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CHAPTER 3

Coordinating metaphors in science, learning and instruction

The case of energy

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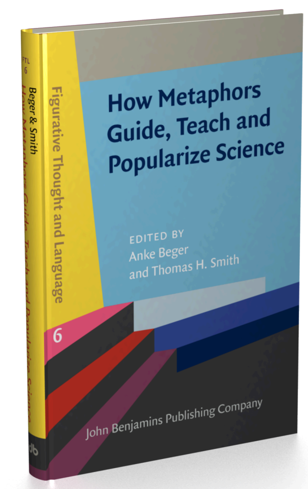

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CHAPTER 3

Coordinating metaphors in science, learning and instruction

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A substantial body of research has accumulated on the use of metaphor and analogy in science, their role in the construction of novel concepts during learning, and their strategic deployment in instruction. Despite this significant body of work, we still do not have a coherent picture of the role of metaphor in how a specific scientific concept comes to be understood. This chapter draws on the theories of conceptual metaphor and blending to put forward a perspective on how metaphor makes a scientific concept accessible; crucially, the account coordinates analyses of the roles of metaphor in science, learning and instruction. The chapter offers a case study of the concept of energy to illustrate the perspective.

Keywords: conceptual metaphor, blending, science, learning, instruction, energy

Introduction

There is a large and important body of work that has taught us a lot about the role of metaphor in science, learning and instruction. We have learned that creative leaps that have been very important in the history of science have often involved metaphor or analogy (e.g. Gentner & Jeziorski, 1993; Nersessian, 2008). We have learned a lot about the kinds of cognitive mechanisms involved when knowledge in an unfamiliar domain is built based on knowledge in another more familiar domain (e.g. Gentner, 1983; Glucksberg & Keysar, 1993). The same mechanisms have been shown to be at work in the minds of scientists as they come up with novel explanations of phenomena and the minds of learners making sense of scientific ideas that they encounter for the first time (Clement, 2009; Gentner, 1989; Gentner & Gentner, 1983).

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We have also learned a lot about *what* metaphors and analogies are effective in teaching difficult scientific ideas and *how* these metaphors and analogies should be introduced in classroom instruction (Aubusson, Harrison, & Ritchie, 2006). For example, we have learned that a single metaphor or analogy is often insufficient (and sometimes harmful) and that multiple metaphors or analogies carefully coordinated are sometimes needed to clarify different aspects of a challenging and complex idea (e.g. Spiro, Feltovitch, Coulson, & Anderson, 1989). This literature has been thoroughly reviewed (Bailer-Jones, 2002; Duit, 1991; Gentner & Wolff, 2000) and edited volumes have compiled these contributions comprehensively (Gibbs, 2008; Hallyn, 2000; Ortony, 1993; Vosniadou & Ortony, 1989).

In this chapter, I aim to offer a different perspective on metaphor and analogy in science, learning and instruction that incorporates three elements: (1) a focus on metaphor as a patterned discursive phenomenon in the language of scientists, textbooks and learners; (2) the embodiment assumption that an understanding of a scientific concept (even by scientists themselves) is grounded metaphorically in knowledge derived from sensorimotor experience and involves the coordination of multiple metaphorical mappings; and (3) the claim that to understand how a particular scientific concept comes to be understood we need coordinated analyses that examine the use of metaphors in science, by learners and in the context of formal instruction in classrooms. That is, I use the word "coordinate" in this chapter in two senses: to understand the role of metaphor in learning science our *analyses* in different contexts – in science, in learning, and in instruction – must be *coordinated*; moreover, we will find that one of the features of scientific expertise is the ability to *coordinate* – that is, use together strategically – a variety of different metaphors in a variety of contexts. Research is increasingly providing accounts of the patterned use of metaphor in the language of science, recognizing the embodied basis of scientific understanding and the implications of these phenomena for formal instruction have been addressed (see contributions in Amin, Jeppsson, & Haglund, 2015). However, no single account has brought together research on metaphor and analogy in the contexts of science, learning and instruction in a specific scientific domain.

A critical mass of research on the use of metaphor to conceptualize the concept of energy (and related concepts such as heat and entropy) has now emerged. Individual studies of my own and studies of others have examined implicit metaphors used by scientists and in the everyday (pre-instruction) language of the learner, described the implicit and explicit metaphors and analogies used by textbook writers and teachers, and discussed the role of metaphorical mapping in learning this abstract concept. In this chapter, I will bring together these individual studies to discuss how scientists ground their understanding of energy metaphorically in multiple image schematic knowledge structures (i.e. abstractions from sensorimotor experiences) and how this is reflected in the language of scientists and communicated in textbooks. I will also discuss some of the obstacles learners face in appropriating metaphors implicit in scientific discourse dealing with energy. Finally, I discuss the implications of these phenomena for formal instruction. Along the way, I will point out where there is a need for further research to fill gaps in our understanding.

The scientific concept of energy

Central to the concept of energy is the notion that there is a quantity that remains unchanged across the many changes that occur in the physical world. Objects interact with each other resulting in changes of speed and the rises and falls in temperature of the objects concerned; gases can be expanded and compressed, resulting in changes in the volume, pressure and temperature of the gas, the container and its surroundings; chemical reactions can occur involving the breaking and forming of bonds between atoms and changes in the temperature of reactants and products; and chemical reactions and physical transformations can occur within biological systems to support the vital processes of life. And, across all such changes, the quantity we refer to as *energy* remains unchanged; this is the principle of *conservation of energy*.

To keep track of this conserved quantity across this variety of changes, scientists follow *energy exchanges* between components of a system such as colliding objects and the interaction of gases with their containers and its surroundings. Heat, the transfer of the (kinetic) energy of motion from hot to cold objects is an example of energy exchange. Scientists also track the different *forms* in which energy can be manifested such as the motion of objects, compressed springs, and chemical bonds. Finally, they distinguish between forms of energy in their capacity "to do work," contrasting say a falling weight that lifts another (a useful form of energy) to the diffuse motion of millions of randomly colliding particles (not very useful). The latter kind of energy is said to be *degraded* in contrast to the former. Entropy is a quantity that captures the tendency of natural processes to occur such that energy is increasingly degraded. So not only is energy conserved (the first law of thermodynamics), spontaneous processes are governed by the principle that entropy will increase, energy transformations will occur such that energy is increasingly degraded (the second law of thermodynamics). Thus, the scientific concept of energy has four basic aspects: it can be exchanged, it can be manifested in a variety of forms, it is conserved across physical changes, and it has a spontaneous tendency to be degraded. Moreover, energy is not "a thing" but is an abstract, mathematical quantity.

Perspectives on metaphor: Conceptual metaphor and blending

Given the abstract mathematical nature of the concept of energy, it is not surprising that metaphor has often been recruited to make sense of all four of its basic aspects. For example, the phrase "energy *exchange*" is often used without awareness of its metaphorical nature. Most literally, the energy of some component of a system is a *state* captured by scientists as a mathematical quantity. When two components interact, there can be a reduction of the energy state of one component and an increase in the other. Nothing is literally *exchanged*; no *thing* passes from one component to another. But the word "exchange" does quickly convey the idea of the reduction of a state of energy of one component concomitant with, and causally related to, the increase (by the same amount) of the state of energy of the other. The simple schematic image of the *transfer of a substance from one location to another* concisely and concretely conveys the various aspects of the idea: reduction of energy state of component 1 (conveyed by the idea of *loss* of a substance/possession), increase of energy state of component 2 (conveyed by the idea of *gain* of a substance/possession), the reduction in 1 is equal to the increase in 2 (conveyed by the idea that with transfer of a substance/possession what is lost *is* what is gained), and interaction between the two is the cause of this mutual change (conveyed by the notion of transfer, which inherently links the gain to the loss of substance and requires some kind of spatial/temporal contiguity).

A similar metaphorical unpacking can be offered for many apparently non-metaphorical expressions that are in common use in talking and writing about energy: 'we find energy *in* various forms,' 'energy is transformed *from* potential *to* kinetic energy,' 'the energy *absorbed ejects* an electron,' 'the energy is *lost* as heat,' and 'the increase in entropy *drives* the process." This kind of implicit use of metaphor is found in the language of science, in the language of the layperson talking about energy and heat as everyday notions, and in the textbooks, lectures and classroom discourse to which learners are exposed. The question I address in this chapter is how to analyze this use of metaphor both within and across different contexts of language use to see the order and pattern in what might seem to be a haphazard phenomenon. Moreover, I try to draw out the pedagogical implications of this patterned, yet complex, discursive phenomenon.

Two related theoretical perspectives from the field of cognitive linguistics – Conceptual Metaphor and Blending – have provided researchers interested in metaphor in science, learning and instruction with useful analytical tools to discern some order in this apparent discursive chaos. In this section, I introduce each of these two theoretical perspectives briefly. I then turn to a discussion of how researchers have used them to study the metaphorical construal of energy (and the related concepts of heat and entropy) in science, learning and instruction.

Conceptual metaphor theory: Identifying conceptual patterns underlying language use

The framework of conceptual metaphor was developed by Lakoff and Johnson in their seminal books *Metaphors We Live By* (1980) and *Philosophy in the Flesh* (1999). In these books, they pointed out that many expressions in everyday language which are assumed to be literal are, on closer scrutiny, actually instances of metaphorical language use. Moreover, they argued that what might seem to be random instances of fossilized metaphorical expressions are in fact manifestations of underlying systematic mappings between conceptual domains. For example, 'I have a cold'/ 'I have patience,' 'I caught a cold'/'I'm losing patience' and 'He gave me a cold'/'Her presence gave me patience' can be seen as reflecting a set of related metaphorical mappings between conceptual domains; namely, STATES ARE POSSESSIONS, CHANGE OF STATE IS MOVEMENT OF A POSSESSION, and CAUSED CHANGE OF STATE IS FORCED MOVEMENT OF A POSSESSION, respectively.

These three mappings can be seen as sub-mappings of a more general conceptual metaphor that Lakoff and Johnson called the Object Event Structure metaphor. The source domains in these mappings include notions like *possession*, *movement*, *force* etc. A key claim of the theory of conceptual metaphor is that many of the source domains of conceptual metaphors derive from our early sensorimotor experiences of moving about, manipulating materials, giving and receiving objects, putting things in and taking them out of containers, etc. Abstractions from these experiences give rise to knowledge structures – referred to as image-schemas – that are analogical representations of those experiences (Johnson, 1987). Because many abstract concepts are conceptualized metaphorically in terms of image-schemas, our understanding of these abstract concepts is said to be embodied.

In addition to systematicity, the phenomenon of conceptual metaphor underlying language also involves subtle shifts of perspective. For example, 'I'm in love,' 'I fell into a depression' and 'He pulled me out of this grim mood' reflect the conceptual mappings STATES ARE LOCATIONS, CHANGE OF STATE IS MOVEMENT, and CAUSED CHANGE OF STATE IS FORCED MOVEMENT, all sub-mappings of the Location Event Structure metaphor. The two conceptual metaphor systems – object and location event structure metaphors – involve subtle figure-ground reversals: in the first, states are things which can move from one location to another, with locations representing the entity the state of which we are concerned with; in the second, it is the state that is construed as the location and it is the entity that is changing state that is construed as moving. These are just two of the very many metaphorical patterns identified by Lakoff and Johnson and other researchers; a vast literature now documents very many metaphorical mappings, sets of mappings, perspectival shifts and a wide range of metaphorical phenomena (Kövecses, 2010).

Blending theory: Conceptual dynamics in the flow of discourse

In parallel, a framework referred to as Blending (or Conceptual Integration) Theory was developed by Fauconnier and Turner (Fauconnier, 1996; Fauconnier & Turner, 2002). Blending theory has also been concerned with mappings between conceptual domains underlying language use. Two key features of blending theory are worth noting that distinguish it from the theory of conceptual metaphor.

First, blending theory describes mappings between more than two domains and does not assume that mappings are always unidirectional from a source to a target domain. Instead, elements of language (and other symbol systems) are seen to invite language users to invoke a number of conceptual frames, identify correspondences between these frames and often map elements of both into a blend. Consider, as an illustration, an example discussed in Turner and Fauconnier (1995). In 1993, a catamaran sailed from San Francisco to Boston in an effort to break the record of a clipper that sailed the same route in 1853. At some point while the catamaran was still at sea, a newspaper reported that "the catamaran was 'barely maintaining a 4.5 day lead' over the clipper."

As Turner and Fauconnier explain, this sentence cannot be understood without invoking two distinct conceptual frames (they use the construct of a conceptual "space"): one in which the catamaran is conceptualized as sailing in 1993; and another in which the clipper is sailing in 1853. To make sense of the sentence a third frame (space) is needed into which the two boats and the route are projected, the dates in the two cases are not projected and the idea of a race is invoked so that the notion of competition and 'breaking a record' can be made sense of. Fauconnier, Turner and many others have now documented many ways in which linguistic elements (and the elements of other symbolic systems) invite language users to invoke mental spaces and selectively project these onto a blended space for the purposes of communication and reasoning (Fauconnier & Turner, 2002).

A second key contrast with conceptual metaphor theory is that blending theory has also been concerned with mappings that are novel and emerge on the fly during the course of discursive interaction. Conceptual metaphors are stable, often very conventional mappings, reflected in conventional language use. Blends can be stable and reflect patterns of projection that are highly conventionalized (consider for example conventional counterfactual constructions such as "If I were you I would …"). However, blends will often be constructed for the first time in a given discursive moment and so interpreting this on the part of the listener will require creative, interpretive leaps performed quickly during an exchange.

The metaphorical construal of energy in scientific discourse

These two perspectives have been used to examine the use of metaphor to construe the concept of energy in scientific discourse. In this section, I synthesize this body of work. I use the term "discourse" to encompass the use of a variety of representational forms such as language, diagrams, gestures, and equations (often used together) to achieve some purpose (Gee, 1996). The set of analyses discussed here provide a picture of a discursive complexity within which order can be discerned when conceptual metaphor and blending perspectives are adopted as lenses of interpretation. The analyses are organized in terms of the four aspects of the concept of energy outlined above: transfer, transformation, conservation and degradation. Considering energy transfer and degradation means that we must also look at the concepts of heat and entropy, respectively.

Metaphorical construal of energy: Transfer, transformation and conservation

In Amin (2009), I reported an analysis of the metaphorical use of the term *energy* in *Feynman's Lectures on Physics* (Feynman, Leighton, R., & Sands, 1963). Feynman's metaphorical construal of energy was found to be extensive. Consider the following sentences from Feynman's text:

> It [the atom] either *gains* or *loses* energy, depending upon whether the piston is moving one way or another when the atom strikes (I–39–7)
>
> …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)
>
> …the energy *goes up* very rapidly because they repel each other (I–14–7)
>
> It is not always easy to *separate* the total kinetic energy of a thing *into two parts*, kinetic energy and potential energy. (I–14–6)

To identify what systematicity exists in Feynman's extensive use of metaphor, I conducted an analysis of a large corpus of sentences in which the term energy appears, organizing all metaphorical construals of energy in terms of the first three aspects of the concept of energy: exchange or transport, transformation and conservation (metaphorical construal of energy degradation is not readily seen simply by analyzing the use of the term *energy*; see discussion of entropy and the second law of thermodynamics below). A conceptual metaphor perspective was used to group metaphorical expressions into categories where each category reflects a mapping between the same source and target domains.

To construe energy *exchange* between different components of a system, Feynman systematically employs sets of mappings that are sub-mappings of the object event structure metaphor (OES) (Lakoff & Johnson, 1999) and elaborations of it. The sub-mappings identified are listed below, with phrase fragments used in brackets to illustrate (for more complete illustrations see Table 2 in Amin, 2009):

1. ENERGETIC STATE IS A POSSESSION ('the energy an object *has*')
2. CHANGE IN ENERGETIC STATE IS MOVEMENT OF A POSSESSION ('it *gains* or *loses* energy')
3. CAUSED CHANGE IN ENERGETIC STATE IS TRANSFER OF A POSSESSION ('how much energy will they have *given to* the material')

The above mappings amount to the application of the OES system of mappings, also found extensively in everyday language as seen earlier, to scientific discourse dealing with the concept of energy. The construal of energy as "possessed" by some component of a system is further elaborated: energy is understood as the content of a container (see 4 & 5 below); this content can also be further construed as a resource that can be used for some purpose (see 6 & 7 below):

4. ENERGETIC STATE IS CONTENT OF A CONTAINER ('energy *in* an electric field')
5. CHANGE OF ENERGETIC STATE IS MOVEMENT INTO (OR OUT OF) A CONTAINER ('we *put* energy *into* the gas')
6. ENERGY IN SOME FORM IS A RESOURCE ('the energy *stored in* inductance').
7. ACCESSING STORED ENERGY IS REMOVAL OF RESTRAINT ('when we burn gasoline energy is *liberated*')

In contrast, *forms of energy* and *energy transformation* are metaphorically construed in terms of the sub-mappings of the location event structure (LES) metaphor. As mentioned earlier, this involves a figure-ground reversal when compared to the OES metaphor (i.e. where, in the OES metaphor, states are construed as possessions and the entities in some state as possessor or container, in the LES metaphor states are construed as the container). Applications of the LES metaphor are as follows:

8. FORMS OF ENERGY ARE LOCATIONS/CONTAINERS ('existence of energy *in* other forms')
9. CHANGES OF FORM OF ENERGY IS MOVEMENT INTO (OUT OF) CONTAINERS ('*goes back* and *forth bet*ween compressing and stretching the spring and the kinetic energy')

In mappings 8 and 9 above, it is the forms of energy themselves that are construed as containers. This construal of energy forms as containers and transformations as movement in and out of containers allows the scientist to keep track of different manifestations of energy.

The third aspect of energy addressed in this analysis was *conservation*. To account for energy conservation, it is necessary to quantify energy states of various components of a system and keep track of contributions of the energy states of components to the energy of the whole system, which must be conserved. A variety of different metaphorical mappings support this process of quantification and documenting conservation:

10. ENERGY STATE IS AMOUNT OF SUBSTANCE ('the *amount of* energy')
11. INCREASE/DECREASE IN ENERGY STATE IS MOVEMENT OF AN OBJECT/ENERGY ON A LINEAR SCALE ('the energy *goes up*')
12. ENERGY STATES ARE LOCATIONS (on a vertical scale) ('they are *in* the lowest energy state')
13. ENERGY STATE INCREASES/DECREASES (OF A SYSTEM COMPONENT) ARE MOVEMENTS (of the system component) ('a *transition from* energy E3 *to* energy E1')
14. CAUSING ENERGY STATE INCREASES/DECREASES IS FORCED MOVEMENT (ON A VERTICAL SCALE) ('*acceleratin*g electrons *to high* energies')
15. ENERGY OF A SYSTEM COMPONENT IS A PART OF A WHOLE ('*separate* the total energy of thing *into two parts*')

The analysis above identifies fifteen different mappings between an aspect of the concept of energy (target domain) and an image-schematic source domain. The presentation above groups these mappings together in sets, often as sub-mappings of a more general mapping between broader source and target domains; thus, there is systematicity that cuts across this diversity of metaphorical usage. Indeed, the fifteen mappings can be distilled to three distinct metaphorical construal types: energy as a substance (which can be construed as a resource *for* some purpose and in terms of parts of a whole and can be exchanged between system components and transformed from one form to another); energy forms as containers; and energy states as locations on a vertical scale.

This summary statement is consistent with the conclusions arrived at by Scherr, Close, McKagan and Vokos (2012) in their analysis of the representations of energy in scientific discourse, including an analysis of the language of scientists and the visual representations they use (e.g. bar and pie charts, energy level diagrams). They highlight energy as a substance and energy as a location on a vertical scale as two alternative representations of energy used by expert scientists. They refer to these as two "ontologies" for energy: two different broad conceptualizations of the nature of energy. Of course, Scherr et al. are well aware that scientists don't take these conceptualizations literally, but that they metaphorically (consciously or not) ground understanding of this abstract concept in image schematic structures.

Scherr and colleagues point out that the substance metaphor is particularly powerful in that it supports understanding of energy conservation, that energy can be localized, can be located and can accumulate in objects, can be transferred between objects, and can change form. Of course, it is important that in scientific contexts energy is conceptualized as a substance that is not *substantial* – that is it cannot be seen, has no mass and can occupy the same physical locations of actual objects. For this reason, authors often caution that it is best to see this metaphor as involving a *quasi*-material construal of energy (Duit, 1987). But despite this caveat, the substance metaphor of energy is useful, when viewed from a conceptual metaphor perspective, because the inferences generated by the image schemas that make up the source domain of the metaphor are preserved when reasoning about the target domain. These can be laid out explicitly in the following correspondences:

i.	When a substance is transferred from a source to a recipient, the amount of substance possessed by the source decreases and the amount possessed by the recipient increases by the same amount.	When energy is transferred between two components of a system, the energy state of one component decreases and the state of energy of the other increases by the same increment.
ii.	A container gains some amount of a substance, *because* it has received this amount of substance from some source.	The energy state of some component of a system increases to some degree, *because* the energy state of another component (with which it has interacted) has decreased to some degree.
iii.	When an object made of some substance is transformed into another object, the amount of substance is the same before and after the transformation.	When some form of energy is transformed into another form the amount of energy is the same before and after the transformation.

The construal of forms of energy as containers and transformation of energy as movement between containers produces a correspondence of inferences that complements (in fact combines) *i* and *iii* above:

iv.	When a substance is transferred from a source to a recipient, the amount of substance possessed by the source decreases and the amount possessed by the recipient increases by the same amount with the total amount of substance remaining the same.	When energy is transformed from one form of energy to another, the amount of energy no longer in one form is the same as the amount of energy that has come to be in another form; thus the amount of energy is the same before and after the transformation.

These correspondences show the value of the construal of energy as a substance. But it is important to realize that this is just one metaphorical mapping that is useful for specific purposes – namely, understanding energy exchange, transformation and, crucially, conservation. But as Dreyfus and colleagues have argued, the substance metaphor does not provide much support for conceptualizing negative energy (Dreyfus et al., 2014). They have pointed out that the construal of energy state as a point on a vertical scale lends itself well to situations in which negative energy needs to be considered.

The presentation of the metaphorical construal of energy so far has focused on individual conceptual metaphors in isolation of one another. Moreover, linguistic illustrations of the metaphorical mappings have been single sentences or phrases, taken out of context. As mentioned earlier, blending theory (Fauconnier & Turner, 2002) has also been concerned with the description of mapping between conceptual frames, but with attention to the emergence of meanings in specific discursive exchanges, with attention to representational modes beyond language and with attention to the blending of elements from multiple conceptual frames, not just unidirectional mapping from a source to a target domain. Dreyfus, Gupta and Redish (2015) have used the conceptual blending framework to analyze a physics professor's lectures. Their analysis attended to multiple representational modes: language, gestures used by the lecturer and graphical representations drawn on the board while lecturing. Using a conceptual blending framework to examine how the conceptualizations of energy were conveyed by the professor in his lectures, they were able to identify what they refer to as an ontological blend of both the substance and the location construal of energy. They identify this blend in the context of a lecture on the formation and breaking of a bond between atoms. The professor draws on the substance metaphor to conceptualize energy *absorbed* (when the bond is broken) and energy *released* (when the bond is formed). He simultaneously makes use of the ENERGY STATE IS A LOCATION metaphor to conceptualize the change in the energy state of the two atom pair. Dreyfus et al. (2015) present a detailed analysis of the coordination and blending of these metaphors by the professor as he explains the causal connections between the input and release of energy and the change in the energy state of the two interacting atoms. They show how language, elements of the graph drawn on the board and gestures play complementary roles in guiding the projection of conceptual frames into a powerful conceptual blend.

Metaphorical construal of energy transfer as heat

To expand this presentation of the metaphorical construal of the concept of energy in science, I turn to two closely related concepts: heat and entropy. I begin with heat. The understanding of energy transfer metaphorically in terms of a substance is further exemplified in the specific case of the concept of heat, which is the exchange of energy between components of a system as a result of heating (i.e. the transfer of kinetic energy). When explicitly defining heat, scientists will treat heat as a process: heat *is* the *exchange* or *transfer* of energy. But, as Brookes (2006) has documented through a careful grammatical analysis of the use of the noun *heat* in widely used introductory physics textbooks, heat is very often construed ontologically as a substance. That is, even when textbook writers are careful to emphasize the nature of heat as a process when defining heat explicitly they will often write as if heat is a substance, as in the following examples (quoted in Brookes, 2006, p. 114, emphases added):

> "Heat … can be *added to* or *withdrawn from* the gas …"
> "… heat *flows from* …hotter cup …*into* …cooler hand."
> "The heat *rejected* by this engine …"

As Brookes discusses, this substance metaphor for heat is an encoding in modern scientific language of the eighteenth century Caloric Theory of heat, in which heat was explicitly conceptualized as a substance that raises the temperature of a material as it accumulates in it. While attempts to weigh this caloric failed and heating was increasingly associated with motion, conceptualizing heat as a substance (in some sense) persisted well into the nineteenth century. Scientists eventually abandoned any explicit belief in heat being a substance. However, construing it metaphorically as a substance continues to be useful in the context of the need to quantify energy exchange via heating and to track this exchange between components of a thermodynamic system.

Metaphorical construal of entropy and the second law of thermodynamics

The aspect of the concept of energy that has not yet been discussed is the relative usefulness of some forms of energy – i.e. energy can be degraded and thus become less useful; and the idea that while all physical changes conserve energy, some changes are more likely to occur spontaneously than others. If the law of conservation of energy is the *first* law of thermodynamics, the *second* law of thermodynamics dictates that any spontaneous process must occur such that the net result is an increase in the degradation of energy in the universe.

The concept of entropy captures this idea: spontaneous processes occur such that the entropy of the universe increases. Conceptual metaphors are used richly to conceptualize this idea as well. The metaphorical mappings used to construe energy transfer, transformation, and conservation presented above illustrate the systematic nature of the use of metaphor in scientific discourse. An analysis of the metaphors used to construe entropy and the second law of thermodynamics also reveal the systematic metaphorical mappings underlying the diversity of metaphorical expressions used in this scientific domain.

Furthermore, three additional metaphorical phenomena are well illustrated in this case: that different conceptual metaphors are used to construe the same concept in different contexts; multiple conceptual metaphors are coordinated together to support scientific reasoning; and a narrative form of thought can emerge as a result of the coordinated use of multiple metaphors thereby grounding and simplifying abstract and complex chains of scientific reasoning.

The results of two studies reported in Amin, Jeppsson, Haglund and Strömdahl (2012) and Jeppsson, Haglund, Amin and Strömdahl (2013) can be used to illustrate these phenomena. Amin et al. (2012) analyzed widely used university level textbooks that cover the concept of entropy and the second law of thermodynamics to identify the implicit conceptual metaphors used to conceptualize aspects of this domain (Bowley & Sánchez, 1999; Young & Freedman, 2003; Zumdahl, 1998). These textbooks spanned different sub-specializations (physics and chemistry) and degrees of sophistication (introductory university coverage and more mathematized treatments for more advanced students). Moreover, they each covered the topic at both the macroscopic level in which thermodynamic systems are characterized in terms of macroscopic variables, such as temperature, pressure and volume; and the microscopic level where very large numbers of interacting particles and their statistical properties are considered. The study identified the conceptual metaphors that were common to all three textbooks and thus could be considered to be representative of the pedagogical discourse in this domain.

The conceptual metaphors identified were reported as sets of conceptual mappings that were commonly used to construe the concept of entropy and the second law of thermodynamics at the macroscopic level, the microscopic level and the relationship between the two levels. A key finding of this study was that a particularly large number of metaphorical mappings could be identified in the macroscopic treatment of the topic. But despite the many mappings identified, they were mostly sub-mappings (sometimes with elaborations) of either the Location Event Structure or Object Event Structure conceptual metaphors applied to thermodynamic systems. The sub-mappings of the Location Event Structure metaphor were as follows:

16. STATES OF A SYSTEM ARE LOCATIONS ("…the three phases are present *in* thermodynamic equilibrium …")
17. CHANGES IN A SYSTEM ARE MOVEMENTS ALONG A PATH ("…the process *goes from* state 1 … *to* state 2 …")

18. CAUSED CHANGES TO A SYSTEM ARE FORCED MOVEMENTS ("…*driving force* for a spontaneous process is an increase in the entropy …")
19. SPONTANEOUS CHANGE IS DIRECTED MOVEMENT ("…the natural progression of things is *from* order *to* disorder …"
20. SPONTANEOUS CHANGES ARE AGENTIVE (SOMETIMES SENTIENT) MOVEMENTS ("… the second law of thermodynamics … determines the *preferred direction* for such processes …"
21. MAINTAINED STATES OF A SYSTEM ARE BLOCKED (POTENTIALLY MOVING) OBJECTS ("…n and T are *held* constant in this experiment …"
22. A SCIENTIFIC LAW/PRINCIPLE/EQUATION IS A SOCIAL LAW ("…a *forbidden* process would be if all the air in your room spontaneously moved to one half of the room …")

The set of conceptual metaphors above (all sub-mappings of the location event structure metaphor and elaborations of it) produce a coherent system of metaphorical interpretation of the states of thermodynamic systems and how they change. The system is construed as an object in some location that moves in different possible directions; this movement can be blocked, but it will naturally prefer to move in some directions more than others; and those preferred directions will be along paths it is allowed, by law, to follow.

Another (smaller) set of conceptual metaphors are sub-mappings of the Object Event Structure metaphor:

23. ENTROPY IS A POSSESSION ("…every substance *has* a positive entropy …")
24. ENTROPY OF COMPONENT/SYSTEM IS A PART/WHOLE ("The *total* entropy is the sum of the *entropies* of the two systems.")
25. CHANGE OF ENERGETIC STATE OF A SYSTEM (DURING SPONTANEOUS PROCESS) IS LOSS OF A SUBSTANCE (HEAT) ("…the energy it *gives up is transferred to* the surroundings … as heat.")

Here states are construed as a possession/substance, states of components of a system are construed as parts of wholes and changes of state are construed as movement of possession/substance. The above mappings apply this to the construal of entropy as a possession/substance and part/whole and energy state change (during a spontaneous process) as loss of a substance (heat). It is important to note here that this construal of energy transfer as *loss* is a metaphorical construal inconsistent with the use of the metaphor of substance exchange to make sense of conservation of energy. Here *loss* (expressed in the example by "gives up") needs to be interpreted differently. While statements that reflect this mapping are statements about *transfer* they are really standing in for *transformation*. This is not really surprising since we have already seen that forms of energy are construed as locations and energy transformation is construed as movement between locations. The notion of loss ("gives up") is capturing the idea that the energy is no longer "in" a useful form. It might be more precise to state/unpack the underlying mappings (inferred from this analysis) as follows:

26. DEGRADATION OF ENERGY IS TRANSFER OF A SUBSTANCE FROM AN ACCESSIBLE LOCATION TO AN INACCESSIBLE LOCATION

Two additional conceptual metaphors used to construe entropy in macroscopic treatments of the topic are:

27. A MATHEMATICAL FUNCTION IS A MACHINE (WITH OUTPUT SUBSTANCE) ("Our new expression for the entropy *gives* …")
28. CORRELATION IS ACCOMPANIMENT ("The entropy change *associated with* the mixing …")

The first applies a generic metaphor used to construe any mathematical function as a machine (whatever variables it may involve) to the concept of entropy. The result is that entropy is construed in this context as a substance produced by the Function/Machine. The second allows us to construe correlation between the variable entropy with another variable or process as the two entities accompanying one another.

This richness of metaphorical mappings was not found when metaphor use to construe microscopic process was examined in Amin et al. (2012). Only two sub-mappings of the Location Event Structure metaphor were identified, namely:

29. MICROSTATES ARE LOCATIONS ("…the number of arrangements (positions and/or energy levels) *available to a* system …")
30. CHANGE OF MICROSTATE IS MOVEMENT INTO/OUT OF A LOCATION ("…the molecules *go into* solution …")

Finally, three independent metaphorical mappings were identified in the context of relating macro- and microscopic levels of description:

31. RELATING IDEAS AT DIFFERENT LEVELS IS TO CONNECT THEM ("… we will *connect* entropy and the probability [of microstates] …")
32. MACROSCOPIC PROCESS ARE MACHINES THAT PRODUCE/MANIPULATE MICROSCOPIC PROCESSES ("A gas expands into a vacuum to *give* a uniform distribution [of particles in the container] …")
33. PROCESSES OCCURRING AT DIFFERENT LEVELS IS ACCOMPANIMENT ("…the decrease in disorder *associated with* the lowered temperature …")

It is important to remember that the sets of conceptual metaphors identified in the different contexts of the topic of entropy and the second law of thermodynamics by

Amin et al. (2012) were common across three different textbooks varying in their treatment of the topic. These spanned sub-specializations (chemistry and physics) and degree of mathematization of the topic. Thus, these sets of metaphorical mappings seem to be a stable feature of the pedagogical discourse to which learners are exposed when they encounter this topic. I assume here that the ability to use these conceptual metaphors in the appropriate way in particular contexts is an aspect of what students will need to learn. I return to this assumption and discuss some suggestive empirical evidence to support it later when I discuss a study comparing the use of conceptual metaphor to solve problems on entropy by students with different degrees of expertise.

But to provide a basis for that comparison, I turn first to a study that sought to explore how conceptual metaphors are used by individuals with a lot of scientific expertise when solving problems on entropy (Jeppsson et al., 2013). The results of this study can be used to illustrate that multiple conceptual metaphors are used together in a coordinated way (and coordinated with other types of cognitive resources) to support scientific reasoning in specific contexts; and that a narrative form of thought can emerge as a result of the coordinated use of multiple metaphors, thereby grounding and simplifying abstract and complex chains of scientific reasoning.

In Jeppsson et al. (2013), my colleagues and I report on a detailed analysis of a think-aloud problem-solving session in which two PhD students specializing in physical chemistry solve a series of problems dealing with the concept of entropy. For example, the first problem presented to the students was:

> *A beaker contains water at temperature 0 °C and is put in a room of air at a constant temperature of –10 °C, so that a layer of ice forms on top of the liquid water. Describe what drives forward the process of freezing the water.*

One of the claims emerging from the analysis performed in this study was that the abstract scientific reasoning involved in this problem-solving session involves recruiting and coordinating multiple conceptual metaphors. To illustrate this, consider an excerpt from the think-aloud protocol dealing with the first problem. (D1 and D2 refer to the two PhD students; the numbers indicate the turn in the transcript; some turns are not quoted below) (Jeppsson et al., 2013, p. 93–94).

[57] D2: /…/ Well, in this case … er, I guess it's simply that … if *I take heat from* this beaker with water … and *move over to* the room … in principle, then … the partition function in … for the room will increase … more than what *I lose* in the beaker, then …

[65] D2: dS is dQ over T, right …?

[66] D1: Delta S is equal to delta Q over …

[67] D2: T…/…/
[75] D2: So, in principle, that means that if the temperature is zero …
[76] D1: Uhum …
[77] D2: …Kelvin … then *you have* an infinite increase in entropy if *you get a small amount* of heat … and in principle … what I mean with this is that … [starts drawing a graph] now, let's see … delta S as a function of [T] for a certain delta Q, *one gets* something like this … so, maybe … the lower the temperature, the bigger the *entropy gain you get* if *you move some* heat *into* this system … so, that means for our heat bath system here … that if *you move a small amount of* heat *from* the water beaker *out to* the room … then, the entropy in the room will increase more than the entropy has decreased in the water beaker … due to the reason that it is colder in the room …

The analysis of the PhD students' discussion as they solved the problems led to a characterization of the role that conceptual metaphors played in arriving at a problem solution. The analysis sought to characterize the image-schematic source domains of conceptual metaphors as intuitive cognitive resources that could contribute to solving the problem. More specifically, of interest was how the PhD students used conceptual metaphors to construe the physical process under consideration qualitatively and to construe the quantities appearing in mathematical equations they evoked to solve the problem. First, a gloss of what the excerpt above reveals about how the students solved the problem might be helpful.

The students partitioned the system into two components: the water being cooled and the cold air surrounding it. They conceptualized the process of freezing of the water as a transfer of heat from the water to the air. They invoked the quantitative relationship between the change in entropy of some component of a system and the loss or gain of energy from that component as heat. The relevant formula is $dS = dq/T$ (i.e. change in entropy is equal to heat energy loss/gain divided by temperature). They compared the resulting dS for the water and air respectively, recognizing that the water lost and the air gained the same amount of heat but that the temperature of water was higher than the air. This meant that the decrease in the entropy of the water was less than the increase in the entropy of the air. Since the net result is an increase in entropy, this will drive the process forward.

Analyzing the excerpt from the perspective of conceptual metaphor reveals multiple metaphors at work in the students' conceptualization of the problem. Three of them we have seen already from the textbook analyses summarized above, but two of them are new to this context of problem solving. The words and expressions reflecting these conceptual metaphors are marked in italics in the excerpt above. The following five metaphorical mappings were identified (the numbers of the first three identify the mappings with those already mentioned earlier):

5. CHANGE OF ENERGETIC STATE IS MOVEMENT INTO (OR OUT OF) A CONTAINER ("…*take heat from* this beaker …*move over to* the room,"
23. STATE (ENTROPY) IS A POSSESSION/CHANGE OF STATE IS MOVEMENT OF POSSESSION ("…the *entropy gain* you get …")
27. A MATHEMATICAL FUNCTION IS A MACHINE (WITH INPUT AND OUTPUT SUBSTANCE) ("…let's see … delta S as a function of [T] for a certain delta Q …the entropy gain you *get*")
34. A PROBLEM SOLVER IS A MANIPULATOR OF A SYSTEM ("… if *I take* heat from this beaker with water …and *move over* to the water …;" "… if *you move* a small amount of heat from the water beaker out to the room …")
35. A PROBLEM SOLVER IS AN OPERATOR OF A MACHINE ("…the lower the temperature, the bigger the entropy gain *you get* …")

The first three conceptual metaphors (5, 23 and 27) have already been discussed. The last two (34 & 35) are new. A PROBLEM SOLVER IS A MANIPULATOR OF A SYSTEM is reflected in the use of the pronouns 'I' and 'you' to refer to some entity manipulating heat in the physical process under consideration. In this conceptual metaphor, the problem-solver construes herself as actively enacting the transfer of the heat from the initially warmer component of the system (the water) to the colder component (the cold air in the room) (conceptual metaphor 34). This conceptual metaphor is closely linked to conceptual metaphor 5 in which change in energy state is construed as movement of a possession (heat) between the components of a system.

Together these provide a metaphorical construal of the linked changes in temperature of the water and the air in the room. This is the qualitative starting point for making sense of this problem. To make sense of the quantitative part of the problem, the relevant equation was identified, $dS = dq/T$, and given a metaphorical interpretation as a machine (conceptual metaphor 27). This construal of the function as a machine, taking substances/objects as input to give out some other substance/object as output, is then coordinated with the relevant construal of change of energy state as movement of a substance (the input to the machine) and change in the state function entropy as movement of a substance (output).

In addition, conceptual metaphor 35 is a kind of linchpin for this coordination, where the problem-solver herself is manipulating the machine (offering input and receiving output). Notice that conceptual metaphor 5 is common in these two sets and serves to align the qualitative and the quantitative reasoning. Figure 1 provides a schematic illustration of this coordination of conceptual metaphors and the alignment between the quantitative and qualitative reasoning.

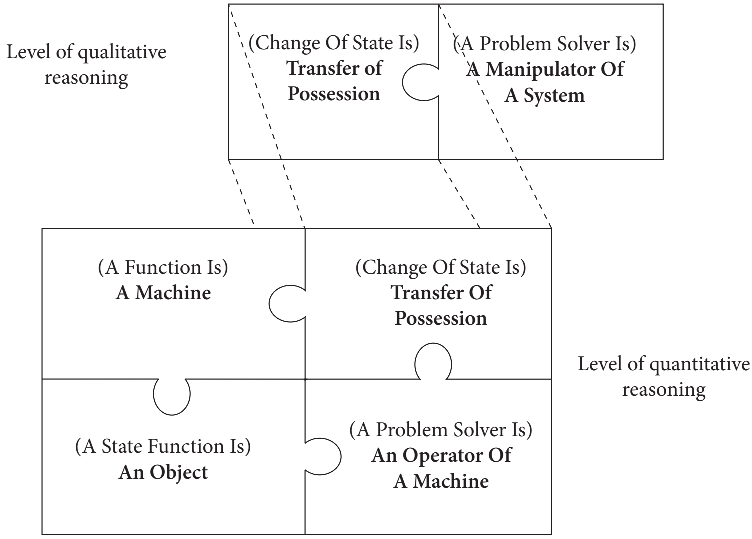

Figure 1. Coordination of multiple conceptual metaphors to align qualitative and quantitative reasoning during problem-solving (figure reproduced with permission from Taylor & Francis (https://www.tandfonline.com/); originally published as Figure 6 (p. 98) in Fredrik Jeppsson, Jesper Haglund, Tamer G. Amin & Helge Strömdahl (2013). Exploring the use of conceptual metaphors in solving problems on entropy, *Journal of the Learning Sciences*, 22:1, 70-120, DOI: 10.1080/10508406.2012.69192f)

One way to think about the coordination of the conceptual metaphors in the problem solution just discussed is that conceptual metaphors are invoked such that sets of source domains combine to create larger, coherent composite source domains. A second excerpt from the same problem-solving session illustrates this further and illustrates how these composite source domains can transform a segment of abstract and complex reasoning into a simpler and more concrete instance of narrative thought. In this excerpt, the PhD students are addressing another problem (Problem 3):

> *Consider a thermally isolated system of an inert gas held in a container by a frictionless piston. Let the gas expand reversibly by moving the piston. What happens to the system's entropy? Does it increase, decrease or remain the same? Justify your answer.*

A reversible process is one that occurs in infinitesimally small increments such that the system is in equilibrium at all times; the reference to the system being thermally isolated means that it does not exchange any heat with the surroundings. Given that both conditions hold $dS = dq/T = 0$ and it can be concluded that the entropy does not change as a result of the expansion of the gas that occurs. A key excerpt from the PhD students' response to this problem runs as follows (quoted from Jeppsson et al., 2013, p. 100)

[488] D2: So, the definition of a *reversible* process actually is that the entropy does not change …

[489] D1: Well, right … [draws a PV diagram] It is that … it's a question of that *one walks along the same line* … if one increases the volume … and then, when one decreases the volume, then …

[490] D2: … *you can get back to* the same state …

[491] D1: Yes, right.

[492] D2: Then you can't have had any entropy losses … because you can never decrease the entropy in an isolated system …

[493] D1: No.

[494] D2: Because if *you are going to be able to get back to the same point*, then you can't increase it either, right, because then you won't get back …

How is metaphor being used in this excerpt (see Jeppsson et al., 2013 for an expanded discussion)? First, notice the language (in italics reflecting the sustained use of a conceptual metaphor that we have already seen: CHANGE OF STATE IS MOVEMENT reflected in the use of *reversible*, *walks along the same line* and *get back to the same point/state.*

Another conceptual metaphor is reflected in the use of the pronouns "one" and "you" (underlined). We saw in the analysis of the previous excerpt two conceptual metaphors reflected in the use of pronouns: A PROBLEM SOLVER IS MANIPULATOR OF A SYSTEM and A PROBLEM SOLVER IS AN OPERATOR OF A MACHINE. Here we find another conceptual metaphor: A PROBLEM SOLVER IS A SYSTEM. That is, the pronouns "one" and "you" above are used with expressions in which the change of state of the system is construed as movement, and the pronouns refer to the entity doing the moving. The composite source domain involved in using these two conceptual metaphors involves an *agent walking along a path freely, able to move back and forth along that path unobstructed.*

This composite source domain is a brief instance of a narrative mode of thought, in which an agent is behaving to achieve some goal in a physical setting. To see the conceptual work that this (narrative) source domain is doing we should notice that metaphorical language in this excerpt is used while the problem-solvers are drawing and referring to a pressure versus volume (PV) graph. Thus, we have a situation where the pronouns "one" and "you" are simultaneously referring to the problem-solver, the physical system of the expanding gas under consideration and the points on the PV graph.

The mini-narrative is standing in for a complex chain of reasoning linking the qualitative consideration of an expanding gas, the quantitative graphical representation of the relationship between the variable of pressure and volume characterizing this gas and the problem-solver himself reflecting on the qualitative and quantitative aspects of the problem. Whereas we saw metaphor being used to *align* qualitative and quantitative reasoning in the discussion of the previous excerpt, here metaphor is used to *integrate* the two types of reasoning.

The challenge of learning to use metaphorical construals of the scientific concept of energy

Up until this point in this chapter, I have documented the use of conceptual metaphor to construe aspects of the concept of energy and the related concepts of heat and entropy in scientific contexts. We have seen that underlying the very many metaphorical expressions used in pedagogical discourse dealing with these concepts are sets of conceptual metaphors that are often sub-mappings of more general conceptual metaphorical mappings.

We have also seen that different conceptual metaphors are used to construe different aspects of a concept (e.g. *transfer*, *transformation* or *conservation* of energy), different levels of description of a topic (e.g. *macroscopic* or *microscopic* treatments of thermodynamic systems and the relationship between them), and different contexts (e.g. textbook presentations versus oral problem solving). Moreover, we have seen that advanced problem-solving involves the coordination of multiple conceptual metaphors in such a way that source domains combine coherently to create composite source domains.

An important question that arises from all this is 'does all this matter for learning?' After all, all that I have done so far is describe patterns of language use in various scientific contexts. The theory of conceptual metaphor, as developed by Lakoff and Johnson (1980, 1999) and others was a claim about *conceptual* mappings between domains that can be *inferred* from *patterns* in metaphorical expressions. The assumption here is that without some underlying conceptual phenomenon at work, we should not expect the systematicity that is in fact observed in language use. I endorse this assumption in the context of scientific discourse as well.

But to confirm the conceptual significance of the phenomenon of conceptual metaphor in scientific discourse and to characterize its contribution to scientific expertise and its acquisition more evidence is needed. In this section, I discuss a number of different sources of evidence. The first is a comparative analysis of the use of conceptual metaphors in solving problems on entropy across different levels of expertise. The second is a description of the conceptual metaphors implicit in everyday use of the word *energy* and how the source domains of these metaphors map onto the alternative conceptions of energy held by middle and high school students learning science in the context of formal education. Third, I summarize the results of a study that provides evidence of a link between the substance metaphor of heat and university students' mistaken treatment of heat as a state function while solving thermodynamics problems. Finally, I discuss evidence that, while a substance construal of heat is implicit in everyday English, this can both support and hinder students' reasoning in different scientific contexts. The framework of conceptual blending helps show how different aspects of this metaphorical construal of heat as substance can emerge selectively in different contexts.

Changes in the use of conceptual metaphors with the acquisition of expertise

In Jeppsson, Haglund and Amin (2015), we asked a pair of undergraduate chemistry students to think aloud together while they solved the same problems solved by the two PhD physical chemistry students previously discussed in Jeppsson et al. (2013). The undergraduate students' problem solving session was transcribed verbatim and the use of conceptual metaphors and their role in problem solving were described. We then compared the use of conceptual metaphors by the undergraduate and PhD students. In this study, we were also interested in the distinct roles of propositional representations (such as linguistically or mathematically expressed scientific principles) and the non-propositional (i.e. analogical) representations (such as the image schemas that constitute the source domains of many conceptual metaphors). Our comparative analysis of the problem solving at these different levels of expertise revealed a number of differences in the use of conceptual metaphors.

First, the undergraduates made much less use of conceptual metaphors in their problem-solving attempts. Second, when they did use conceptual metaphors this use was not 'productive.' That is, while the PhD students used conventional metaphors widely found in textbooks (e.g. CHANGE OF STATE OF A SYSTEM IS MOVEMENT) they combined these conceptual metaphors with others to create novel composite source domains in specific contexts and they used novel metaphorical expressions that reflected the same underlying conceptual metaphor (e.g. 'If I *walk* along the line). The more productive use of conceptual metaphors by the PhD students was also reflected in the more frequent metaphorical use of pronouns in which the problem solver is construed as interacting with or even identified with the thermodynamic system under consideration. As discussed above, this use of metaphor was strategic in simplifying and concretizing (in narrative form) a highly abstract chain of reasoning that required connecting qualitative and quantitative aspects of the reasoning.

This use of metaphor was not observed in the undergraduates' problem solving attempts. Thus, the few uses of conceptual metaphors by the undergraduates were isolated and highly conventionalized repetitions of metaphorical expressions to which they would have been exposed in lectures and textbooks. One could sum this up by saying that the undergraduates seemed not to have yet learned to use the conceptual metaphors productively like those with greater expertise in the domain.

In Jeppsson et al. (2013), we noted another indication that learning to use conceptual metaphors is implicated in conceptualizing and reasoning about entropy. In that study, we discussed an explicit hesitation among the PhD students as they discussed the expansion of a gas in a thermally isolated piston. The students did initially provide an accurate macroscopic interpretation of the problem and drew the correct conclusion that the entropy of the gas did not change. However, after providing this response they commented that the conclusion was not intuitive (Jeppsson et al., 2013, p. 95).

[507] D1: It's always strange to think that [the entropy] is the same … but, well … I guess that's what it is … it [the problem solving approach] goes straight to the entropy … that *it would be presupposed that one gets more locations to be in …*

[508] D2: Uhum … what I think happens there … is that you … if you get enthalpy losses, that turn into entropy …

[509] D1: Uhum … that you, well … lose in energy, there … then you get the entropy … well, it … *one maybe gains on larger volume, but one loses on not having accessible … all the energy states …*

[510] D2: Uhum …

[511] D1: And hence … the entropy is unchanged …

This exchange is full of metaphorical expressions that are all interesting to analyze in their own right. But what is of particular interest for the argument being developed in this section is that it provides evidence of the challenge of metaphorical mapping. At a microscopic level, change of entropy is linked to changes in the number of microstates that could be occupied by the system. The MICROSTATES ARE LOCATIONS conceptual metaphor is implicated here. However, the microstates potentially "available" to a system are not just spatial, involving the locations occupied by the particles that make up the system. Energy states also need to be considered. What the exchange above reveals is that the idea that entropy is linked to accessible microstates is intuitively related to the change of volume of the gas because an increase in volume provides the system with "more locations" to be in. That is, the significance of spatial/configurational microstates is obvious, and would lead one to conclude that change of volume results in an increase in entropy.

While less intuitive, the students are able to push their understanding of "accessible microstates" to include "energy states." Crucially, this involves a metaphorical mapping: energy states are construed metaphorically as locations. The excerpt above is revealing that some cognitive work is being done to guide this mapping. Their principled reasoning at the macroscopic level and their confidence in the conclusion that the entropy change should be zero has guided these students in the metaphorical mapping required at the microscopic level.

Conceptual metaphors in everyday language and learners' alternative conceptions

I turn next to another indication that conceptual metaphors are implicated in developing scientific understanding of the concept of energy. What is involved here though is the use of everyday metaphors and their role in shaping learners' alternative conceptions en route to their developing scientific understanding. In Amin (2009), I argued that the alternative conceptions that have been repeatedly identified in science education research on learner conceptions can be traced to conceptualizations implicit in everyday language, much of which is metaphorical.

Many of students' conceptions of energy at different educational levels can be traced to a relatively small set of conceptions originally identified by Watts (1983). He described six different conceptions of energy: (a) energy as a causal agent stored in an object which is needed for its activity; (b) energy as an 'ingredient,' with some triggering event leading to its release (c) energy as activity or movement itself, 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 or transfer conception of energy. Many studies since Watts (1983) using a variety of different methods have repeatedly identified subsets of these six conceptions (see Amin, 2009 for review).

In a conceptual metaphor analysis of the everyday use of the word *energy* (reported in Amin, 2009), I identified a number of literal and metaphorical construals of energy implicit in lay language use. These correspond quite readily to the six conceptions of energy found in the science education literature. This correspondence is summarized in Table 1. In his account of cognitive development in cultural context, Tomasello (1999) points out that much (if not most) of our conceptual representations cannot be derived from direct interaction with the physical and social environment, but originate in the subtle perspectival options that language offers the developing child and language user. He draws on the cognitive linguistics literature to illustrate the range of construal options implicit in natural language, including metaphorical construals, that can shape conceptual representations. While not conclusive evidence, the close correspondence between the construals of energy implicit in everyday language and students' alternative conceptions repeatedly identified in the literature suggests that these language-based construals might be the source of these conceptions.

But how does this relate to learning the *scientific* concept of energy? First, the conceptions that students hold as they encounter formal instruction constitute

Table 1. Correspondence between construals of energy implicit in everyday language and students' alternative conceptions of energy. Conceptions a-f are from Watts (1983) and are described above).

Language-based construals	Illustrative phrases	Corresponding conceptions [from Watts (1983)]
Literal		
Materials (e.g. coal, oil) and food are sources of energy	Some fat is necessary to supply the body with a ready *source of* energy	Conception (b)
Energy as a resource	*Stores* … energy *to help you* run faster	Conceptions (a) & (e)
Energy is activity	…victory was certain if other members … *showed* similar energy	Conception (c)
Metaphorical		
ENERGETIC STATE IS A POSSESSION	She has never *got much* energy in the morning as you know.	Conception (a)
CHANGE IN ENERGETIC STATE IS MOVEMENT OF POSSESSION	When they feel *drained of* spiritual energy the students go there and lie on the floor.	Conception (f)
CAUSED CHANGE IN ENERGETIC STATE IS TRANSFER OF POSSESSION	The fame thing … isn't where creative energy *stems from*.	Conception (d)
ENERGETIC STATE IS AMOUNT OF MATERIAL IN A CONTAINER	He appeared happy, *full of* energy and suppressed excitement.	Conception (b)
ENERGY IS A RESOURCE	He's been *living on his reserves of* nervous energy.	Conceptions (a) & (e)
ENERGY TRANSFER IS FORCE	But while Clinton is *bursting with* energy now, what toll will the next four years take if he enters the White House?	Conception (b)
MORE ENERGETIC IS UP; LESS ENERGETIC IS DOWN.	… it represents the *lowest* state of emotional energy, as well as physical and mental energy.	---

the conceptual resources they will draw on as they construct their more abstract scientific understanding. These resources may both support or hinder learning the scientific concept; either way, they are implicated in the learning process. In turn, tracing these resources to construals implicit in everyday language in turn implicates everyday language in the learning process. Moreover, comparing the conceptual metaphor analyses of everyday and scientific use of the term *energy* reveals a great deal of overlap in the source domains used to construe energy in lay and scientific contexts. The similarity in the source domains and the fact that many of these are image schematic, suggests a significant degree of continuity across the learning process. It shifts the burden of understanding the process of learning the concept of energy to characterizing how the learner learns to apply the right construal in the appropriate context.

Errors in student reasoning and the substance metaphor of heat

As a third indication that conceptual metaphors are implicated in the process of learning, I turn to the concept of heat; specifically, its metaphorical construal as a substance. As discussed above, scientific purists will insist that heat is a process: it is the exchange of energy via the process of heating. But also, as pointed out above, the language of science metaphorically construes heat as a substance-like entity via grammar and metaphor. Does this pervasive metaphor impact student learning?

Brookes and Etkina (2015) have recently provided evidence that it is at least *connected* to student learning. In this study, three kinds of data were collected from 10 undergraduate physics students who had already been introduced to some thermodynamics at the university level. The students were presented with a description of an ideal gas in a piston surrounded by a jacket of water and the steps of a thermodynamic cycle that the gas underwent. At each step, the students were presented with questions such as 'was there net work done on/by the gas?' 'is there a net flow of energy between the gas and the water?' and 'does the total kinetic energy of the gas molecules increase?' They were asked to explain their answers. The researchers analyzed the accuracy of students' responses and their reasoning. A second type of data was the language they used to talk about heat while responding to the questions. The extent to which a substance ("caloric") metaphor was used was documented. Third, participants were explicitly asked to define heat.

A key finding of this study was that students with substance/caloric definitions were more likely to use a substance metaphor implicitly while talking about heat and were also more likely to incorrectly treat heat as a state function while reasoning. That is, they concluded that if a gas was compressed but with the temperature remaining constant, the net heat transfer should be zero. This conclusion is incorrect because as a gas is compressed the total kinetic energy increases; for the temperature to remain constant there must be some transfer of energy to the surrounding water jacket. Students who reasoned incorrectly were treating temperature as a measure of the amount of heat in the gas, thus treating heat as a substance, and giving it the status of a state function. Brookes and Etkina resist making a strong causal claim that it is students' exposure to the material substance language that is affecting their reasoning. They acknowledge that it is possible that an underlying conception of heat (independent of the language to which they are exposed) may be giving rise to both the language they use and their reasoning about the thermodynamic system. They suggest that some kind of bi-directional interpretation of the effect of language and underlying conceptions of heat is most likely.

Brookes and Etkina's bi-directional interpretation seems reasonable but of course, more empirical research is needed to tease apart competing interpretations of these findings and to fine-tune our understanding of the influence of language, and its implicit metaphors, in shaping an understanding of the scientific concept of heat. Relevant evidence would be whether young children exhibit a substance view of heat before they have been exposed to scientific language. The literature suggests a substance view of heat is very rare among very young children (about 4–6 years of age) but it starts to appear after that age, especially when language is used that prompts for it (Haglund, Jeppsson, & Andersson, 2014).

These findings do support the suggestion that language plays some role in shaping a substance conception of heat. However, what complicates the story is the role of everyday language. In Amin (2001), I analyzed the conceptualizations implicit in the grammatical constructions and metaphors used to talk about heat in everyday language. The analysis shows that a substance-like conception of heat is deeply entrenched in everyday English. If exposure to language with this implicit conception shapes children's conceptions it is surprising that it is not until about the age of 7 that this substance conception of heat can be elicited. More research is certainly needed to clarify the role that construals implicit in language play in shaping conceptions of heat at different ages and educational levels.

I conclude this discussion of the substance metaphor of heat and student reasoning by pointing out what a conceptual blending perspective can alert us to, namely the role that the context of reasoning can play. In Amin (2001), I showed how a high school student reasoning about heat-related phenomena can draw productively on the substance metaphor in one context and unproductively in another. I argued that students, having been exposed to everyday language have internalized a lay model of heat that includes the notions that heat can be localized, that it can move from one location to another and can have a causal effect such as raising the temperature of an object. However, that model does not include heat as *substantial*, in the sense that it has weight and cannot occupy the space occupied by another object. The lay model of heat implicit in everyday language has some features of the substance ontology but not all. In a conceptual blending analysis of students' reasoning in a variety of contexts, I found that a student could make productive use of heat as a substance in the context of reasoning about heat conduction in a metal rod, but reasoned incorrectly when reasoning about how thermal insulation works. In the first context a construal of heat as substantial was not invoked but in the second it was.

The conceptual blending analysis indicates why this might be by suggesting that the substantive construal of heat *emerged* in the context of reasoning about insulation. This illustrates one distinctive contribution of the blending framework: that it allows us to characterize mappings between conceptual domains that emerge on-the-fly during reasoning. In contrast, the perspective of conceptual metaphor tends to direct the analyst to identify conventional mappings that are entrenched in language use. Therefore, the perspective of conceptual blending can be a very useful complementary lens to reveal the relative contributions of stable and contextually emergent conceptualizations to learners as they attempt to make sense of natural phenomena when learning science.

Conceptual metaphor and teaching the concept of energy

So far in this chapter, I have surveyed the range of conceptual metaphors used in scientific discourse to conceptualize the concept of energy and the related concepts of heat and entropy. I have shown that despite this apparent diversity of metaphors, a conceptual metaphor analysis reveals underlying systematic mappings between a relatively small number of image-schematic source domains and aspects of these abstract scientific concepts. I have also suggested that an aspect of scientific expertise is to use multiple metaphors flexibly to conceptualize different aspects of these concepts in different contexts. In addition, I have illustrated that subtle coordination of multiple metaphors can support scientific problem solving, in particular, by coordinating qualitative and quantitative reasoning and by concretizing and simplifying chains of abstract reasoning.

I have also discussed that learning how to use conceptual metaphors seems to be an aspect of developing scientific expertise: that the use of conceptual metaphors to solve problems on entropy varies across levels of expertise; alternative conceptions of energy formed early during instruction correspond to the construals (including conceptual metaphors) implicit in everyday language; and that errors in reasoning about heat exchange in the context of thermodynamic processes is linked to the substance metaphor of heat. The issue addressed in this final section is what implications for formal instruction can be drawn from these findings.

I organize this discussion of instructional implications around various aspects of the findings discussed so far – namely, the *implicit* nature of conceptual metaphors in scientific discourse; that understanding a scientific concept involves invoking a number of *particular* image-schematic source domains strategically; and that a challenge of construing scientific concepts metaphorically is to perform a scientifically sanctioned mapping of the source domain to the target. I discuss the instructional implications of each of these points in turn.

The implicit nature of conceptual metaphors

Without the development of the theory of conceptual metaphor and systematic analyses of lay and scientific language from this perspective, many of the metaphorical construals of energy described in this chapter would not have been recognized. The language that has now been shown to reflect underlying conceptual mappings was at best dismissed as just a linguistic phenomenon and at worst not recognized as metaphorical at all. Scientists, textbook writers and teachers typically use this language without any awareness that they are using metaphor. And yet, as I have argued, these metaphors are used systematically, coordinated meaningfully to achieve cognitive goals, and seem to be a feature of scientific expertise. So what are the instructional implications of this implicit aspect of expertise?

Research on learning has, for some time, recognized that there are elements of expert competence that are unarticulated and embedded in practice (Lave, 1988; Rogoff, 1990). From carpentry to theoretical physics, these elements can be implicit in the experts' use of material and symbolic tools, in the structure of the practice itself which has been shaped by the history of the trade or profession, or implicit in the cognitive procedures required for successful performance since it is in the nature of how the brain works that many (if not most) processes do not surface to the level of awareness (Evans, 2003). This implicit aspect of expertise usually cannot be articulated and conveyed explicitly via a traditional instructional format relying on transmission from teacher to learner. Participation, albeit peripheral at first, in the real practices of the trade or profession is needed. Therefore, learning to use conceptual metaphors to construe concepts like energy, heat and entropy in the way that scientists do will require exposure to real expert discourse in the context of cognitive apprenticeships (Brown, Collins & Duguid, 1989) across a range of reasoning contexts that are important in the domain. Take the metaphorical use of pronouns by scientists described earlier as an example. We saw that these metaphorical construals played the subtle but important roles of integrating qualitative and quantitative reasoning and simplifying complex chains of reasoning. How would someone learn these skills? The kind of conceptual mappings and coordination involved are much too complex for a teacher (even with the unreasonable assumption that they were aware of them themselves) to articulate explicitly to a learner. Instead, learning such skills would most likely come from exposure to a teacher thinking aloud and through the teacher scaffolding the learner's thinking and language use through guided problem-solving.

This chapter has shown that scientific thinking about energy includes a number of implicit skills involving conceptual metaphors: to construe thermodynamic systems at different levels of description (macroscopic and microscopic) and relate these levels; and to align and coordinate of qualitative and quantitative reasoning sometimes involving the use of a variety of representational tools. The research discussed here has not surveyed systematically the range of reasoning contexts that span the variety of ways in which conceptual metaphors are used to construe the concepts of energy, heat and entropy. This kind of research is needed, however, if our understanding of the use of conceptual metaphors to construe these concepts is to translate into the design of effective learning environments. With the range of reasoning contexts involving the skillful implicit use of conceptual metaphors documented, instructional designers would be able point to the range of contexts in which scaffolding of learner thinking and talking would be of value.

While more research of the kind just mentioned is needed, this discussion of the instructional implications of the implicit nature of conceptual metaphors can be used to evaluate a pedagogical proposal that has been discussed in the science education literature. I mentioned earlier that heat is defined as energy *exchange*; that is, technically, heat belongs to the ontological category of process. However, as we have seen already, the metaphorical construal of heat as a substance is pervasive in scientific discourse. Thus, there is an ontological inconsistency between what heat *really is* as explicitly defined and the ontology construed implicitly through scientific language.

This inconsistency has been seen as a pedagogical problem and it has been proposed that the substance metaphor of heat should be avoided in textbooks and instruction (see Brookes, 2006 for discussion). Given the pervasive use of conceptual metaphor in scientific discourse dealing with the concepts of energy, heat and entropy documented in this chapter, I suggest that it is clear this proposal is wildly unrealistic. Implicit use of conceptual metaphor, often resulting in ontological inconsistency, is just a fundamental feature of how language works and subtle construal shifts are an inherent part of communication and reasoning in science (see also Amin, 2009, 2015; Gupta, Hammer, & Redish, 2010; Jeppsson et al. 2013). Pedagogical strategies need to embrace this fact, not try to avoid it.

Invoking particular source domains strategically

A conceptual metaphor analysis of how the concepts of energy, heat and entropy are expressed in scientific discourse identifies the specific image-schematic source domains that are used to conceptualize various aspects of these concepts in various contexts. Since image schemas are simple knowledge structures derived from sensorimotor experience early in life, they can be assumed to be available to all learners in any context of formal instruction. They are, therefore, readily available cognitive resources the learner can use to make sense of abstract scientific concepts. The pedagogical challenge, therefore, becomes guiding learners to invoke the right image-schemas at the right time. Apprenticeships in practice can help, as just mentioned. But more can be done to design effective learning environments to achieve this goal.

To start with, it is very useful to know the range of image schematic resources learners are already drawing on to conceptualize energy, heat or entropy at a particular point in their learning. Analyzing the language used by learners in classroom settings or as they explain natural phenomena and solve scientific problems can reveal the image schematic resources they have. A conceptual metaphor perspective can provide a systematic way of conducting such analyses. Lancor has used this approach to identify the resources university students have for conceptualizing energy (Lancor, 2013, 2014, 2015). Using an assessment framework of six different conceptual metaphors of energy, all variations of a substance construal of energy, she catalogues the construals of energy used by students taking introductory college physics and an interdisciplinary science course. She also uses the framework to compare students' construals of energy across a variety of disciplinary and topical contexts. This kind of information can serve as a starting point for instruction because it informs the teacher if students are not drawing on the needed range of conceptual resources and if their application of the resources they do have is problematic in some way.

Conceptual metaphor analysis of how a concept is expressed in scientific discourse can also inform specific instructional strategies; in particular, it can inform what visual representations and instructional analogies are likely to be effective when teaching the concept. In their Energy Project, Scherr and colleagues have honed in on the key role that the substance metaphor of energy plays in scientific understanding of energy (Close & Scherr, 2015; Scherr, Close, Close, & Vokos, 2012a; Scherr et al., 2013; Scherr, Close, McKagan & Vokos, 2012). As we have seen, the object event structure metaphor plays a central role in the conceptualization of energy where energy states are construed as possessions/substances, changes in energy states are construed as movement of a possession/substance and caused changes are construed as forced movement of a possession substance.

This set of conceptual mappings is further elaborated such that the energy/substance is construed as a resource for various outcomes. Moreover, and crucially, construing energy as a substance provides a sound intuitive understanding of the conservation of energy across various physical transformations. Scherr and colleagues have exploited the centrality of a substance construal of energy when teaching university students and conducting professional development with science teachers. They have used various representations – such as energy "cubes" and the human body itself in a learning environment they refer to as Energy Theater – to embody the energy as substance metaphor. They have documented success with these strategies in deepening learners' understanding of the concept of energy. The substance metaphor of energy has also served as an anchor for a novel curricular reorientation in the teaching of introductory university physics (Brewe, 2011).

The selection of instructional analogies is another well-known strategy in teaching for conceptual understanding. By "instructional analogies", I am referring to analogies teachers or textbook writers explicitly bring up in their effort to teach a challenging concept. The challenge of selecting the source domain of the analogy is of finding one with relationships between the various component ideas that would really help restructure understanding in the difficult target domain. But all analogies can potentially mislead. The intended mapping between source and target domains can, in principle, be helpful. However, there are always aspects of a source domain that should not be mapped to the target. Moreover, analogies can vary in how many of the relations between concepts in the target domain are captured by the source domain. Throughout this chapter, I have been discussing mappings between source and target domains used to conceptualize aspects of the concept of energy. But the mappings discussed have been those that are implicit in the language of science in this domain and are only recognized after careful analysis. The question that arises here is how the choice of explicit instructional analogies by teachers and textbook writers relates to the mappings of the various conceptual metaphors implicit in the scientific discourse in the domain.

What instructional analogies are most effective to teach the concept of entropy has been debated in the literature (see Amin et al., 2012 for review). A popular textbook analogy is Entropy as Disorder where a system is said to change spontaneously in a direction from a more ordered (lower entropy) state to a less ordered (higher entropy) state. A rich discussion of the merits and drawbacks of this metaphor can be found in the literature (see Lambert, 2002; Leff, 2007; Styer, 2000). One advantage of the metaphor is to provide a vivid mnemonic for capturing the direction of spontaneous change of a thermodynamic system (from less to more entropy/disorder). It also gives an intuitive appreciation for the statistical aspect of the concept of entropy: there are many more ways for a collection of objects to be in disorder as opposed to ordered; thus, disorder is just more statistically likely. A problem with the analogy, however, is its highly spatial nature. Extending disorder to energy states is not intuitive and we have seen that relating entropy to energy states (not just configurational states) is a challenge.

Another problem with the disorder analogy is seen when we compare the mapping involved in the entropy as disorder analogy to the pervasive Location Event Structure metaphor. Disorder refers to haphazard spatial arrangement of objects – e.g. objects scattered randomly around a room as opposed to neatly arranged in drawers and on shelves. When we think of *change* using this analogy we think of a transition from order to disorder; we imagine neatly ordered objects getting scattered around. While this analogy provides a vivid illustration of entropy and the second law of thermodynamics, it does not capture the location event structure mapping which pervades scientific discourse on the topic. That is, the MICROSTATES ARE LOCATIONS conceptual metaphor, and related sub-mappings, involve mapping complex configurational and energetic states to single locations. The disorder analogy does not help with this.

Consider in contrast, ENTROPY IS FREEDOM. A system locked into a rigid, ordered structure is not free; it does not have many configurational or energetic options. Increasing entropy is greater freedom; more energetic states and configurations can be accessed. The notion of freedom is generative of many intuitive inferences that are very consistent with the scientific concept of entropy and mappings are consistent with the sub-mappings of the Location Event Structure conceptual metaphor used to construe entropy and the second law of thermodynamics. In sum, consistency with the mapping of the conceptual metaphors implicit in scientific discourse can be used to judge the relative merit of two instructional analogies. Entropy as Freedom wins out over Entropy as Disorder on this criterion (see Amin et al., 2012 for an extended discussion).

We can argue then that the Entropy as Freedom analogy is a promising choice to guide the strategic deployment and mapping of a useful image schematic source domain that can help learners develop an understanding of entropy. Moreover, we have seen that multiple conceptual metaphors are needed to construe a particular concept: different metaphors are useful for different aspects of a concept and in different contexts. The selection of explicit instructional analogies is not a matter of choosing the *best* one, but selecting the appropriate set of analogies that allow learners to effectively understand the various aspects of a concept, and avoid erroneous interpretation of misleading aspects of some analogies (Spiro et al., 1989).

Mapping source domains to target concepts appropriately

In this final subsection, I turn briefly to the details of the mapping between source and target domains of conceptual metaphors and the implications of these details for instruction. The clearest example seen earlier was the over interpretation of heat as a substance leading university students to treat heat as a state function. The substance construal of heat is useful for conceptualizing *transfer* of energy via heating. But as we saw, it can lead to incorrect conclusions when thermodynamic systems are considered statically, or when initial and final states are compared. Moreover, we saw that mapping locations to energetic states, not just configuration states, can be challenging.

An analysis of learning difficulties in terms of the challenge of making the right mappings between a source and target domain can contribute to instruction. Specifically, it can alert teachers to specific problems learners might face and suggest points of focus for classroom discussion. Indeed, it has been well documented for some time now that teaching scientific concepts effectively can often require alerting the learner explicitly to potential erroneous conceptions that may initially appear intuitive (Amin & Levrini, 2018; Amin, Smith, & Wiser, 2014).

Developing "metacognitive awareness" of problematic intuitive conceptions helps the learner take control of the concept learning process (Sinatra & Pintrich, 2003; Smith, 2018). The application of this idea to the challenge of learning to use conceptual metaphors in science would involve, as we have seen, developing awareness of the metaphorical nature of much of scientific language and awareness of specific errors of mapping between source and target domains that might hinder understanding. Listing this instructional implication is an acknowledgment that implicit learning via exposure to the discourse skills of scientists and guided participation in scientific reasoning and problem solving cannot be the only pedagogical strategy where learning to use conceptual metaphors in science is concerned. There will be times when explicit reflection on scientific language and how it might mislead will be necessary.

Conclusion

In this chapter, I have tried to show that metaphors are pervasive and patterned in scientific discourse dealing with the concept of energy, and the related concepts of heat and entropy. One conclusion from this line of work is that the theories of conceptual metaphor and blending can be useful tools to characterize features of scientific discourse and associated patterns of thought. We have seen that despite the vast numbers of metaphorical expressions that can be found in scientific discourse on energy, we can discern substantial systematicity in the mappings that underlie these expressions. We have also seen that scientists construe the different aspects of the concept of energy in distinct ways, employing systematically a collection of different conceptual metaphors. Moreover, when reasoning or solving problems, they coordinate multiple conceptual metaphors creating coherent, simplifying interpretations of the qualitative and quantitative components of the problems they tackle.

Since the theories of conceptual metaphor and blending complement each other – one focusing on characterizing conventional conceptual mappings and the other capturing conceptualizations that emerge in particular contexts of reasoning and communication – they draw attention to both stable and more flexible features of scientific discourse and conceptualization. Conversely, applying these theoretical tools to the domain of scientific discourse, as discussed in this chapter, shows the value of these theories more generally as analytical tools to investigate human language and thought. This is especially true when they are used to analyze metaphorical expressions, not as single isolated sentences, but as collections of metaphorical construals coordinated together to achieve particular discursive goals.

This perspective on scientific discourse has also been rewarding in providing a way to diagnose the difficulties that learners face when learning science. We have seen evidence suggesting that coordinating multiple metaphors when reasoning is a skill that learners need to develop. We have also seen that the metaphors implicit in everyday language and in the language of science itself, while often helpful, might lead to problematic alternative conceptions that hinder learning.

All this offers clues for instruction. First, since the use of conceptual metaphor is implicit and pervasive in scientific discourse and thought, it is unrealistic to think that problematic metaphors can be avoided. Instead, instruction can help learners use them appropriately through exposure and guided reasoning. Second, documenting the various conceptual metaphors scientists use to construe scientific concepts provides a lens through which to analyze learners' discourse so as to identify the resources they have and those that they lack. It also gives us a way to evaluate the relative merits of candidate explicit instructional analogies. Third, particular mappings between source and target domains may pose particular challenges for learners. These could be addressed explicitly in instruction by inviting learners to consider the metaphorical nature of the language of science and alert them to problematic interpretations of these metaphors. Overall, I have used the cluster of concepts energy, heat and entropy as a case study to illustrate that if we want to use metaphors and analogies to communicate about or teach a given domain effectively we will need coordinated analyses of the use of metaphor across the different contexts of science, learning and instruction.

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