can be construed as *left, relocated,* or *fled,* and, through tense markers, situated in either the past, the future, or the here-and-now), and, most important for the purposes of this paper, language allows for events and participants to be construed in terms of vastly different types of things via metaphor as discussed above. As Tomasello [1999] noted, the significance of learning language is that it 'leads children to conceptualize, categorize and schematize events in much more complex ways than they would if they were not engaged in learning a conventional language, and these kinds of event representations and schematizations add great complexity and flexibility to human cognition' (p. 159).

The perspectival nature of language draws attention to the fact that appropriating a community's ways of construing the world cannot occur through direct interaction with the world. Both Nelson [1996] and Tomasello [1999] have argued that learning these language-based construals must occur in discursive interaction between the child and adult. On their accounts, a variety of elements in the context of discursive activity form the basis for appropriating conventional construals. These include (a) the joint attentional scene itself that forms the sociocognitive basis for interpreting the linguistic symbols used; (b) the fact that different linguistic symbols are often used in the same situation pointing to the need to identify contrasting perspectives on the scene, and (c) the use of the linguistic context itself to provide clues to the intended meaning of a linguistic symbol. In effect, the child appropriates a conventional construal through a process of inference, a bootstrapping process based on these discursive elements.

Working from the perspective of structure-mapping theory, Gentner and colleagues [Gentner, 2003; Gentner & Loewenstein, 2002; Rattermann & Gentner, 1998] provided a closer examination of the mechanisms by which the experience and acquisition of elements of language might affect cognitive development. A learner's direct observation of two similar situations invites comparison via a process that seeks to maximize the structural alignment between representations of the two situations and that often involves the transfer of relational structure between them. Gentner and colleagues suggested that language, in the form of explicit requests to make comparisons or implicitly through the use of a common label, invites comparison of situations that are unlikely to be juxtaposed through direct experience. They have focused on the role of relational language in inviting these more remote comparisons, showing, for example, that young children are more successful at tasks requiring mapping between two situations when spatial relational language is used [Rattermann & Gentner, 1998]. Note that verbal metaphors are a kind of relational language. Bowdle and Gentner [2005] have recently suggested that comprehending verbal metaphors involves aligning two knowledge structures, potentially resulting in the transfer of relational structure from one to another.

This discussion of the role of language in development, and the claim that many concepts may be represented metaphorically brings us full circle to the search for sources of conceptual change. That is, the exposure to and appropriation of relational language, especially verbal metaphors, can be seen as an invitation to establish mappings and engage in transfer of relational structure from one domain of knowledge to another. Of course, establishing the correct conventional mappings is not an automatic process but a process of inference that needs to be understood. That said, the pervasiveness and systematicity of metaphorical construals implicit in language suggests that appropriating these language-based construals may be an important, and previously unacknowledged, source of conceptual change. The following sections attempt to provide support for the plausibility of this hypothesis by examining the case of learning and teaching the highly abstract scientific concept of energy.

From Naïve to Scientific Understanding of the Concept of Energy

A large body of research in science education has addressed how the highly abstract and inherently mathematical scientific concept of energy might be learned. Some progress has been made in characterizing the nature of students' naïve understanding prior to (and often after) instruction. While there are some suggestions that everyday discourse is the source of these naïve ideas, these accounts have not been elaborated. Moreover, there are starkly contrasting views of the nature of the scientific concept of energy in the science education literature. With the *target* of conceptual change in the case of energy not well understood, little progress is being made in understanding the *process* of change and how to induce it via instruction. I argue that a useful contribution to the challenge of understanding the process of conceptual change in the case of the concept of energy can be made by drawing from the theory of conceptual metaphor and views of development that put the appropriation of language use at center stage. Specifically, results of analyses of construals implicit in the use of the noun *energy* in lay and scientific usage are presented. We find that most of the naïve conceptions of energy found in the science education literature are reflected in construals implicit in everyday usage, suggesting that it is exposure to these language-based construals that may be an important source of these naïve conceptions. With the theory of conceptual metaphor as the analytic lens, we find that many of these construals in both lay and scientific usage are metaphorical and grounded in experiential knowledge gestalts. Moreover, we find substantial overlap among the two sets of construals. When viewed from a conceptual metaphor perspective, this overlap, together with the experiential nature of the construals that seem to ground much of scientific understanding of the concept, motivates a hypothesis regarding the nature of the continuity between lay and scientific understanding of energy. Moreover, identifying experiential knowledge gestalts as construals implicit in scientific language, suggests that scientific discourse itself provides the learner with initial clues to constructing an understanding of the scientific concept in terms of conceptual resources already available to the learner.

Science Education Research on Learning and Teaching the Concept of Energy

As with other concepts, science education research has documented that students' ability to solve formulaic, quantitative problems leading to successful performance on school test questions involving the concept of energy does not mean that they have an adequate qualitative understanding of the concept [Driver & Warrington, 1985; Duit & Haeussler, 1994; Goldring & Osborne, 1994]. The difficulty students face can be sensed in the following passage from the famous lectures of the respected 20th century physicist, Richard Feynman:

> There is a fact, or if you wish, a law, governing all natural phenomena that are known to date. There is no known exception to this law – it is exact so far as we know. The law is called the conservation of energy. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same. (Something like the bishop on a red square, and after a number of moves – details unknown – it is still on some red square. It is a law of nature.) [Feynman, Leighton, & Sands, 1963, I, 4-1][2]

Constructivist accounts of how this abstract concept might be learned have begun with an attempt to characterize the learners' naïve understanding of energy prior to instruction. Research has repeatedly identified a diverse collection of naïve understandings of energy among young students [Bliss & Ogborn, 1985; Nicholls & Ogborn, 1993; Solomon, 1983a, b, 1985; Trumper, 1990, 1993; Watts, 1983]. Watts [1983] provided an initial indication of the richness of pre-instruction ideas associated with energy. In this study, he identified a number of alternative frameworks used by 14- to 18-year-olds when asked to decide if 'pictured situations illustrate their concept of energy and to give a reason why' (p. 213). In summing up Watts' findings, it is useful to distinguish the different conceptions of energy and the sorts of things

[2] The sources of quotations from Feynman's lectures are identified with a code indicating volume, chapter, and page number in which the quotations appear. Pages are numbered in this way in these lectures.

to which students apply these conceptions. Watts identified six different conceptions of energy: (a) energy as a causal agent that an object has stored within it, which is needed for activity; (b) energy as an 'ingredient,' the release of which can be 'triggered' somehow; (c) energy as overt activity or movement, not its cause; (d) energy as the output or byproduct of some process; (e) energy as a generalized fuel that makes things go, and (f) a 'flow-transfer model of energy' [Watts, 1983, p. 216] commonly taught in schools where energy is understood as a material-like entity that is 'put in,' 'given,' 'transported,' and 'conducted.' Watts' findings included the additional observations that students tend to associate the notion energy with human beings or other things which they treat as having human-like attributes and that 'energy as a generalized fuel' is associated with running appliances and other technological devices important for human comfort. Watts pointed out that in his study the same children often exhibited more than one framework and thus warned against attempting to classify a given child's understanding in terms of a single framework.

Other studies have reinforced the picture of naïve understanding of energy as a collection of different conceptualizations, with strong preferences for applying them to human beings, human-like entities, and technological devices [Bliss & Ogborn, 1985; Nicholls & Ogborn, 1993; Solomon, 1983a, b, 1985; Trumper, 1990, 1993]. The frameworks described by Watts formed the basis for Trumper's [1990] analysis of Israeli high-school students' (9th, 10th and 11th graders) verbal contributions to a discussion triggered by showing pictured situations such as melting ice, a man eating, and a man in the snow, and then asking the question 'Is there energy here?' While two conceptualizations ('energy as causal agent' and 'energy as product') were particularly frequent, individual students of all ages produced responses that spanned the majority of Watts' conceptualizations with the exception of 'energy as ingredient.' Trumper [1993] also found a similar range of conceptualizations with groups of children at each grade between grades 5 and 9. Solomon [1985] identified a tendency on the part of many 4th graders to talk about 'sources of energy' often expressing the view that 'energy could suddenly erupt out of something which did not itself have energy' (p. 166). This constitutes evidence for the conceptualization of 'energy as an ingredient' absent in Trumper's later [1990, 1993] studies.

In both these studies, Trumper [1990, 1993] found energy to be frequently associated with human beings but rarely with machines and other technological devices. The association with human beings declined between grades 5 and 9 [Trumper, 1993]. In Bliss and Ogborn's [1985] study, 13-year-old girls considered energy to be 'needed' or 'used' in pictured situations presented to them where there was an 'obvious display of activity,' often associated with some animate entity. In a free writing task given to 1st, 2nd, and 3rd grade comprehensive school students, Solomon [1983a] also found associations of energy with human beings (e.g., we need energy to live; we need energy to move). However, she also found nonhuman associations: 'machines of various sorts … working because of an input from electricity or some fuel' and the idea that there is a shortage of energy that is consumed and leads to concern about the future. Nicholls and Ogborn [1993] analyzed 11- and 13-year-old student evaluations of the acceptability of applying certain designations to various entities. For both age groups, the analysis revealed a pattern of designations in which 'it needs energy' and 'it uses up energy from other things' are associated frequently with living things and energy-using devices, while the designations 'we can get energy from it,' 'it can pass on energy' and 'it is energy' are associated frequently with foods/fuels and natural phenomena.

Overall, studies have consistently shown that students have a range of naïve conceptualizations that are selectively evoked given the method employed to elicit their understanding and the entities appearing in the situations they are considering. There is a strong association of energy with living things, especially human beings, that decreases with age. Energy is also seen to be associated with technological devices that support human activities, food and fuels, and situations that display some kind of activity including natural phenomena. Where do these naïve ideas about energy come from?

Discussions of the source of these naïve ideas have focused on the content and form of everyday discourse [Lijnse, 1990; Solomon, 1983b, 1985]. Lijnse [1990] suggested that pupils' initial ideas reflect how energy is conceived in written documents for the general public. Based on a qualitative analysis of pamphlets, reports, and newspaper articles, Lijnse [1990] summed up the conception of energy identified as follows: 'energy is something "material" (fuels or a kind of fuel) which has limited availability, which is used or consumed for our benefit and is lost in that process, and which therefore must be dealt with carefully' (p. 577). Lijnse [1990] listed a few examples of phrases and sentences reflecting this conception and noted what he considers to be a striking similarity with the frameworks identified by Watts [1983]. Lijnse's [1990] description of naïve understanding of energy reflected in everyday documents incorporates Watts' frameworks (a) and (e): 'energy conceived as a causal agent that an object has stored within it, which is needed for activity,' and 'energy conceptualized as a generalized fuel that makes things go.' However, it does not capture other frameworks of understanding identified by Watts and others.

Similarly, Solomon [1983b] traced the diversity and occasional contradictory nature of naïve conceptions of energy to the conceptual content as well as the form of everyday discourse. She commented: 'informal meanings are not only different from the tight definitions of science, they are also various and multipurpose' (p. 225), elaborating that 'socially acquired meanings are not consistent and logical; they more resemble maxims like "Too many cooks spoil the broth" – true for soup-making but not for peeling large quantities of potatoes. This kind of familiar general knowledge is always situation-bound, and quite unlike the coherent world view that we aim for in science' (p. 227). She gave examples of contradictions tolerated by 4th grade students with regard to whether or not you *gain* or *lose* energy by exercising. In a class vote, a large number of students thought that both were possible. In addition, Solomon [1983b, 1985] has argued that naïve understanding of energy is 'strongly causal' [Solomon, 1983b, p. 52] referring to the kind of direct, mechanistic causality reflected in beliefs such as 'friction is the cause of heat energy,' whereas scientific understanding involves reasoning in an abstract, symbolic realm.

These suggestions for tracing the naïve conceptualizations of energy to everyday discourse are reasonable and are consistent with the general claim regarding the importance of the appropriation of language-based construals to development [Gentner, 2003; Nelson, 1996; Tomasello, 1999]. However, Tomasello's discussion of the range of construals language invites us to adopt, and in particular, the ubiquity of conceptual metaphor as a basis for understanding abstract ideas suggests that more could be said about the contribution of everyday discourse as a source of naïve understandings of energy. I return to this issue at the end of this section in light of results of a systematic analysis of everyday use of the noun *energy* carried out from the perspective of the theory of conceptual metaphor.

This review of the science education literature on the concept of energy continues with a focus on the attempt to characterize the nature and target of conceptual change. Given the naïve understandings of energy reviewed above, how does the learner come to understand the abstract, mathematical concept of energy? Tracing the naïve understanding of energy to everyday discourse, Solomon [1983b, 1985] and Lijnse [1990] characterized the learning challenge by drawing a distinction between two discursive domains, the everyday and the scientific. Solomon [1985] suggested that because the multiple and often contradictory understandings are grounded in everyday discourse, it is unrealistic to view learning the coherent, symbolic scientific understanding in terms of the eradication of the naïve view. Instead, we should expect that both will coexist, and so, acquiring the new understanding 'implies the need both for learning and discrimination' between two domains of understanding [Solomon, 1983a, p. 228]. Similarly, Lijnse [1990] suggested that the specific learning challenge in the case of the concept of energy derives from the challenge of bridging from the life world to scientific thinking where 'ultimately, energy can only be framed as a mathematical abstraction' [Lijnse, 1990, p. 571].

Both Lijnse [1990] and Solomon [1985] rejected a view of learning the scientific concept of energy as eradication of the naïve view, and both see the learning challenge as acquiring the abstract understanding of the concept, and then flexibly applying the appropriate conception in everyday and scientific situations. While Lijnse and Solomon accept that everyday ideas are not eradicated in the process of learning, there is little attention to any continuity between naïve and scientific understanding. Thus, the bootstrapping problem looms large in these accounts of learning the scientific concept of energy.

There have been some piecemeal attempts to bridge between naïve and scientific understanding of energy. Some attention to continuity is found in Trumper's [1990, 1991] research on teaching the scientific concept of energy. Trumper has focused on helping students to extend their naïve conceptualizations of energy beyond situations they perceive as human-like or animate and to coordinate their use of 'energy as causal agent' and 'energy as product' conceptions. Trumper acknowledged that these dominant features of students' naïve conceptions are not incorrect as much as limited. Learning will involve refinement in the use of naïve conceptions. Some continuity between naïve and scientific understanding of energy has also been noted in the similarity between students' understanding of energy as stored and consumed with the idea of energy degradation represented in the second law of thermodynamics [Duit & Haeussler, 1994; Ogborn, 1986]. This has led some to suggest the second law as an appropriate entry point for teaching the concept of energy [Goldring & Osborne, 1994; Solomon, 1985].

A more comprehensive attempt to conceive of a continuous learning trajectory between the naïve and scientific concept of energy has involved a proposal to reconceptualize the scientific concept itself as a substance-like entity for pedagogical purposes [Duit, 1987; Schmidt, 1982]. Schmidt [1982] reports on a comprehensive approach to teaching physics from this perspective. In this approach, energy is seen as a substance-like entity that: can be contained and thereby stored in some system; can flow from some source to a receiver; this flow is via some other substance-like entity which can be referred to as a 'carrier'; when a substance is received into some container it can then function as a source, thereby functioning as a point in a chain of energy exchanges. The conservation of energy on this view is understood as the conservation of a substance-like entity. However, to capture the principle that processes in nature are not reversible, Schmidt includes the notion of energy loss noting that this energy is called heat.

Duit [1987] has championed this quasi-material conception of energy. He has argued that treating energy as a substance-like notion is justifiable on the grounds that such a notion has played a productive role in the history of physics, even after the substance-like notion of heat as caloric was abandoned and the mathematical law of conservation of energy proposed. He also considers the notion to be justified on pedagogical grounds given its greater concreteness and its resemblance to the everyday notion of energy, which would need to be referred to anyway in the context of constructivist pedagogical approaches.

Duit [1987] did acknowledge two limitations. One difficulty is that it is not appropriate to interpret energy transformations in terms of a notion of substance that maintains some integrity across these transformations. Second, the notion of *transport* in the analogy is problematic given that descriptions of the transport of energy sometimes need to be decoupled from the nature of the movement of the entities that would be considered carriers. Despite these limitations, Duit suggested that we treat the limitations of the scientific validity of the analogy as pedagogical challenges, helping students become aware of the limitations of the conception as is the case with any analogy. Duit noted further that the gap between a quasi-material conception and the abstract mathematical nature of the concept of energy can be bridged through an additional analogy of energy to money. Indeed Kaper and Goedhart [2002a, b], working in the domain of thermodynamics, have suggested that limitations in the formulation of scientific concepts for pedagogical purposes are warranted as long as the formulation is sufficiently valid given some specified range of phenomena and sufficiently consistent such that it can be subjected to empirical testing by students.

What are seen by Duit as minor limitations to be addressed pedagogically as unproductive aspects of an analogy are, to Warren [1982, 1986], an unacceptable corruption of the inherently abstract, mathematical nature of the scientific concept of energy. This substance-like understanding of energy is strikingly at odds with the abstract, mathematical concept as described by Feynman, leading Warren [1982, 1986] to suggest that the concept should not be taught at the elementary level. Similarly, Lijnse [1990] has insisted on this abstract conceptualization of energy in physics, emphasizing that the concept needs to be very precisely defined and demarcated from other notions, even questioning the possibility of expressing the necessary notion linguistically.

Thus we find an impasse in the attempt to conceive of a learning trajectory between many naïve, mechanistic conceptions of energy and energy as an abstract, mathematical quantity conceived through the symbolically rigorous discourse of science. I suggest that some progress can be made if it is recognized that abstract concepts are understood in terms of multiple, experientially grounded metaphors structuring understanding of different aspects of the concept. The rest of this section seeks to enrich attempts to trace naïve understanding of energy to everyday discourse and to characterize the nature of the scientific concept such that the continuity between the naïve and scientific concepts can be recognized. Conceptual metaphor analyses of the lay and scientific use of the noun *energy* contribute to both objectives.

Table 1. Construals of energy in everyday discourse

Domains of use	Construal types	Examples
Domain 1: Reference to energy in relation to human technological needs	*Literal* Materials like coal, oil, nuclear material are sources of energy	Coal and nuclear power will be the most 'readily available' energy *sources* when oil reserves start to run out
	Material resource schema	And as we 'progress' towards the twenty-first century we are rapidly *consuming* all the *stores* of energy Council bid to *save* energy Under this agreement Russia would provide oil, natural gas and nuclear energy in *exchange* for meat, milk and dairy products
	Metaphorical More energy is up and less energy is down	Another important factor will be the increase in the number of fuel efficient or '*low* energy' houses
Domain 2: Reference to consumption of food and associated energy intake	*Literal* Foods are sources of energy	Some fat is necessary to supply the body with a ready *source* of energy
	Material resource schema	It is the total *amount* of energy *consumed* that is important and there are no specifically 'fattening' foods *Stores* and releases energy *to help you* run faster
Domain 3: Reference to human activity and vitality	*Literal* Energy is human activity (energetic state)	It was almost *superfluous after the loud cheering* … for Calthorpe to assure his fellow abolitionists that victory was certain *if other members … showed similar energy*
	Metaphorical Object event structure metaphor Energetic state is a possession Change in energetic state is movement of possession Caused change in energetic state is transfer of possession	She has never *got much* energy in the morning as you know When they feel *drained of* spiritual energy the students go there and lie on the floor The fame thing … isn't where creative energy *stems from*
	Elaborations of object event structure metaphor Energetic state as amount of material in a container Energetic state as a resource Force dynamic structuring of transfer of energy	He appeared happy, *full of* energy and suppressed excitement He's been living on his *reserves* of nervous energy But while Clinton *is bursting with* energy now, what toll will the next four years take if he enters the White House?
	Extension of object event structure metaphor to collective human activity and institutional practices	… the notion British fiction *lacks* experimental energy, or even just quality, still survives … much energy and organization has been *diverted from* politically motivated activities
	More energetic is up; less energetic is down	… it represents the *lowest state* of emotional energy, as well as physical and mental energy

Conceptual Metaphor Analysis of the Lay and Scientific Concept of Energy

In this section, I summarize an analysis of the lay and scientific use of the noun *energy* from the perspective of conceptual metaphor theory which claims that many abstract concepts are understood metaphorically with systematic mappings reflected in patterns of metaphorical expressions, and that this understanding is ultimately grounded in experientially based knowledge gestalts. Thus, the objective of this analysis was to identify the sets of experiential knowledge gestalts that are reflected in the lay and scientific use of the noun *energy*. The contribution of these findings to the challenge of understanding conceptual change in the case of the concept of energy is then discussed.

The analysis of lay usage is based on a random sample of 200 sentences from the British National Corpus (BNC) in which the noun *energy* appears. The BNC is a 100-million-word database of written and spoken language representing current British English. Sentences originating from a technical scientific treatment or appearing in the title of an organization or institutional position of some kind were not included in the analysis. Thus, these sentences are considered to be representative of those to which English-speaking students are exposed in their everyday life. The analysis of scientific usage is applied to sentences drawn from *The Feynman Lectures on Physics, Volumes 1 and 2* [Feynman et al., 1963]. The raw data consisted initially of 150 sentences selected randomly from a larger sample compiled based on identifying all sentences including the word energy in chapters dealing with the topic of energy. Categories of construals were identified, then additional sentences from the larger sample were considered. This process continued iteratively until no new construal categories were identified.

Analysis of the BNC sample revealed three distinct categories of sentences which I will refer to as *domains of use* (see table 1 for the results of the analysis with examples) involving reference to energy in relation to: (a) human technological needs; (b) the consumption of food and associated energy intake, and (c) energy construed in relation to human activity and vitality. Note first some literal construals that do not involve understanding energy in metaphorical terms. Materials such as oil, coal, nuclear material, as well as food items are understood as sources of energy. Also, a 'material resource schema' was found to underlie many uses of the noun *energy* in the first two domains. This knowledge structure incorporates the ideas that a certain material can be stored, quantified, have a value assigned to it, and be used up as some valued purpose is achieved [Lakoff & Johnson, 1980, p. 65]. Another literal construal, which appears only in the domain of human activity, is the construal of energy as activity itself. No metaphorical construals were identified in the second domain. While a metaphorical understanding of energy was identified in the first domain (More Energy Is up; Less Energy Is down), metaphorical understanding was the dominant mode of understanding in the third domain (human activity and vitality). The variety of metaphorical expressions in this third domain can be seen as reflecting the Object Event Structure conceptual metaphor as well as elaborations and extensions of it.

The Object Event Structure conceptual metaphor with its submappings was described in detail by Lakoff and Johnson [1999]. Some of the submappings of this important metaphor are:

- Attributes Are Possessions (e.g., I *have* a headache)
- Changes Are Movements of Possessions (acquisitions or losses, e.g., I *got* a headache; The headache *went away*)
- Causation Is Transfer of Possessions (giving or taking, e.g., The noise *gave* me a headache)

Examples from the BNC sample reflecting the use of this conceptual metaphor in construing human activity are included in table 1 [see e.g., *has got much energy* (Possession), *drained of energy* (Movement of Possession), and *energy stems from* (Transfer of Possession)].

Once energy is understood as a possession, this construal can be further elaborated in various ways. It can be conceptualized as contained in the person (e.g., *full of energy*); it can be conceptualized further as a resource (e.g., *reserves of energy*) and with the substance contained displaying force dynamic properties [Talmy, 1988], namely, that it is under pressure in the body container with the tendency to emerge from it (e.g., *bursting with energy*). The Object Event Structure metaphor is also extended to situations where the activity that is construed involves collective human activity and institutional practices, as in 'British fiction *lacks* energy' and 'energy *diverted from* politically motivated activities.' Finally, we find the More Energetic Is Up; Less Energetic Is Down metaphor (e.g., *lowest state of emotional energy*).

The results of the analysis of scientific use of *energy* are summarized in table 2. All of these are metaphorical. We saw in the passage quoted earlier that in his attempt to be as careful as possible in clarifying what energy is, Feynman limited himself to pointing out that it is a quantity that does not change despite the many changes taking place in nature. That is what we understand about the *nature* of energy. There is no concrete mechanism whereby the conservation of energy can be understood. However, analysis of Feynman's use of the noun *energy* reveals how he himself, in the very same text in which he insists on the abstract nature of the concept, recruited conceptual metaphor to make sense of it. There are four key aspects to the scientific concept of energy [Duit & Haeussler, 1994; Feynman et al., 1963]: (a) components of a system can gain or lose energy (transport); (b) energy can manifest itself in different forms – for example, gravitational energy, kinetic energy (transformation); (c) bookkeeping that keeps track of the quantities of energy gained, lost, and transformed reveals that for a specified isolated system the total amount of energy is constant (conservation), and (d) although energy is always conserved, some forms of energy are more useful to us than others (degradation).

The analysis was organized in terms of these four aspects of the scientific concept, referred to as domains of use in table 2 to parallel the terminology used in the case of lay usage. Taking the first domain, *transport,* we find that the metaphorical expressions can be organized in terms of the Object Event Structure metaphor and a straightforward elaboration of it in terms of containment. In this case, we find reference to the fact that an object *has* energy (Energetic State Is a Possession), an atom *gains* or *loses* energy (Change in Energetic State Is Movement of Possession), and energy will be *given to* some material (Caused Change in Energetic State Is Transfer of Possession). The elaboration in terms of containment is seen in references to the 'possessor' of energy as having energy 'in' it, or 'put into' it.

Moving to the second domain, we find that the Location Event Structure conceptual metaphor as well as the resource schema and force dynamic elaborations of this schema are utilized to make sense of energy transformation. The Location Event

Structure conceptual metaphor is a second set of mappings identified by Lakoff and Johnson [1999] as structuring our understanding of events. Some of the submappings that constitute this metaphor are:

- States Are Locations (e.g., I'm *in* love; He's *in* a depression)
- Changes Are Movements (e.g., She got *out of* this mood she's *in*; He *fell in* love)
- Causation Is Forced Movement (e.g., The defeat *sent* the crowd into a frenzy)

The understanding of energy transformation in terms of the Location Event Structure Metaphor is revealed in references to energy being *in* some form (Form of Energy as Location) and energy *going back and forth between* forms of energy [Changes in Form of Energy Are Movements into (out of) Containers]. The understanding of energy *in* some form is further elaborated to include understanding it as a resource, for energy is 'stored in inductance,' for example (Energy in Some Form Is a

Table 2. Construals of energy in scientific discourse

Domains of use	Construal types	Examples
Domain 1: Transport	*Metaphorical*	
	Object event structure metaphor	
	Energetic state is a possession	… gravitational potential energy – the energy which an object *has* because of its relationship in space, relative to the earth (I-4-4)
	Change in energetic state is movement of possession	It either *gains* or *loses* energy, depending upon whether the piston is moving one way or another when the atom strikes (I-39-7)
	Caused change in energetic state is transfer of possession	How much energy will they have *given to* the material when they have stopped? (I-16-9)
	Elaboration of object event structure metaphor in terms of containment	
	Energetic state as content of a container	… the potential energy *in* an electric field is just charge times this quantity (I-14-9)
	Change of energetic state as movement into (or out of) a container	… when we *put* energy *into* the gas its molecules move faster and so the gas gets heavier (I-16-8)
Domain 2: Transformation	*Metaphorical*	
	Location event structure metaphor	
	Forms of energy are locations/ containers	We can continue to illustrate the existence of energy *in* other forms (I-4-6)
	Changes in form of energy is movement into (out of) containers	… the elastic energy … is converted to kinetic energy and it *goes back and forth between* compressing and stretching the spring and the kinetic energy of motion (I-4-6)
	Energy in some form is a resource	Therefore, the energy *stored in* an inductance is … (II-17-12)
	Force dynamic elaboration of resource schema	
	Counterforce	… all we would have done would be to *extract* energy *from* the reservoir at T2! (I-44-6)
	Removal of restraint	When we burn gasoline energy is *liberated* because the potential energies of the atoms in the new atomic arrangement are lower than the old arrangement (I-14-7)

Table 2 (continued)

Domains of use	Construal types	Examples
Domain 3: Conservation	*Metaphorical* Energy state as amount of substance	… ΔQ is the *amount of* heat energy added to the gas as it expands isothermally at temperature T … (I-45-2)
	Energy as object located/moving on linear scale	When we try to push the atoms very close together the energy *goes up* very rapidly, because they repel each other (I-14-7)
	Location event structure metaphor Energy states are locations (on a vertical scale)	When the two oxygen atoms have settled down … they *are in the lowest* energy state … (I-14-5)
	Energy state changes are movements	Therefore the frequency of the light which is liberated in a *transition from* energy E3 *to* energy E1 (for example) is ... (I-38-7)
	Causing energy state change is forced movement	The operation of a betatron – a machine for *accelerating* electrons *to high* energies – is based on this idea (II-17-4)
	Energy construed in terms of part-whole schema	It is not always easy to *separate the total* energy of a thing *into two parts,* kinetic energy and potential energy, and such a *separation* is not always (I-14-6) … so we *put the two together* and say that the *total* kinetic energy inside an object is *partly* heat, *partly* chemical energy and so (I-14-6)

Resource). The conceptualization of energy as a resource incorporates the idea that there is some goal achieved or desired. The construal of energy as contained in objects, states, or processes combines with this emphasis on goal in conceptualizations that involve various force dynamic schemas: either energy is conceptualized as resisting being available for use and a force is required to counteract that resistance (Counterforce) – for instance, energy is *extracted from* some form; or some restraint is removed to let loose energy, the resource with an inherent tendency to make itself available for use but otherwise restrained (Removal of Restraint) – for example, energy is *released* or *liberated*.

Another very important aspect of the concept of energy, if not *the* aspect of central significance, is that it is a quantity that is conserved despite the many interactions taking place within a system. That energy is quantified and that various quantities need to be understood as adding up to some conserved total quantity is made sense of through a variety of conceptual metaphors. We find Energy as Amount of Substance (e.g., *amount* of energy added to) and Energy as an Object Located/Moving on a Vertical Scale (e.g., energy *goes up*). Here again we find the Location Event Structure conceptual metaphor, but now with a figure/ground reversal. Energy transformation was construed in terms of this metaphor. In that case, energy was construed as an object moving from one location to another. Here, in contrast, we find that energy state is the location and objects move with respect to *it*. So we find reference to oxygen atoms being 'in the *lowest* energy state' (Energy States Are Locations), electrons making *transitions from* one state *to* another (Energy State Changes Are Movements) and *accelerating* electrons *to high energies* (Causing Energy State Change Is Force Movement). The last conceptual metaphor identified structuring understanding of energy conservation is the construal of amounts of energy in terms of a part-whole schema. Feynman wrote of '*separating* total energy' of something 'into parts,' these 'parts' can be 'put together' and so on.

The fourth aspect of the concept of energy, degradation, refers to the idea that while energy is always conserved in an isolated system, processes spontaneously take place such that there is a decrease in the usefulness of the energy. Trying to identify what conceptual metaphors are involved in understanding degradation draws attention to the limitations of an analysis limited to the noun *energy*. A key omission from this analysis has been the recognition that understanding a concept will depend on other concepts which themselves are likely to be metaphorically structured. A more extended conceptual metaphor analysis addressing this fourth aspect and other details of the metaphors discussed above is a work in progress.

Implications for an Account of Learning the Lay and Scientific Concept of Energy

The implications of this analysis of lay and scientific use of the noun *energy* from the point of view of the theory of conceptual metaphor for understanding conceptual change in the case of the concept of energy can now be considered. The analysis enabled the identification of a range of experiential knowledge structures implicit in lay and scientific usage. These findings motivate a number of hypotheses regarding the source of naïve understanding and the process of change toward scientific understanding. First, with regard to naïve understanding, all of the conceptions identified in prior research on pre-instruction understanding of energy emerged in the analysis of lay usage. The majority (see Watts' frameworks a–f) map fairly neatly onto the literal construals identified in the analysis described above: that materials such as coal and oil, as well as foods are sources which can release energy and that these materials and the energy they contain constitute a resource to achieve desired purposes often involving some kind of activity (i.e., either of a machine or of a human being) with activity itself sometimes considered to *be* energy. In addition, a range of metaphorical conceptualizations were identified, particularly in relation to human activity and vitality, often involving cultural and institutional practices. These were organized as reflecting the structuring of the Object Event Structure metaphor and elaborations and extensions of it. While it has sometimes been noted in the literature that students reveal a kind of material-like understanding of energy as something that an entity 'has,' can be 'put in' and 'given to' [see e.g., Watts, 1983], these have been attributed to encounters with simplified presentations at the early stages of schooling. The analysis presented here shows that such notions are extensively used in everyday discourse as well.

Overall, this analysis supports claims that everyday discourse is the source of many naïve conceptions of energy [Lijnes, 1990; Solomon, 1983a, b, 1985]. However, drawing on tools from the theory of conceptual metaphor, it suggests that many conceptualizations are actually metaphorical. Moreover, we find that the vast majority of the sentences in lay usage can be seen as reflecting either a resource schema (used literally and metaphorically) or the Object Event Structure conceptual metaphor with elaborations and extensions. Thus, a certain degree of coherence can be noted underlying apparently diverse everyday use of the noun *energy.*

The case of the pre-instruction understanding of energy thus supports the general claims regarding the important role of language in the child's appropriation of culturally sanctioned ways of construing experience [Nelson, 1996; Tomasello, 1999]. It is worth noting that the lay understanding of energy itself has quite abstract elements where conceptualizations cannot be attributed to direct experience of objects and processes in the world. It is possible that literal conceptualizations of energy can derive from direct experience of materials and the uses to which they are put. However, many construals of energy are associated with attempts to understand human emotions and motivation, as well as institutional and cultural practices. Understanding these aspects of human experience in terms of energy itself requires a bootstrapping account in terms of already available conceptual resources. Everyday understanding in these cases seems to involve metaphorical structuring drawing on knowledge gestalts that are themselves derived from direct experience such as the material resource schema, possession of objects, movement of possessed objects, containment, and force dynamic construals. It is language, in the form of the vast collection of verbal metaphorical expressions, that invites the layperson to adopt such construals of human experience and practices.

Based on the analysis of scientific usage of the noun *energy,* and in conjunction with the findings from the analysis of lay usage, a number of hypotheses can be formulated regarding the nature of the scientific concept and the process of conceptual change. The analysis of the scientific use of the noun *energy* revealed sets of conceptual metaphors associated with different aspects of the concept of energy: energy transport, transformation, and conservation. These findings from the analysis of Feynman's text (table 2) translate into specific hypotheses that various subconceptual experiential knowledge gestalts are drawn on to ground understanding of different aspects of this scientific concept. These hypotheses require further independent confirmation in expert reasoning and problem-solving studies. However, they provide a way to conceptualize the nature of the scientific concept of energy that constitutes a useful alternative to either emphasizing the abstract, mathematical nature of the concept or accepting a quasi-material conception for pedagogical purposes.

The findings suggest that what is insisted on as a very abstract concept seems to be understood in terms of projections from experiential knowledge structures. It might seem then that what has been identified in Feynman's text is precisely the quasi-material conception of energy advocated by Duit [1987] and others. The difference between that view and the one advocated in this paper can be appreciated as the difference between a rich image and understanding structured in terms of multiple image schemas (via metaphorical projection) for different purposes. While both rich images and image schemas are analogical representations, the latter are more abstract knowledge gestalts that preserve only the topological relational structure of the experiences from which they are derived. Recall the image schema of containment discussed earlier. This schema includes three elements: inside, outside, and the boundary between them. As noted earlier, Johnson [1987] suggested that it structures our understanding of the notion of the law of the excluded middle, that everything is either P or not-P, with no third option. It is the abstract structure of the image schema that allows it to function in this way. Having a concrete image of something in a container is very different. The object contained could be in one of many locations in the container, including, for example, near its opening if it had one making it difficult to judge whether it is in or out of the container. No ambiguity of this kind arises with an image schema. Hence, the emphasis in this account is on the idea that it is the topological structure of an image schema that structures understanding.

When we say that energy can be conceptualized as possessed or contained, its possession lost or gained, or that it moves into or out of a container, there is no suggestion that some rich image can be constructed. As seen earlier, the scientific understanding of the transfer of energy from some object A to another B is sometimes structured in terms of the abstract topological structure of the image schema of transfer of possession. The gestalt simply includes the notion of the possessor A, the possessor B, the entity possessed, and the vector indicating which is the source and which is recipient of the transferred entity. Such a gestalt does not sanction the questions: Where was the energy on the way from A to B? What was the path taken by the transferred energy? How quickly did the transfer happen?

What then does it mean to say that understanding a concept can be structured in terms of multiple image schemas, how does the structuring by each image schema relate to the next, and how is coherent understanding of a concept possible? Lakoff and Johnson [1980] discussed two metaphors that structure different aspects of the concept of argument: An Argument Is a Journey (e.g., We *have arrived at* a disturbing conclusion), which primarily structures *the progress toward a goal* aspect of argument, and An Argument Is a Container (e.g., I'm tired of your *empty* arguments), which primarily structures the content aspect of the concept. Lakoff and Johnson explained that these metaphors cohere in that the entailments of the two metaphors overlap. That is, as we proceed in a journey more of a surface of the ground is traversed and as we make a container more of a surface is created. Thus, both metaphors overlap in the entailment that as we make an argument more of a surface is created. This overlap renders certain mixed metaphors coherent. For example, 'if we keep going the way we are going we can fit all of the facts in' is coherent since as the surface of a container gets larger the container can hold more [see Lakoff & Johnson, 1980, p. 93, for this and other examples]. Lakoff and Johnson [1980] pointed out, however, that coherence across metaphors does not imply that a consistent image can be evoked:

> It is this overlap of entailments between the two metaphors that defines the coherence between them and provides the link between the amount of ground the argument covers and the amount of content it has. This is what allows them to 'fit together,' even though they are not completely consistent, that is, there is no 'single image' that completely fits both metaphors. The surface of a container and the surface of the ground are both surfaces by virtue of common topological properties. But our image of ground surface is very different than our images of various kinds of container surfaces. The abstract topological concept of a surface which forms the overlap between these two metaphors is not concrete enough to form an image. In general when metaphors are coherent but not consistent, we should not expect them to form consistent images. (p. 94)

We can apply this argument to the scientific concept of energy discussed here. For example, a physicist can make sense of the sentence 'the potential energy lost went into kinetic energy' relying only on the inferences associated with possession and containment. Two metaphors are implicated here: Change in Energetic State Is Movement of a Possession and Change in Form of Energy Is Movement into Containers. The coherence in this case can be recognized by noting that the schema of an entity moving into a container is a more specific instance of the schema of acquiring a possession; the container can be said to 'have' the entity contained in it. Therefore, in this sentence kinetic energy, construed as a container, also plays the role of the recipient in a *transfer of possession* schema. Because *movement into a container* is a more specific instance of *transfer of possession,* all the entailments of the latter are shared by the former: for example, that which has been transferred to a recipient is no longer possessed by the source. We can get a quick glimpse then of the role that the gestalts of *transfer of possession* and *movement into a container* might play in the bookkeeping involved in reasoning about energy exchange and conservation. However, there is no suggestion that what is involved is a rich image of a substance-like material moving along some imagined path from the object to the kinetic energy.

This has important consequences for the position taken in the energy-as-quasi-material-substance debate. Recall the problems with the analogy of energy as material substance noted by Warren [1982] and acknowledged by Duit [1987]: that the notion of transformation of energy is hard to understand in terms of substance-like entity that maintains its integrity, and that the particulars of transport, such as direction, sometimes need to be decoupled from the direction of the objects or process associated with the transport. The problems with the material-substance analogy noted by Warren and Duit derive from expectations that understanding is based on invoking an internally consistent rich image. These problems dissolve when we recognize that metaphorical understanding and reasoning need to be characterized in terms of the topological features of image schemas and the inferences they entail.

With regard to the process of conceptual change, a number of proposals can be put forward. The analyses of lay and scientific use of the noun *energy* together point to a bootstrapping account of learning the scientific concept that relies on two sources. First, the analysis of scientific usage of *energy* identifies many experiential knowledge gestalts that can be assumed to be available in the learner's repertoire (e.g., resource schema, possession, movement of possession, forced movement, containment, and part-whole schema) either because of their nature as experiential knowledge gestalts that can be assumed to have been formed earlier through direct interaction with the physical world (granting possible contributions from innate predispositions), or because similar conceptualizations were identified in lay usage as well. Particularly notable is the use of the resource schema in both lay and scientific usage, with the schema serving as a source domain for metaphorical projection in both cases. Also, the Object Event Structure metaphor systematically structures conceptualization in both domains. Second, because scientific language itself implicitly codes experiential knowledge gestalts, the patterns of verbal metaphors in scientific language constitute invitations to the learner to adopt such construals. Thus, the suggestion is that just as everyday language seems to be the source of naïve understanding, scientific language itself provides clues to scientific understanding in terms of conceptual resources available to the learner. Whereas Lijnse [1990] and Solomon [1983b, 1985] emphasized the distinctions between everyday and scientific discourse as an obstacle to conceptual change, the continuity between the two and the positive contribution of scientific language itself is noted here. In light of this discussion of the concept of energy, the general hypotheses of this paper gain plausibility: it thus seems plausible to view the metaphorical, experientially grounded representation of many abstract concepts and language-based construal as additional sources of conceptual change.

The discussion of the literature on learning and teaching the scientific concept of energy above showed that these hypotheses constitute a small contribution to a complex theoretical challenge. These hypotheses can be seen as invitations to researchers: to validate and specify the role of the proposed experiential knowledge gestalts in scientists' understanding of energy; to examine the process of appropriation of language-based construals in contexts of science instruction; to explore productive instructional strategies implied by the experiential grounding of scientific understanding of energy. These themes are addressed briefly in the next two sections in the context of a discussion of how the present view relates to others in the literature and the general research and pedagogical implications motivated by it.

Language, Grounded Conceptual Metaphors, and Conceptual Change

This paper began with a discussion of the challenge of identifying sources of conceptual change in its narrow sense, where concepts themselves change – not simply the beliefs defined over them. The case of energy discussed in detail in this paper suggests that developing an understanding of an abstract concept may rely extensively on metaphorical projection from experiential knowledge gestalts and that these projections are invited by verbal metaphors pervasive in both everyday and scientific language. Three features of the present account help clarify how it relates to others in the literature. First, the image-schematic knowledge gestalts – such as possession, movement of possessions, containment, and part-whole – that structure (via metaphor) our understanding of abstract concepts are abstractions from (often bodily based) experience. That is, conceptual metaphors are said to be *grounded in experience*. Second, the findings of the conceptual metaphor analysis of *energy* presented here supported Lakoff and Johnson's claim that many abstract concepts are structured by *multiple* grounded metaphors. Third, the metaphorical construals identified are language based: linguistic forms invite the adoption of these metaphorical construals of experience.

These features can help situate the present position with respect to three important positions in the conceptual change literature. The first position can be identified as the knowledge systems view [see diSessa, 1993; diSessa et al., 2004] which models conceptual change as the reorganization of multiple (often subconceptual, experientially based) knowledge elements: from the loosely organized and highly context-sensitive elements of the novice to the conventionally structured elements of the expert that support coherent prediction and reasoning. The closely related 'theory change' [Carey, 1985, 1999; Smith, 2007; Smith et al., 1997; Wiser, 1995; Wiser & Amin, 2001, 2002] and 'framework theory' [Ioannides & Vosniadou, 2002; Vosniadou, 2002] views attribute greater coherence to the understanding of the novice, which is viewed as theory-like while acknowledging that naïve theories can be much narrower, less elaborated and less abstract than scientific theories. From this second point of view, the process of conceptual change is also seen to be gradual and to involve the reorganization of many elements of a knowledge system, including the particularly challenging change in the ontology of concepts. Finally, the third position singles out ontological reassignment as central to the process of conceptual change for many important concepts [Chi, 1992, 2005; Chi & Slotta, 1993; Slotta, Chi, & Joram, 1995]. Radical conceptual changes involving fundamental reassignments of concepts from one ontological category to another are posited.

The position put forward here shares a great deal with the knowledge systems view, reflected in the claim that multiple, experientially based conceptual resources are drawn on to structure understanding of a scientific concept. Moreover, it is consistent with diSessa's [2000] questioning of domain-specific assumptions, noting connections and overlaps in people's reasoning about the physical and social worlds. For example, diSessa has pointed out that people often appeal to the same p-prims (e.g., Ohm's p-prim) when reasoning in both domains. It differs from that view in hypothesizing the importance of linguistic elements (e.g., metaphorical expressions) in inviting particular experientially grounded metaphorical construals of physical situations.

The present position, however, is noncommittal with regard to the issue of the coherence of naïve understanding that distinguishes the knowledge systems view, on the one hand, and the theory change and ontological change views, on the other. This is assumed to be a matter of degree and to require empirical demonstration on a case-by-case basis. Note, for example, that Mandler [2004] has proposed an account of the continuity between infant and adult concepts in terms of precisely the same image-schematic structures discussed here. In her account, small collections of image schemas form the basis of a highly stable conceptual distinction in infancy between animate and inanimate entities. Moreover, it is worth noting that some coherence is reflected in the phenomenon of conceptual metaphor itself, where consistent mappings are posited to underlie *many* metaphorical expressions. Amin [2001] identified this kind of coherence when positing a core cognitive model as underlying the everyday use of the verb *heat* and the nouns *heat* and *temperature*. Evidence for a coherent cognitive model was obtained from analysis of the syntactic and semantic patterns of these terms, as well as two sets of metaphorical mappings associated with the use of the noun *heat* in American slang. However, to the extent that multiple construals structure the understanding of a concept, the extent and depth of coherence needs to be empirically demonstrated by investigating whether a set of mutually consistent *inferences* are generated by the user of the metaphors.

The latter point draws attention to an important limitation of the conceptual metaphor perspective and the methods employed. The perspective does provide a rich analytical tool for identifying construals implicit in language use that may be relevant to accounts of naïve and scientific understanding of a concept. It also suggests that elements of scientific language itself provide the learner with clues to scientific understanding via metaphorical projection of experiential knowledge gestalts reflected in systematic use of verbal metaphors. What is not addressed extensively here, and is central to the task of modeling understanding and the process of conceptual change, is what conceptualizations are actually drawn on, in what way, in what contexts for the purposes of reasoning and problem solving. This is what has been studied using careful analysis of interview protocol data by conceptual change researchers. However, the present language-based analysis generated specific hypotheses regarding a variety of conceptual metaphors that may structure understanding of a scientific concept of interest. Conceptual metaphor analysis, thus, complements reasoning and problem solving protocol analysis – and indeed may constitute a productive initial phase of hypothesis generation – by identifying potentially relevant conceptual resources that can ground understanding of, and reasoning with, abstract concepts. This contribution is far from trivial as many relevant conceptual resources are likely to be from distant conceptual domains that would not be intuitively apparent to the researcher investigating conceptual change in some domain.

In addition, adopting a conceptual metaphor perspective on the representation of concepts and viewing language as a versatile tool for adopting diverse construals of experience has other important methodological implications for research on conceptual change, especially claims about ontological reassignment. Particularly noteworthy is the work of Chi and colleagues [e.g., Chi, 1992, 2005; Slotta et al., 1995] in which predicates used by novices and experts in the context of reasoning and problem solving served as the basis for inferences about the ontological categories to which concepts are assigned. Chi and colleagues concluded that students commonly assign scientific concepts they are learning incorrectly to a material substance ontological category instead of the more abstract constraint-based (or emergent) process category. Predicates such as block (e.g., 'keeps,' 'bounces off'), move (e.g., 'goes,' 'leaves'), and consume (e.g., 'gets used up,' 'drains') are all taken as reflecting a material substance ontological assignment for a concept.

There is a problem with such an approach from the perspective of conceptual metaphor. The use of these words and phrases can often reflect the use of a conceptual metaphor to structure understanding of some concept in both lay and scientific discourse. If such phrases were taken as evidence for ontological assignment, one would have to claim that Feynman entertained a material substance assignment of energy. Even in everyday discourse metaphorical expressions are pervasive and reflect the mapping of inferential structure from experiential source domain to an abstract target domain. From this perspective, the findings of Slotta et al. [1995] that novices and experts display a significantly different use of material substance and process predicates would need to be re-interpreted as reflecting change in the profile of conceptual resources (often metaphorical) used in problem solving as expertise develops (for similar critiques of the claim for the stability of ontological commitments, see also Amin [2001], and Gupta, Hammer, & Redish [2008]).

Finally, it is important to point out that proposing the appropriation of language-based metaphorical construals as a component of conceptual change addresses the recent call for bridging cognitive and situated approaches to conceptual change [see e.g., Mason, 2007; Vosniadou, 2007]. Increasingly, it is being acknowledged that accounts of both the nature of cognitive structures and discursive processes will be required for a comprehensive account of the process of conceptual change. More specifically, a theoretical proposal has been made for acknowledging the appropriation of patterns in linguistic forms (and other artifacts) that cognitive linguists claim reflect image-schematic grounding of abstract concepts and reasoning, and processes of conceptual emergence, as important foci for cognitive developmental studies that articulate cognitive and situated approaches [Amin & Valsiner, 2004]. Some attempts have been made to draw jointly from both perspectives, highlighting the processes of meaning negotiation in the process of concept learning [e.g., Duit, Roth, Komorek, & Wiblers, 1998; Pea, 1993]. What these attempts have not done is identify the particular linguistic elements that are the sites of meaning negotiation most relevant to conceptual change in particular domains. The argument put forward throughout this paper suggests that verbal metaphors are likely to be particularly important sites of meaning negotiation that should be examined in the context of scaffolded reasoning and problem solving.

Pedagogical Implications

A number of pedagogical implications can be drawn from the present perspective. First, the claim that scientific concepts are structured by multiple metaphors has implications for how we conceive of learning objectives, the targets of conceptual change. Often a scientific concept is given an abstract definition or characterization which is viewed as the learning objective. This may take the form of a verbal definition, the positing of a single abstract theory (specifying a set of relationships to other concepts), or the ontological assignment of a concept. As exemplified by the case of energy discussed above, there is often insistence on the abstract nature of the target concept. In their discussion of the implications of the conceptual metaphor perspective for mathematics education, Núñez, Edwards, and Matos [1999] noted that the insistence on the rigorous, abstract characterization of concepts misses the reality of their grounding in multiple experiential intuitions. As shown here, this applies equally to science education.

Recognizing the role of experiential intuitions in the characterization of a scientific concept draws attention to the importance of everyday experiences for grounding scientific abstractions. A number of researchers of conceptual change have examined how physical objects [Clement, 1993; Zietsman & Clement, 1997] and a series of computer-based visual representations interfacing with manual manipulation of a joystick [White, 1993, 1995] can be strategically selected and designed to trigger learners' application of experiential intuitions in scientific reasoning and problem solving. The intuitions in these cases, however, fall within the same domain of the target concept (e.g., agentive impulses grounding a Newtonian understanding of force). Systematically extracting the image-schematic basis of a certain concept projected via metaphor suggests that many of the experiential notions identified will not be directly related to the domain of phenomena that the concept addresses. That is, while the concepts of heat, temperature, and energy deal with thermal phenomena, understanding these concepts is likely to appeal to experiential notions such as part-whole, containment, and force, along with many others.

The tools of conceptual metaphor can also support the design of instructional representational tools. The value of using a variety of representations to support conceptual change has been widely recognized. In particular, visual models of abstract concepts have been extensively and successfully utilized as teaching tools to induce conceptual change [see e.g., Smith, 2007; Smith et al., 1992; White, 1993, 1995; Wiser, 1995; Wiser & Amin, 2002]. In this literature, target concepts are characterized in terms of abstract definitions and key misconceptions guide the design of visual representations to address these particular misconceptions (e.g., differentiating extensive and intensive quantities such as weight and density, heat and temperature). The visual representations are designed to embody the abstract relations among the target concepts. However, the design process is not theorized in this literature, but is intuitive, relying on the creativity of the researcher. Conceptual metaphor can contribute to this literature by suggesting an initial phase of systematically identifying the image-schematic basis of a scientific concept being taught. Visual representations can then be designed to reflect the concept's image-schematic grounding. Such an approach has already been applied successfully to improve 12- to 14-year-old students' performance on mathematics word problems involving time [Danesi, 2007]. Visual representations were designed that concretize two conceptual metaphors: Time Is a Point, and Time Is a Quantity. Students were taught to construct timeline and container diagrams to represent the information provided and set up an algebraic expression that would form the basis for solving the problem. Students were able to solve similar problems to those they had been unable to solve before instruction.

Mathewson's [2005] discussion of the *visual core* of scientific understanding relates closely to this proposal. He has made the case for the central role of visual representations in scientific understanding and has catalogued a list of 'master images' that repeatedly appear as central to understanding in diverse domains of scientific knowledge such as conduits, containers, paths, boundaries, points, cycles, and so forth. It is these master images that repeatedly constitute the structural and functional characteristics of scientific models of nature. Mathewson identified many of these with the image schemas that Johnson [1987] described as grounding abstract reasoning. Therefore, extracting the image-schematic grounding of a scientific concept constitutes the identification of the master images relevant to understanding the concept. As just mentioned, this forms the basis for concretizing the concept in visual terms. Mathewson's discussion of the instructional uses of master images suggests other pedagogical implications: reflection on master images can form the basis for visual metacognitive development; discussion of master images allows for a consideration of themes that cut across specific concepts, and skill with thinking based on master images enriches students' modeling sophistication.

An additional pedagogical implication is that the theory of conceptual metaphor can help identify potential obstacles to conceptual change. Using the framework of conceptual metaphor, Brookes and Etkina [2007] identified conceptual metaphors used by physicists in the domain of quantum mechanics. They showed how students made overly literal interpretations of metaphorical expressions. For example, the conceptual metaphor Potential Energy Graph Is a Physical Object identified in the language of physics to which students were exposed prompted students to use the physical form of the graph too literally resulting in them drawing on inappropriate analog physical situations while reasoning. As argued in this paper, the conceptual metaphors underlying metaphorical expressions provide a basis to bootstrap the understanding of abstract concepts by inviting the transfer of relational structure from an experiential source domain to the abstract domain being learned. However, not all aspects of the source domain should be transferred. What Brookes and Etkina identified as ontological misclassifications of concepts by students reflects errors in transfer. More specifically, the errors reveal that students respond to the invitation to compare a familiar and an abstract domain in terms of surface similarity rather than in terms of deeper relational structure. A general hypothesis deriving from these considerations is that learning the conventional mappings underlying the metaphoric expressions in scientific discourse constitutes an underappreciated obstacle to achieving conceptual change.

In sum, this paper has attempted to motivate the hypothesis that appropriating language-based construals and the metaphorical representation of concepts are sources of conceptual change not previously addressed in the literature. If this proposal is seen as plausible, future research will need to systematically explore the details of this process in formal and informal learning environments and to examine its influence on everyday and scientific understanding and reasoning. Recognizing the appropriation of language-based metaphorical construals as a source of conceptual change can help identify potential learning obstacles as well as productive entry points for instruction.

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