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Conceptual Metaphor and the Study of Conceptual Change: Research synthesis and future directions

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Many of the goals of research on conceptual metaphor in science education overlap with the goals of research on conceptual change. The relevance of a conceptual metaphor perspective to the study of conceptual change has already been discussed. However, a substantial body of literature on conceptual metaphor in science education has now emerged. This work has not yet been synthesized or related explicitly to the goals of conceptual change research. This paper first presents a broad sketch of the study of conceptual change, characterizing the goals of this body of work, its contributions to date, and identifying open questions. Next, the literature on conceptual metaphor in science education is reviewed against this background. The review clarifies the natural theoretical connections between the conceptual metaphor perspective and the phenomenon of conceptual change. It then examines the contributions made by the literature on conceptual metaphor in science education to the goals of research on conceptual change—namely, characterizing student conceptions, identifying obstacles to learning, understanding the process of conceptual change, and designing productive pedagogical strategies that could achieve conceptual change. The paper concludes with a discussion of further avenues for research into conceptual change, suggested by adopting a conceptual metaphor perspective.

Key words: *Science education; Conceptual change; Conceptual metaphor; Research synthesis*

Introduction

This paper reviews the contributions of a growing literature on conceptual metaphor in science education to the study of conceptual change in science learning and instruction. There is a vast literature on conceptual change in science education and related

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fields. This work has characterized learners' pre-instruction conceptions and expert scientists' conceptual understanding, contrasted learners' initial conceptions with those of scientists, proposed accounts of the process of concept learning and applied the emerging understanding to the design of curricula and instructional environments (for reviews see Amin, Smith, & Wiser, 2014; diSessa, 2006; Duit & Treagust, 2003). In an early paper, Andersson (1986) used the cognitive linguistic theory of conceptual metaphor (Lakoff & Johnson, 1980, 1999) to identify a common feature of learner preconceptions in many domains of science (what he called an 'experiential gestalt of causation'). More recently, a body of literature has emerged that is applying this theory to a wide range of issues in science education (e.g. Amin, 2009; Amin, Jeppsson, Haglund, & Strömdahl, 2012; Brookes & Etkina, 2007, 2009; Gupta, Hammer, & Redish, 2010; Jeppsson, Haglund, Amin, & Strömdahl, 2013; Lancor, 2013, 2014a; Niebert, Marsch, & Treagust, 2012; Scherr et al., 2013; Scherr, Close, McKagan, & Vokos, 2012). This research has recognized that implicit in the language of science are systematic metaphorical mappings between abstract scientific concepts—such as *heat*, *energy*, and *entropy*—and concrete image schemas such as *material object/substance*, *possession*, *containment*, *object movement*, and *forced object movement*.¹ These implicit mappings (referred to as conceptual metaphors) are reflected in the language of science, as in 'The molecule *has* kinetic energy'; 'The energy *stored in* the compression of the spring was released'; and 'Heat was *lost to* the surroundings'. This literature has been exploring the implications of this phenomenon for science learning and instruction.

In Amin (2009), I analyzed the conceptual metaphors implicit in everyday English and in the language of science that are used to construe the concept of energy. I used this analysis to identify how image schemas (abstractions from sensorimotor experience) such as possession, containment, movement of possessions, and forced movement of possessions are used to construe energy in lay and scientific contexts. I argued that identifying these image schemas helps science educators identify continuity across the learning process. That is, a learner can draw on image schemas he or she already has as a cognitive resource to learn an abstract scientific concept like energy. I also suggested that naïve preconceptions might originate in construals implicit in everyday language (many of them metaphorical). But I also suggested that the implicitly metaphorical language of science can, itself, cue productive resources for the learner. So while I acknowledged that overly literal interpretations of metaphorical language might be a source of naïve preconceptions, I hypothesized that appropriating conceptual metaphors implicit in language might be a source of conceptual change. Moreover, I proposed that conceptual metaphor analysis of scientific language might help in the design of visual representations that would support meaningful learning.

A few years on and there is now a substantial body of literature on conceptual metaphor in science education that is providing some support for these hypotheses and has been exploring other implications of the phenomenon of conceptual metaphor for science teaching and learning. The literature has documented that the phenomenon of conceptual metaphor in the language of science textbooks is pervasive and

systematic (Amin, 2009; Amin et al., 2012). It has suggested that expert and novice reasoning and problem-solving rely on the coordination of conceptual metaphors and other cognitive resources (Dreyfus et al., 2014; Dreyfus, Gupta & Redish, 2015; Jeppsson, Haglund, Amin, & Strömdahl, 2013). It has compared how novices and experts use conceptual metaphors in scientific problem-solving (Jeppsson, Haglund, and Amin, 2015). Moreover, it has shown that the construct of conceptual metaphor is useful for characterizing student conceptions (Lancor, 2014a, 2014b, 2015) and for identifying the source of naïve conceptions (Brookes & Etkina, 2007, 2009, 2015). It has used the perspective to evaluate the effectiveness of instructional analogies (Amin et al., 2012; Niebert et al., 2012) and to design instructional interventions, based on the strategic design of representations, that would develop meaningful understanding of challenging scientific concepts (Brewer, 2011; Close & Scherr, 2015; Niebert & Gropengießer, 2015; Scherr et al., 2013).

It is clear that many of the goals of this work on conceptual metaphor in science education overlap with the goals of research on conceptual change. The purpose of the present paper is to synthesize the substantial body of literature on conceptual metaphor in science education, discuss its contributions to the study of conceptual change and identify directions for future work. To do this, the paper first presents a broad sketch of research on conceptual change. Next, the literature on conceptual metaphor in science education is reviewed against this background. The review clarifies the natural theoretical connections between the conceptual metaphor perspective and the phenomenon of conceptual change. It also examines the contributions made by the literature on conceptual metaphor in science education to the goals of research on conceptual change—namely, characterizing student and scientist conceptions, identifying obstacles to learning, understanding the process of conceptual change, and designing productive instructional environments that could achieve conceptual change. In a final section, I discuss what further avenues for research into conceptual change can be opened up if we take a conceptual metaphor perspective, but point out that the perspective itself may need a more elaborated account of concepts.

A Thumbnail Sketch of Research on Conceptual Change

In this section, I present a highly condensed sketch of research on conceptual change, relying primarily on a recent historical review of this literature spanning the last four to five decades (Amin et al., 2014). This sketch offers a perspective on the conceptual change literature with the specific purpose of clarifying the emerging contributions of research on conceptual metaphor in science education.

Conceptual change research has been conducted from a very wide range of perspectives and, as with any healthy scientific endeavor, disagreements between researchers persist (see Vosniadou, 2013a, for contributions representing a wide range of perspectives on conceptual change). However, Amin et al. (2014) argue that across this diversity of views, we can discern three phases of a trajectory of progress. In the 1970s and 1980s, the dominance of Piaget's stage view of development gave way to a domain-specific view of conceptual development and learning (Carey, 1985). Researchers

recognized that it is necessary to describe changes in the content and structure of the learner's prior conceptions in order to make sense of how a learner comes to understand a scientific concept in some domain (e.g. force and motion; heat, temperature and energy; living things). Many detailed qualitative descriptions of learners' conceptions prior to, and during, instruction in a domain were reported in the literature. Learner conceptions were found to differ in significant ways from scientists' conceptions and were seen as obstacles to, and yet important starting points for, successful instruction. Creating cognitive conflict by making explicit and then challenging learners' naïve conceptions was proposed as an effective way to initiate instruction for conceptual change (see Driver & Easley, 1978; Scott, Asoko, & Driver, 1992, for reviews).

During the 1980s and 1990s, researchers scrutinized these conceptions and their transformations closely and attempted to induce change through instruction that targeted specific problematic conceptions. This scrutiny uncovered various components of the process of conceptual change. Four components were most widely studied. One component was the role of beliefs and assumptions about broad classes of entities (ontological categories) within which concepts were classified (e.g. it was proposed that many scientific concepts such as heat, energy, and electric current are incorrectly classified as material substances) (e.g. Chi, Slotta, & De Leeuw, 1994). The second component was the role of metacognitive beliefs *about* knowledge, learning, and science, such as *to learn is to remember* and *scientists arrive at new knowledge through discovery* (e.g. Hofer & Pintrich, 1997). The third was the role of useful intuitions and concrete/familiar conceptual structures that could serve as analogs of scientific concepts. These were strategically invoked by providing models or guiding students through modeling activities (e.g. the intuitive understanding of the agency of a compressed spring can be recruited to understand the concept of the normal force exerted by an apparently inert object such as a table) (Brown & Clement, 1989). Finally, the fourth component was the role of social interaction through which conflicting views trigger concept revision (e.g. Howe, Tolmie, & Rodgers, 1992) and collective thought supports the construction of more sophisticated knowledge (e.g. Hatano & Inagaki, 1991).

A third phase of research now sees researchers embracing the need to understand conceptual change as a complex process with multiple components and interactions. Some researchers realized early on the importance of understanding the complexity of learners' conceptual 'ecologies' and the multiple knowledge types and interactions that influence learner conceptions and the process of change (e.g. diSessa, 1993; Strike & Posner, 1985). A broader consensus on this point (not always explicitly acknowledged as such) now seems to be emerging (Brown & Hammer, 2008; diSessa, 2002; Vosniadou, 2013b; Wiser & Smith, 2013). Moreover, the design of instructional interventions and curricula has also begun to take this complexity seriously (e.g. Corcoran, Mosher, & Rogat, 2009).

Just as there is now widespread recognition that many types of knowledge play an important role in conceptual change, understanding the *representational format* of that knowledge is also seen as significant (Carey, 2009; Cheng & Brown, 2010;

diSessa, 1993). Researchers contrast *iconic* and *propositional* representations, albeit not always using this terminology. Iconic representations are analogical representations that bear a resemblance to what they represent such as imagery, image schemata, and mental models. Imagery is the mental reenactment, or simulation, of a previous perceptual experience in the absence of the object or events—for example, imagining rods, coils, and springs of different forms in an effort to predict whether a weight stretches springs with different diameter coils to different degrees (Clement, 1989). Image schemata are abstractions from sensorimotor experiences and are invoked to dynamically and causally interpret perceived or imagined objects and events—for example, what diSessa (1993) has called p-prims, such as *force-as-mover*. Together imagery and image schemata support the construction of mental models that can serve as analogs of physical objects and events. Researchers have shown that mental models support learners' and scientists' creative insights during scientific reasoning and problem-solving (Clement, 2009). Propositional representations are composed of arbitrary, symbolic representations that are constructed according to formal rules and express a claim about the world (i.e. they have a 'truth value'). Examples include linguistic expressions such as *A whale is a mammal* and mathematical representations, such as $F = ma$.

Brown (1993) contrasts these types of representations in terms of the degree to which they are explicit and accessible to conscious thought. Image schemata (or what Brown calls 'core intuitions') are triggered automatically in particular contexts and most likely remain implicit, beyond conscious awareness. Propositional ('verbal-symbolic') representations are by nature explicitly invoked and guide conscious chains of reasoning. Imagery and mental models can be either implicit or explicit. Making these distinctions has been important in understanding concept development and learning. During the normal course of conceptual development some concepts develop by simply assembling and jointly invoking iconic representations (e.g. lay concept of *animal*), while others require integrating iconic and propositional representations (e.g. the concept of natural numbers) (see Carey, 2009; Mandler, 2004). During science learning, conceptual understanding, and reasoning of students drawing on integrated iconic and propositional representations are more powerful than those who rely on iconic representations alone (Cheng & Brown, 2010).

I assume that what has been sketched thus far is either agreed on by most conceptual change researchers or tacitly assumed. However, theoretical diversity and points of disagreement are important to acknowledge. Theoretical diversity can be seen in the 'grain size' seen to be important in the characterization of learner and scientist conceptual understanding (diSessa, 2006). In order of *decreasing* grain size, researchers have characterized conceptual understanding in terms of (unanalyzed) theories—for example, a naïve impetus theory (McCloskey, 1983); mental models—for example, a naïve source-recipient model of heat (Wiser, 1995); framework theories analyzed in terms of ontological presuppositions—for example, the presupposition that unsupported things fall which constrains the construction of naïve models of the earth, and the beliefs generated from them (Vosniadou & Brewer, 1992); and

image schematic phenomenological primitives (p-prims)—for example, *force-as-mover* (diSessa, 1993).

Related to this contrast in preferences for grain size, researchers have disagreed on two key (related) points: the extent to which pre-instruction conceptions are likely to be coherent and stable; and the extent to which conceptual change should be viewed as restructuring as opposed to gradually increasing organization of knowledge elements triggered strategically in specific contexts. A broad range of views can be identified where conceptual change is viewed as ontological recategorization (arguably the most extreme coherence view) (Chi, 2005; Chi et al., 1994); revision of conceptual structures embedded in framework theories with an emphasis on the revision of ontological presuppositions (Vosniadou, 2013b); coordinated revision of networks of beliefs (domain specific and epistemological) and mental models (Wiser & Smith, 2013); and the gradual organization of multiple (often intuitive) cognitive resources, which assumes that pre-instruction knowledge is highly fragmented (diSessa, 2002). While these views are usually presented in the literature as in opposition to one another, Brown and Hammer (2008) have suggested that most can be reinterpreted as special cases of a more general account of conceptions and conceptual change formulated in terms of dynamic systems theory.

Among the open questions that are only just beginning to be explored are the following: How can the coherence and fragmentation of conceptions be studied within a single unifying perspective that can accommodate both phenomena on a case-by-case basis (e.g. Brown & Hammer, 2008)? What are the multiple knowledge elements that need to be integrated for successful conceptual change to be achieved (e.g. diSessa, 2014; Wiser & Smith, 2013)? More specifically, how are propositional language-like representations integrated with iconic knowledge structures during conceptual change (e.g. Cheng & Brown, 2010; Jeppsson et al., 2013; Sherin, 2001, 2006)? How can instruction and curriculum design guide the assembly of multiple knowledge elements of various types (Corcoran et al., 2009)?

Investigating Conceptual Metaphor in Science Education: Taking stock of contributions to the study of conceptual change

In this section, I review the literature on conceptual metaphor in science education in light of the sketch of the conceptual change literature just presented. The goal is to clarify the contributions that this body of work makes to the study of conceptual change. The review first highlights natural theoretical connections between the cognitive linguistic theory of conceptual metaphor and the phenomenon of conceptual change. Next, I present the contributions of research on conceptual metaphor in science education to characterizing student and scientist conceptions and identifying obstacles to learning, understanding the process of conceptual change, and designing productive instructional strategies that could achieve conceptual change.

Natural Theoretical Connections Between Conceptual Metaphor and Conceptual Change

There are natural theoretical connections between the cognitive linguistic theory of conceptual metaphor and conceptual change. As we saw in the sketch above, at the heart of research on conceptual change is the question of how pre-instruction conceptions are transformed to increasingly approximate conceptions sanctioned by scientists. Of particular interest is how pre-instruction conceptions of the novice learner contribute to the conceptual structures of the (emerging) expert scientist. The theory of conceptual metaphor has a ready response to these questions, albeit at a general level.

The central claim of the theory of conceptual metaphor is that abstract concepts are understood metaphorically in terms of more concrete knowledge structures (Lakoff & Johnson, 1980, 1999). That is, concrete source domains are mapped metaphorically onto abstract target domains; the mapping facilitates understanding and reasoning in the abstract domain by drawing on the intuitive understanding of the concrete source domain. I use the descriptor ‘concrete’ to refer to the fact that many concepts (e.g. chairs, sitting, and dog) can be represented directly in terms of iconic representations such as image schemas, which are generalizations over sensorimotor experiences. In contrast, I use ‘abstract’ to describe concepts that cannot be represented directly in terms of such perception and motor-based experience. Abstract concepts will need to be represented in terms of propositional representations such as language or mathematical symbols. For the latter to be understood in a way that goes beyond pure manipulation of symbols, metaphorical projection from image schematic knowledge structures would be needed. For example, our conception of time cannot simply be described in terms of perception-based imagery or generalizations over sensorimotor experiences. Language, numbers, and other representations are needed. But making sense of these representations relies on mappings from spatial conceptions that are based on perception and action. That is, recurring patterns in our everyday sensorimotor experiences result in more general knowledge structures with multiple related components, *gestalts*, such as *moving objects*, *paths with a starting point and destination*, and *obstacles to movement along a path*. These *gestalts*—so-called image schemas—are mapped onto the concept of time. The result is that time is construed metaphorically in terms of image schemas and inferences inherited from the structure of these spatial image schemas (see Lakoff & Johnson, 1999, for extended discussion of the metaphorical understanding of time). For example, we speak of ‘approaching’ a deadline; getting to some important point in a career as being ‘a long journey’; and of having to ‘get things out of the way’ before beginning a new project. These metaphorical uses reflect systematic underlying conceptual mappings such as *A Moment In Time Is A Location Along A Path*; *Passage Of Time Is Movement Toward A Location*; and *Carrying Out Intermediate Tasks Is Removal Of Obstacles*. Inferences that we would arrive at intuitively in the spatial domain—where objects move along a path and removing obstacles can be needed to reach a destination—map onto and support inferences in the domain of time. From a conceptual metaphor perspective, developing an understanding of the concept of time is (at least in part) to construct

the appropriate mapping between spatial image schemas and the conceptual domain of time (see Williams, 2011/2012, for an investigation into how a teacher guides children into constructing these mappings as they learn to tell the time).

Thus, the theory of conceptual metaphor is ready with a partial answer to the question: How do learners understand abstract concepts in terms of resources already available to them? That is, expert scientific understanding can be understood (again, at least in part) as the strategic use of image schematic knowledge structures to construe abstract concepts metaphorically. Sometimes understanding an abstract scientific concept may require multiple metaphorical mappings, with different conceptual metaphors used in different contexts. Therefore, to understand a concept, the learner will need to construct the appropriate mappings and draw strategically on a number of conceptual metaphors across contexts. From this perspective, a misconception could result from drawing on an inappropriate source domain in a particular context or incorrectly mapping an aspect of an appropriate source domain onto the abstract target.

The grounding of understanding of abstract scientific concepts in generalizations from sensorimotor experience has been recognized in the science education literature for some time in the constructs of phenomenological primitives (diSessa, 1993) and anchoring intuitions (Clement, 1993) and in model-based instruction designed to trigger physical intuitions (White, 1995). The theory of conceptual metaphor suggests that analyzing language can help us identify the image schemas that ground abstract scientific understanding. It also raises questions about how learners might be able to establish the appropriate metaphorical mappings sanctioned by science and points to instructional interventions that might support learning. The following section illustrates how these themes have been examined in research on conceptual metaphor in scientific expertise, science learning, and instruction.

Contributions to the Goals of Conceptual Change Research

In this subsection, I review the literature on conceptual metaphor in science education, highlighting how this literature contributes to the same goals of research on conceptual change—namely, characterizing scientist and learner conceptions and identifying obstacles to learning; understanding the process of conceptual change; and suggesting productive pedagogical strategies.

Characterizing learner and scientist conceptions and identifying obstacles to learning. As described earlier, a key claim of the theory of conceptual metaphor is that in human cognition concrete source domains are frequently mapped onto abstract domains and that these mappings are reflected in metaphorical expressions. This is a mundane phenomenon, not a feature of special creative thought. Thus, we should expect that this phenomenon is a common feature of the thinking of scientists and learners and will be frequently reflected in scientific and lay language. A number of studies have used the conceptual metaphor framework to describe scientist and

learner conceptions and to suggest possible obstacles to learning by comparing the two.

Most of these studies have adopted a similar approach. They begin by analyzing scientists' language use from a conceptual metaphor perspective. This analysis identifies how abstract concepts in some scientific domain are construed in terms of image schemas. They then identify student conceptions in this domain and interpret these conceptions from a conceptual metaphor perspective. The findings from the two analyses are then compared with an eye to answering some or all of the following questions: (1) How do the source domains used by scientists and students to ground their understanding of some domain compare? (2) Do scientists and learners differ in the contexts in which they invoke particular source domains to metaphorically construe a scientific concept? (3) When the same source is selected to construe the same abstract concept, does the mapping differ?

In Amin (2009), I presented an analysis of the use of the term energy in *The Feynman Lectures on Physics* from a conceptual metaphor perspective. I described what conceptual metaphors are used by Feynman to construe various aspects of the concept of energy—transport, transformation, and conservation (degradation was not addressed). Multiple metaphorical mappings were used to construe each aspect of the concept of energy, but a great deal of systematicity could be discerned. For example, the many metaphorical construals of energy transport involved construing energy as a substance/possession and energy transport as movement of a possession between components of a physical system; energy transformation was also construed in terms of the movement of a possession, with energy often construed as a stored resource. In contrast, forms of energy themselves were construed as containers. Construing energy as a substance, as movement on a vertical scale and in terms of a part-whole schema helped in making sense of energy conservation.

This analysis of a scientific text was followed by a review of the literature on learners' alternative conceptions of energy. Then to help in interpreting these conceptions, the use of the term energy in everyday English was analyzed from a conceptual metaphor perspective. In that analysis, it was found that reference to energy came up in the context of human use of technology, food consumption, and human activity and vitality. As in the scientific text, there was also pervasive use of metaphor in everyday English. Again there was construal of energy as a location on a vertical scale, as a resource stored or contained and changes in energy as movement of a substance. Most of learners' alternative conceptions of energy found in the science education literature corresponded to metaphorical construals that are implicit in everyday language. On comparing the two sets of mappings (in Feynman's text and those in everyday English), a great deal of overlap was noted in which source domains were used to construe energy. One key difference was the absence of the part-whole schema as a source domain in everyday English, which was associated only with energy conservation in the scientific text.

Brookes and Etkina (2007, 2009) took a similar approach in the domains of quantum mechanics, and force and motion. Again, as a first step, they identified metaphorical expressions in scientists' language and inferred the underlying conceptual

mappings between more concrete conceptual domains and abstract domains. They then studied student reasoning and characterized their conceptions in terms of the mapping of concrete onto abstract domains. In this work, they point out that the scientists' language implies a particular ontological categorization of concepts (Chi et al., 1994) and examine how this language is interpreted by learners. For example, Brookes and Etkina (2007) point out that the scientific language of quantum mechanics includes implicit metaphors in which a potential well is construed as a physical container. In a later study (Brookes & Etkina, 2009), they show that in the history of scientific thinking about force, four distinct metaphors were explored, most of which continue to find a place in the modern language of science: force as an agent, force as an internal drive, force as a passive medium of interaction and force as a property of an object. In both studies, they provide evidence that student misconceptions mirror these ontological metaphors implicit in the language they are exposed to during instruction. Similarly, in a recent study (Brookes & Etkina, 2015), they have shown that university students reason about heat incorrectly in some contexts as if it is a state function, mirroring metaphorical language inviting a construal of heat as a substance. In all these cases, the source of learner misconceptions seems to be that they map too much of the source domain implied by scientists' language.

Lancor (2013, 2014a, 2014b, 2015) has used the tools of conceptual metaphor to develop a framework to analyze how university students understand and communicate their ideas about the scientific concept of energy in a variety of contexts. In Lancor (2014a), students were asked to write analogies that would explain their understanding of the role of energy in ecosystems (biology), chemical reactions (chemistry), and mechanical systems and electric circuits (physics). She classified student conceptions in terms of a framework composed of six conceptual metaphors: energy as a substance that can be accounted for; energy as a substance that can change forms; energy as a substance that can be carried; energy as a substance that can be lost; energy as a substance that can be an ingredient or product; and energy as a process or interaction. Lancor found that students used these conceptual metaphors differently in different disciplinary contexts. In Lancor (2015), she uses the same analytical framework to analyze student essays explaining the role of energy in interdisciplinary scientific contexts widely discussed in the media, including radiation, transportation, generating electricity, earthquakes, and the big bang theory. Across these two studies, Lancor finds that the same framework can be used to analyze students' conceptions in disciplinary and interdisciplinary contexts. Both within, and across studies, different conceptual metaphors are favored in different contexts.

Niebert and Gropengießer (2015) also use the conceptual metaphor perspective to analyze learner conceptions. In addition, they analyze scientist conceptions and compare the two. They suggest that analyzing conceptions in terms of conceptual metaphors is a particularly useful 'grain size'. It allows researchers to generalize across conceptions without losing out on interesting variation. It also helps describe the differences between scientist and learner conceptions, enabling the researcher/

educator to specify the ‘learning demand’ for a particular scientific topic. Niebert and Gropengießer are particularly interested in the bodily basis of the image schematic source domains of the conceptual metaphors they examine. They adopt the view that human beings are designed to make sense of their world at the level of medium-scale dimensions, what they call the mesocosm (in between the micro- and macrocosm). This is the scale at which the senses evolved to function. Sense making in science (by both learner and scientist) usually involves the attempt to draw on image schemas to make sense of more abstract ideas associated with the microcosm (e.g. cell division) or macrocosm (e.g. carbon cycle).

Niebert and Gropengießer use a conceptual metaphor perspective to identify the difficulties that learners can face in a specific scientific domain. For example, learners might map only a *container* image schema onto the target concept of myelin sheath making it difficult for them to make sense of the effect of myelin on signal speed in neurons. Scientists, in contrast, use the image schema of a *bridge* together with the *container* schema to construe the myelin sheath. This enables them to conceptualize signal travel as *jumping*, which helps them understand the effect of myelin on signal speed. Niebert and Gropengießer generalize across the different domains in which they analyze learner and scientist conceptions. They suggest that they need to appeal to a limited number of image schemas to understand student and scientist conceptions and that students and scientists often make use of the same ones but in different ways. They argue that the difficulties students have are often with selecting which ones to map to which target concepts, but note that sometimes student difficulties are due to the absence of the relevant experiences needed to construct the right image schema.

The literature on conceptual metaphor in science education reviewed in this subsection makes a number of contributions to the study of conceptual change. It provides an additional tool to help in characterizing student conceptions, with an emphasis on what image schemas students use to understand a scientific concept and how they use them. The conceptual metaphor framework also suggests a way of analyzing how *scientific* concepts are understood. In much of the conceptual change literature, the researcher assumes knowledge of the scientific concept that is the target of learning and instruction. Adopting a conceptual metaphor perspective encourages the analyst to ask what image schemas are used to understand a scientific concept. In turn, identifying the image schemas that both students and scientists use in a particular scientific context and comparing the two, we can identify a learning demand in the context. This type of analysis contributes to the broader goal that some conceptual change researchers see as important of identifying the intuitive knowledge structures relevant to learning in some domain and describing the learning challenge in terms of these structures (e.g. Brown, 1993; Brown & Hammer, 2008; Clement, 2009; diSessa, 1993, 2014).

Understanding the process of conceptual change. A number of conclusions can be drawn from the literature reviewed in the previous subsection that are relevant to attempts to understand the *process* of conceptual change. First, even before instruction, learners

metaphorically map image schematic source domains unconsciously onto target conceptual domains. This mapping is relevant to instruction, but the relevance can be either positive or negative. On the positive side, some mappings are similar to those implicit in scientific language and thought and so contribute positively to learning. On the negative side, some either involve mapping the wrong source domain or involve an incorrect mapping of the right source domain, potentially leading to misconceptions in both cases.² Second, the research reviewed earlier has shown that many of the source domains drawn on by learners and scientists consist of image schematic knowledge structures, which are abstractions from sensorimotor experience. Finally, the close connection between these cross-domain mappings and language implicates language in the process of conceptual change itself. I take each of these points in turn, discussing implications for understanding the process of conceptual change.

Since the phenomenon of conceptual metaphor is a mundane characteristic of human cognition, science learners have already implicitly constructed a number of mappings by the time they begin to receive formal instruction in some topic. Some of the mappings they have constructed are consistent with those in the scientific domain they are learning, but others are not. Those that are not consistent will sometimes be the source of misconceptions and so will need to be revised during the concept learning process. One could then say that *an aspect* of conceptual change is the revision of metaphorical mappings between source and target domains. If this claim is correct, this has implications for the debate in the conceptual change literature regarding the extent to which conceptual change involves transformation of a fairly coherent naïve conceptual structure to another coherent (more) scientific conceptual structure. As reviewed earlier, researchers have disagreed on the degree of coherence of learner pre-instruction conceptions. Given that the phenomenon of conceptual metaphor is a fairly systematic phenomenon, even in everyday language and thought, some degree of systematicity in the mappings implicit in learner thinking is to be expected. This of course is something that needs to be investigated on a case-by-case basis in each domain of interest. One example of such coherence deriving from metaphorical mappings in learner thinking is the ontological classification implicit in the language of science in the domains of quantum mechanics and force and motion, investigated by Brookes and Etkina (2007, 2009); another is the pervasive use of the energy as substance metaphor in everyday language and thought (Amin, 2009; Vosniadou, 2009).

Many of the source domains of the conceptual metaphors found in the thought of learners and scientists are image schematic knowledge structures such as possession, movement of possession, movement along a path, and containment. These are abstractions from sensorimotor experience and are constructed early in life through repeated interactions with the physical world. A conceptual metaphor perspective suggests that learning a scientific concept involves learning to map particular image schemas to abstract scientific concepts strategically. Learners need to map the right image schemas in the right way to the abstract scientific concepts they are trying to understand. Assuming that most image schemas originate in sensorimotor

experiences early in life implies continuity across the learning process at the level of image schemas. This claim is equivalent to the claim made in the conceptual change literature that an important aspect of learning scientific concepts is the reorganization of phenomenological primitives (p-prims) (diSessa, 1993). Indeed, many p-prims can be seen as image schematic source domains of conceptual metaphors (see Amin, 2009, and Jeppsson et al., 2013, for discussion). Jeppsson et al. (2013) have suggested that scientists use image schemas strategically to construe scientific concepts while solving problems. For example, they found that construing heat metaphorically as a substance and a mathematical function as a machine that takes substance as input helps in seamlessly coordinating qualitative and quantitative reasoning. This strategic use of image schemas seems to be an aspect of what needs to be learned when expertise is acquired. Jeppsson et al. (2015) have recently suggested that novices do not display the same productive use of image schemas when engaged with the same problems, but are often limited to invoking conventional metaphorical expressions that they have been exposed to in pedagogical discourse.

Finally, conceptual metaphors are reflected in language—that is, in metaphorical *expressions*. This implicates language in the process of conceptual change. Pre-instruction learner conceptions have been found to mirror conceptual metaphors reflected in everyday language (Amin, 2009). Moreover, ontological misclassifications by learners on initial exposure to a scientific domain have been traced to conceptual metaphors implicit in the language of science (Brookes & Etkina, 2007, 2009, 2015). Moreover, the pervasiveness and systematicity of the phenomenon of conceptual metaphor in everyday language and in the language of science textbooks is well documented (e.g. Amin, 2009; Amin et al. 2012). This means that both informal and formal concept acquisition are likely to involve the appropriation of metaphorical construals implicit in language. The cognitive developmental literature has recognized a role for language in the process of conceptual development in specific areas (Carey, 2009; Gentner, 2010). These considerations suggest that language (through the conceptual metaphors that it expresses) may have a significant influence on conceptual change in the context of science learning (see Amin, 2009, for discussion). However, much more direct empirical evidence is needed to support this claim.

Suggesting productive pedagogical strategies. A conceptual metaphor perspective on student and scientist conceptions and on the process of conceptual change has pedagogical implications. Some of these have only been hypothesized as implications of empirical studies of scientific expertise and learning, while others have been empirically investigated directly.

Taking a conceptual metaphor perspective has suggested a tool for the formative assessment of student conceptions. Lancor (2013) has suggested that a framework of seven conceptual metaphors can be used as a formative assessment tool to provide useful information about student conceptions of energy. The framework clarifies what each conceptual metaphor affords in understanding aspects of the concept of

energy and what its limitations are. Thus, the framework allows teachers to identify some resources students have for thinking about energy and to anticipate difficulties they might face. Lancor suggests that this form of assessment is preferable to directly asking students ‘What is energy?’

I showed earlier that the conceptual metaphor perspective can be used to analyze scientific language to reveal how scientists make use of image schemas to conceptualize abstract scientific concepts. Uncovering the image schematic grounding of a concept can guide the design of visual representations that are likely to support learning by strategically triggering the appropriate image schemas (Amin, 2009). This is consistent with Mathewson’s (2005) case for the important role of ‘master images’ in scientific understanding. Mathewson argues that across a wide range of scientific domains key images such as conduits, containers, paths, boundaries, and others recur to ground understanding of abstract concepts. Conceptual metaphor analysis can help identify master images that are implicit in the language of some scientific domain.

The imagistic basis of understanding scientific concepts has prompted a number of researchers to design visual representations to help students understand challenging concepts. Scherr and colleagues have developed a program of research, The Energy Project, that uses a conceptual metaphor perspective to design representations, and instructional environments more generally, to improve understanding of the concept of energy (Close & Scherr, 2015; Scherr, Close, Close, & Vokos 2012; Scherr, Close, McKagan et al., 2012, 2013). To design the instructional environment, they begin by assuming that energy is construed metaphorically as substance-like and that this construal is central to a scientific understanding of energy transfer and transformation. Based on this assumption, Scherr, Close, McKagan et al. (2012) evaluated common representations of energy and revealed their strengths and limitations. They pointed out that common representations such as bar charts, pie charts, and others do not adequately afford conceptualizing energy as a substance-like entity that flows between components of a system. In follow-up research, Scherr, Close, Close et al. (2012) designed energy tracking representations to support modeling of energy flow and transformation in physical processes. In addition, they have designed the Energy Theater learning environment where participants use their bodies to represent units of energy and regions on the floor marked with rope represent components of a physical system (Close & Scherr, 2015; Scherr et al., 2013). The Energy Theater was designed to help in-service teachers participating in a professional development program develop their understanding of the concept of energy. It encouraged teachers to engage in conceptually rich discussions about how to model energy flow and transformation and what representations best capture aspects of the concept of energy. When these discussions were analyzed it was evident that teachers’ understanding of the concept of energy improved by participating in this professional development program.

Assuming that energy is construed metaphorically as a substance in scientific thinking has also prompted a *curricular* innovation for teaching introductory university physics (Brewer, 2011). In designing this curriculum, Brewer selects modeling as an

important aspect of scientific thinking for learners to develop and a useful vehicle for concept learning. Brewe suggests that when energy is conceptualized as a substance, energy transfer, storage, and transformation are easily represented visually and these representations facilitate modeling of physical systems. In his curriculum, the concept of energy is introduced before the concept of force (in a reversal from traditional instruction) and students return to the topic of energy repeatedly throughout the course. This approach allows students to make connections across topics that are typically presented in isolation. While this novel curricular approach has not been systematically evaluated, Brewe presents a qualitative analysis of classroom discussion as evidence for its promise.

Interest in the concept of energy has dominated much of the work applying a conceptual metaphor perspective to the design of instructional representations and learning environments in science education. However, Niebert and Gropengießer (2015) have used this perspective to design instructional representations in other conceptual domains. They have addressed the topics of cell division, the greenhouse effect, nerve signal transmission, and the carbon cycle. In this work, they use a conceptual metaphor perspective to analyze student and scientist conceptions so as to characterize the learning demand in each domain. Based on this analysis, they design external representations that they use in teaching experiments. They illustrate that they are able to use these representations to get learners to map an image schema that they had previously failed to map to a particular target scientific concept.

The conceptual metaphor perspective has also been used to evaluate instructional analogies. Amin et al. (2012) analyzed the conceptual metaphors implicit in pedagogical discourse dealing with entropy and the second law of thermodynamics. They identified which conceptual metaphors are commonly and systematically used in a range of science textbooks to construe entropy and the second law. They argued that this can help educators select instructional analogies that are likely to be particularly effective, if it is assumed that learners must appropriate the mappings implicit in the language of science they encounter. If this assumption is correct, then an explicit instructional analogy is more likely to be effective if the mappings it involves are consistent with those implicit in the language students encounter. For example, Amin et al. hypothesized that entropy-as-freedom is likely to be more effective than entropy-as-disorder. They showed how the mappings of the entropy-as-freedom analogy are more consistent with the mappings of the conceptual metaphors implicit and yet pervasive in pedagogical discourse on the topic. Whether or not this analogy is particularly effective still needs to be confirmed empirically. Niebert et al. (2012) also used a conceptual metaphor perspective, but took another approach to evaluating instructional metaphors and analogies. In their study, they surveyed the science education literature and reanalyzed 199 instructional metaphors and analogies from a conceptual metaphor perspective. They concluded that effective metaphors and analogies are those that incorporate source domains that derive from bodily based experience—that is, image schematic source domains.

Amin et al. (2012) considered the pedagogical implications of conceptual metaphors implicit in the scientific language that students encounter. In contrast,

Haglund, Jeppsson, and Ahrenberg (2014) have examined the instructional implications of conceptual metaphors implicit in *everyday* language. Using analyses of large everyday language corpora (in English and Swedish), Haglund et al. (2014) reveal the extensive metaphorical use of the word ‘momentum’ in many everyday contexts including sports, politics, and others. They compare how the word is used in these everyday contexts to how it is used in physics. They conclude that there is substantial overlap in these uses, in contrast to the much noted discrepancy between the everyday and scientific use of ‘force’. They argue that their analysis suggests that it might be productive to introduce the concept of momentum in science curricula much earlier than is typical.

In sum, a conceptual metaphor perspective can guide the design of formative assessment tools and instructional representations and learning environments, can help in the evaluation and selection of analogies, and can suggest curricular innovations. The role of representations and analogies as tools to induce conceptual change is well known (e.g. Clement, 2009; Gentner, 2010; Gilbert & Treagust, 2009). However, the perspective of conceptual metaphor offers a novel basis to approach the design and selection of representations and analogies. That is, the design and selection can be performed with knowledge of the image schematic grounding of scientific concepts and the metaphors implicit in everyday and scientific language.

New Directions for Research on Conceptual Change Suggested by Adopting a Conceptual Metaphor Perspective

We saw in the previous section that the existing literature on conceptual metaphor in science education makes a number of contributions to the study of conceptual change. However, this research has been presented so far as if it draws on a single, monolithic perspective. Moreover, a positive slant has been taken to point out the contributions of the perspective to studying conceptual change. In this section, I discuss points of contrast between the assumptions made by different researchers in this emerging area of research as well as some limitations of the perspective. Highlighting these points of contrast and limitations raises empirical questions about the role of conceptual metaphor in conceptual change and points to directions for further theoretical development. So in this section, I discuss the potential for further contributions suggested by adopting a conceptual metaphor perspective. Three themes are highlighted: the contrasting views of language, either as a tool for the researcher or as a tool for thought; stability versus contextual variation in conceptualization; and the need for an explicit account of concepts that incorporates the phenomenon of conceptual metaphor within it.

Language as a Medium of Conceptualization Versus a Tool for the Researcher

As is clear from what has been discussed in this paper so far, there is a close connection between language and conceptual metaphor. The systematic mappings between conceptual domains are reflected in metaphorical expressions. However, researchers

using a conceptual metaphor perspective in science education have treated language differently. This difference can be expressed as the difference between viewing language as a tool for the researcher or as a medium of conceptualization and, thus, a tool of thought (Budwig, 1999). Many of the researchers reviewed earlier have treated language as a tool for the researcher to identify underlying metaphorical conceptions of students, teachers, or scientists (e.g. the work of Close, Lancor, Niebert, Scherr, and colleagues). In this work, when those studied use specific linguistic markers (e.g. verbs or prepositions), researchers treat these as indicating the use of image schematic knowledge structures to conceptualize physical situations. The idea that there are systematic mappings between particular abstract scientific concepts and certain image schemas is used to categorize instances of participant conceptions into broad classes (Lancor, 2014a, 2014b; Niebert & Gropengießer, 2015). Moreover, instructional analogies are evaluated by determining whether the source domains of the analogies consist of readily accessible image schemas (Niebert et al., 2012). In addition, when instructional environments have been designed in a way that embodies a conceptual metaphor (e.g. the construal of energy as a substance or vertical location), the focus has been on the design of *visual* representations (Scherr, Close, McKagan et al., 2012) and three-dimensional models (e.g. the human body in the Energy Theater strategy) (Close & Scherr, 2015; Scherr et al., 2013).

Using language as a tool for the researcher to identify student conceptions is reasonable (indeed necessary). However, it does not address the role of language as a tool of thought for the learner. Some of the work drawing on the construct of conceptual metaphor in science education has suggested that concept learning may involve appropriating language-based conceptual metaphors (Amin, 2009; Amin et al., 2012; Brookes & Etkina, 2007, 2009, 2015). In Amin (2009), I suggested that naïve conceptions of energy can be traced to metaphorical construals implicit in everyday language. I also suggested that metaphorical expressions in scientific language might trigger source domains that help learners understand scientific concepts. Brookes and Etkina (2007, 2009, 2015) have provided evidence for the importance of this process of appropriation. They show that overly concrete interpretations of metaphorical expressions in the language of science can lead to misconceptions. By showing that learning obstacles can be traced to construals implicit in the language of science, they are providing evidence that appropriation of construals implicit in scientific language is part of the concept learning process.

This finding leads to an important conclusion: metaphorical expressions invite the reader/listener to map some source domain onto some target, but the details of the mapping may vary from one person to another. Considering language as a tool for the learner raises various questions: How are learners' and scientists' interpretations of metaphorical expressions in the language of science different? What features of prior knowledge and the design of learning environments guide learners to interpret such expressions as scientists do? Moreover, an important methodological question arises when considering language as a tool for the researcher: How can a researcher

infer the nature of student conceptions when a piece of linguistic data is observed? Further research that addresses these questions is needed.

Stability Versus Contextual Variation in Conceptualization

The stability versus the contextual variation in conceptualization has been debated in the conceptual change literature for some time. A clear example of this debate has been the disagreement over the role of ontological classification of concepts in conceptual change. Chi (2005) and Chi et al. (1994) have argued that many misconceptions arise from a misclassification of scientific concepts within a substance, as opposed to a constraint-based interaction, ontological category. On this view, concept learning is seen to involve the reclassification of concepts from one incorrect, yet stable, ontological view to another. diSessa (1993) has argued that pre-instruction conceptions are not stable in this way, and questions the extent to which ontological classification of a concept can provide an adequate picture of pre-instruction knowledge.

In the science education literature using a conceptual metaphor perspective, parallel contrasting views on ontology in learner conceptions can be identified. In their initial work from this perspective, Brookes and Etkina (2007) assimilated the phenomenon of conceptual metaphor and the misconceptions that arise from interpretations of metaphorical language into Chi's ontological view (2005; Chi et al., 1994). They argued that students' overly literal interpretations of substance metaphors implicit in the language of science lead them to ontological misclassification of some scientific concepts. In contrast, Amin (2001) suggested that ontological construal of heat in student thinking could possibly *emerge* in specific reasoning contexts. Moreover, Dreyfus et al. (2014) and Gupta et al. (2010) have appealed to the phenomenon of conceptual metaphor to critique Chi's view. They argue that the pervasive use of substance metaphors by learners as well as scientists suggests a more flexible, dynamic view of ontological classification of concepts. Gupta, Elby, and Conlin (2014) provide evidence for very productive use of a substance construal of gravity by teachers in a professional development program while trying to explain why objects of different masses fall with the same acceleration. Similarly, Jeppsson et al. (2013) provide evidence of flexible ontological construals in the context of scientific problem-solving. More recently, Brookes and Etkina (2009, 2015) have acknowledged the variation in ontological construals of concepts across contexts of use (although noting some stability *within* contexts). The stable ontologies proponents tend to advocate avoiding ontologically misleading language during instruction. In contrast, those granting flexibility and the productive use of 'naïve' ontologies argue that this instructional strategy is not practical given the pervasive use of implicit metaphor in scientific language and could be harmful because it suppresses potentially useful conceptions. There is empirical evidence supporting both views. So before instructional implications of ontologies implicit in language can be adequately explored some resolution of this debate is needed.

It has been suggested (Amin et al., 2014; Jeppsson et al., 2013) that one way out is to make the distinction between explicit ontological stances and implicit ontological construals. Stability might be discerned when someone is asked to explicitly state his or her ontological belief regarding some concept or to reason with a concept when the ontology is explicitly represented. On the other hand, the phenomenon of pervasive use of conceptual metaphors implicit in language includes subtle shifts in construal that users of these metaphors are not aware of. Thus, it may be theoretically coherent to acknowledge *both* explicit conceptual stability and implicit contextual variability. Another approach to this dilemma might be to accept that the issue of ontological stability versus contextual variability may be resolved differently in different cases. For example, there might be stability in some cases due to consistency in the use of a conceptual metaphor (e.g. the substance metaphor of energy) (Amin, 2009; Vosniadou, 2009). A third possibility is to acknowledge that multiple ontologies might be used but combined into a stable conceptualization. This latter possibility is suggested by the work of Dreyfus et al. (2015) who show that both a learner and scientist readily blend two ontological metaphors: energy-as-substance and energy-as-location. Repeated use of this blend in certain contexts (e.g. reasoning about physical systems when considering a potential energy graph) might stabilize this blend of two ontological construals. This third possibility has become theoretically visible through Dreyfus et al.'s use of the theory of conceptual blending (Fauconnier & Turner, 2002) as an analytical framework. All three possibilities are theoretically plausible phenomena. Further empirical research addressing the question of ontological stability versus contextual flexibility is needed that considers all three hypotheses.

Incorporating Conceptual Metaphor into a View of Concepts

Throughout this paper, the word 'concept' has been used but there has been no explicit discussion of what the term means. Indeed, there is no explicit discussion of how to understand concepts in the literature on conceptual metaphor in science education. Moreover, the previous two subsections reveal that two themes—the relationship between language and conceptualization, and between stable and contextually varying conceptions—need greater clarity in the literature on conceptual metaphor in science education (if not the literature on conceptual change more generally). This clarity is needed if a sustained program of research is to emerge. In this final subsection, I briefly, yet explicitly suggest a way to incorporate the phenomenon of conceptual metaphor into a view of concepts that could help establish this emerging literature on conceptual metaphor in science education as a programmatic effort.

There already are various theoretical perspectives on concepts and conceptual change in the science education literature, with two perspectives dominating over the last two to three decades: the 'coherence' (e.g. Vosniadou, 2013b; Wiser & Smith, 2013) and 'knowledge-in-pieces' (e.g. diSessa, 1993, 2002, 2014) perspectives. The literature drawing on the notion of conceptual metaphor reviewed in this paper suggests that at least this construct needs to be incorporated into any

account. But neither the coherence nor the knowledge-in-pieces views have made much progress in incorporating attention to the role of language in concept representation and change (see Amin, 2009, for a discussion). Finally, the fault line of stability versus contextual variation no longer seems to reflect an accurate representation of disagreements in the science education literature on conceptual change more broadly (Amin et al., 2014). For all these reasons, attempting to formulate a new perspective seems warranted.

It is proposed here that a version of the view of concepts put forward by Susan Carey (2009) can help to address these issues. Very briefly, in Carey's view, concepts per se are understood as unitary, language-like symbols, whereas the *content* of a concept is understood in terms of the network of inferences in which it participates (its 'inferential role') and how it refers to entities in the world. The inferential role of a concept is specified in terms of a network of beliefs expressed in terms of propositional representations (e.g. language and mathematical representations) in which the concept participates as well as the iconic knowledge structures (e.g. images, image schemas, and mental models) that interpret these propositions.

I will illustrate this view of concepts by using the case of *energy*. Let us accept that the concept per se is simply some mental token triggered by the word energy (or symbol E). In order to characterize the content of this concept we must characterize the network of beliefs that it participates in (e.g. 'Energy is conserved across physical transformations'; 'Energy is transformed *from* potential *to* kinetic energy as an object falls to the ground'; 'When an object hits the ground, energy is *exchanged between* the object and the ground'; $KE = \frac{1}{2}mv^2$).³ These statements are interpreted and generate further beliefs based on images and image schemas, both possibly assembled into larger scale analogical mental models. These propositionally expressed beliefs and the imagistic representations that interpret them constitute part of the concept's inferential role. Those situations in the physical world to which it is appropriate to apply these statements and serve as the basis for their contextual interpretation constitute the second aspect of the content of the concept, its referential component. Carey does not discuss conceptual metaphor, but this phenomenon can be incorporated into this account through the propositionally expressed beliefs that implicitly mark mapping between the abstract concept of interest (e.g. energy) and image schemas. The linguistic pointers to these mappings are italicized in the examples above—the conceptual metaphors illustrated being *Forms Of Energy Are Containers* and *Change Of Energetic State Is Transfer Of A Possession/Substance*. Thus, the image schemas of *container* and *transfer of possession/substance* will contribute to the inferential role of the concept.

While this presentation is brief, I hope it can give a sense of how this view of concepts takes the role of propositional (language and mathematics) and iconic representations (images, image schemas, and mental models) seriously. Distinguishing these knowledge types and acknowledging their joint contributions to conceptual understanding in science education is not new (see Brown, 1993; diSessa, 1993), but this has not been discussed in an explicit account of concepts per se. Moreover, this

brief discussion has pointed out where the construct of conceptual metaphor relates to the notion of concept.

This view does not commit to one side of the longstanding stability versus contextual variation debate or the other. From this perspective a scientific concept's inferential role is made up of a vast network of beliefs applied adequately across a wide range of physical situations. Conceptual stability can be represented via the repeated (and joint) use of subcomponents of the network of beliefs/image schemas, whereas contextual variation can be captured by inconsistent and independent use of these subcomponents (Wiser & Smith, 2013). The extent of stability/contextual variation for both students and scientists should be seen as an empirical question examined in each domain of interest (see also Brown & Hammer, 2008, for an account in which stability and contextual variation can both be accommodated within a dynamic systems perspective). Finally, this account changes our view of ontology and how it relates to conceptual metaphor. The content of a concept is represented in terms of a network of propositional and iconic representations, with conceptual metaphors (sometimes concrete substance metaphors) implicit in beliefs. Therefore, an instance of use of metaphorical expression that reflects a conceptual metaphor (e.g. energy-as-substance) cannot be seen as classification of *the concept* within an ontological category, but rather a local, momentary construal. Instead, how concepts might be classified within broad ontological categories has to be determined by comparing whole networks of beliefs with one another.

This view of concepts suggests questions for future research. Two themes are highlighted here: first, characterizing student conceptions; and second, evaluating and designing instructional interventions that focus on the use of instructional analogies. First, with regard to characterizing student conceptions, the approach taken so far has been to catalogue the implicit metaphors in student speech and then infer the conceptions they hold. The research by Lancor reviewed earlier exemplifies this point. Identifying substance language to infer substance construals of energy in various scientific contexts is useful but constitutes a small part of characterizing students' *concepts* of energy. These metaphorical conceptions are implicit in beliefs that are themselves part of larger networks which need to be described. Moreover, the scope of application of these beliefs to physical situations needs to be determined. Future research from a conceptual metaphor perspective will need to conduct these more comprehensive characterizations. Second, with regard to evaluating instructional analogies, it is important to keep in mind that the content of concepts is to a large extent represented in terms of propositionally expressed beliefs. While these beliefs are *interpreted* in terms of images, image schemas, and models, these iconic representations do not fully characterize the target concept. Therefore, evaluating instructional analogies purely in terms of the extent to which accessible image schematic source domains are employed or strategically triggered (see e.g. Niebert & Gropengießer, 2015) is not sufficient. It is important to also evaluate the propositionally expressed beliefs that they encourage as well as their scope of application.

The extent to which the proposal made here will help synthesize and motivate programmatic research on conceptual metaphor in science education can only be

evaluated in hindsight. Any framework can only be evaluated by how productive it turns out to be. The goal of this proposal was to give a sense of key features of a view of concepts that incorporates the construct of conceptual metaphor and the types of questions that it motivates.

Conclusions

This paper has tried to show that a literature on conceptual metaphor in science education is emerging with goals that overlap significantly with those of research on conceptual change. This work has identified image schemas that students invoke when trying to understand scientific concepts; these can be productive but can also lead to misconceptions. It has identified multiple image schemas that ground understanding of scientific concepts through metaphor. It has shown that implicit metaphorical mapping between domains can be described by analyzing lay and scientific language. Moreover, it suggests that an aspect of the process of conceptual change might be the appropriation of metaphorical construals implicit in language. These findings have instructional implications. They suggest a way to approach formative assessment of student conceptions by identifying their repertoire of conceptual metaphors for a given concept. They suggest ways to design instructional representations that would trigger productive image schemas and select promising analogies that are consistent with conceptual metaphors implicit in pedagogical discourse. In addition, they have curricular implications, such as pointing to productive points of entry in some domain.

Identifying points of difference among researchers working on conceptual metaphor in science education suggests some directions for future work. In this paper, I have discussed differences in how language is viewed, either as a tool for the researcher or as a tool for thought. The fact that interpreting metaphorical language can vary from person to person poses challenges to the researcher trying to infer student conceptions from linguistic data. It also raises questions about what conditions (student knowledge and instructional environments) encourage interpretations that are more consistent with those of scientists. I have also discussed differences in assumptions about the stability versus contextual variability in conceptualization, with a focus on ontological classification. Different researchers provide evidence pointing to both stability and variability in ontological classification of concepts by learners and scientists. A number of hypotheses (not mutually exclusive) were put forward that might resolve this disagreement. I suggested that the degree of stability may vary from case to case; that it might be necessary to distinguish explicit ontological classification and implicit construals, where the former is stable and the latter contextually variable; and that stable and yet combined use of more than one ontological construal is a third resolution. Further work is needed to decide if any or all of these cases are plausible and common. Finally, the literature on conceptual metaphor in science education lacks, at present, an explicit view of the nature of concepts and one that incorporates the phenomenon of conceptual metaphor. I described one such view where the content of a concept is characterized in terms of a network of beliefs (the concept's inferential role) and the situations in the world to which it refers. This network of beliefs will include statements

that incorporate conceptual metaphors. This way of thinking about concepts suggests a number of directions for future work using a conceptual metaphor perspective. Chief among them is the need to describe learners' use and interpretation of metaphors as part of a wider characterization of their network of beliefs in a conceptual domain.

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Notes

1. The use of the descriptors "abstract" and "concrete" in this paper will be clarified later.
2. This latter point regarding metaphorical mappings implicit in everyday language is parallel to the point made in the science education literature about explicit instructional analogies. Even if a potentially productive source domain is provided by teachers, incorrect mappings performed by students can lead to misconceptions (see Glynn, 1989).
3. In principle, such a network is limitless! However, space limitations prohibit engaging with this issue here. See Carey (2009) for a proposal for how to identify that subset of beliefs that is key to the characterization of the content of a concept.

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