THE NARRATIVE STRUCTURE OF CONTINUUM THERMODYNAMICS

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Abstract: If a good story and a well-formed argument are considered different natural kinds, there does not seem to be much hope for narrative structures in a formal theory. However, when we apply cognitive linguistics to recent theories of continuum thermodynamics, a different picture emerges. We can show that the concepts of continuum physics are embodied and result from our figurative mind operating on experiences of nature. A basic structure of experience is the *gestalt of forces*—causative powerful phenomena ranging from music to justice to electricity and heat. Humans have developed narrative approaches to understand such phenomena.

In this paper, I will show that image schematic structures, metaphoric projections, and an extended model of narrative apply to the cognitive structure of continuum physics. Since the use of natural language in continuum physics literature is fairly limited, I will apply cognitive schematic analyses to the equations and make the results transparent by introducing visual schemas and metaphors for the concepts. The gestalt of forces such as fluids or heat is structured in terms of three main aspects. The three basic schemas that are projected metaphorically are those of *quality* (intensity), *quantity* (object, fluid substance), and *force* or *power*.

In a continuum model of thermal conduction, the law of balance of entropy is analogous to that of chemical substance or electric charge. Add to this the meaning of temperature as a (vertical) scale and the relation of temperature and entropy to the power of heat and you end up with a minimal Cognitive Model of heat as a powerful agent. Agents are perfect elements of narrative. Therefore, a narrative approach to science is not limited to humans acting in the endeavor of science. The most formal theories of continuum physics tell stories of forces of nature—they *are* narratives.

Keywords: thermodynamics, dynamical theory of heat, temperature, caloric, entropy, energy, figurative structures, forces of nature, image schemas, metaphor, visual metaphor, narrative and story.

INTRODUCTION

If we accept Bruner's (1987) dictum that "a good story and a well-formed argument are different natural kinds," there does not seem to be much hope for finding narrative structures in a theory as formal and mathematically demanding as continuum physics

(Truesdell and Toupin, 1960; Truedell and Noll, 1965). However, when we apply modern cognitive science and cognitive linguistics (Johnson, 1987; Lakoff, 1987; Lakoff and Johnson, 1999; Evans and Green, 2005; Tucker, 2007) to recently developed theories of continuum thermodynamics (Fuchs, 2010; Müller, 1985; Truesdell, 1984), a different picture emerges. We can show that the fundamental concepts of continuum physics are embodied and result from our figurative mind operating on experiences of nature. A basic structure of experience is the *gestalt of forces* where the term *force* is used to denote any type of causative powerful phenomenon ranging from music to justice to electricity and heat (Fuchs, 2006, 2011). Since humans have developed narrative approaches to talk about and understand such phenomena (Fuchs, 2013c) it does not seem far-fetched to propose that story and continuum physics are related natural kinds. Indeed, the conceptual structure of continuum physics is narrative at its roots.

The main result presented in this paper is the demonstration of the narrative structure of a particular *product of formal science*—namely, continuum thermodynamics. This leads to the claim that we can use stories and narrative not only *about* science (the context of science, Klassen, 2006); or for *communication* in the classroom (Kubli, 2001); or for *historical* aspects of nature such as evolution (Norris et al., 2005). Rather, we can tell stories that correspond to models produced in formal science. Therefore, stories appear in a new light: they are instruments of good teaching and good learning in and *of* science (Fuchs, 2013a-c).

To prepare the ground for the present discussion, I will briefly introduce some important sources pertaining to cognitive science and cognitive linguistics (Section 2.1), the application of narrative in science (Section 2.2) and modern continuum thermodynamics (as a branch of continuum physics, Section 2.3). In Section 3, I will demonstrate the figures of mind from which thermodynamics and analogous theories of continuum physics are created. Finally, possible consequences for science learning will be discussed in Section 4.[1]

BACKGROUND

In this paper, I will make use of research and development in cognitive linguistics, the use of narrative in science, and a modern dynamical theory of heat. To prepare the reader for the contribution made in this paper (Section 3), some aspects of these developments will be presented in the present section.

Cognitive Linguistics and the Model of the Embodied Mind

In the last three decades, we have witnessed an interesting development in the sciences of the human mind away from dualistic and computational approaches to a philosophy of the embodiment of mind. Today, we understand at least to some extent how the mind is a product of the interaction of an organism (body and brain) with its physical and social worlds (Dewey, 1925; Gibson, 1966; Maturana and Varela, 1987 [1998]; Pfeifer and Bongard, 2007; Tucker, 2007; Chemero, 2009). This notion has been supported by various strands of research ranging from philosophy, anthropology and biology, through robotics and cognitive linguistics (for the latter, see Lakoff and Johnson, 1999; Evans and Green, 2005). Lately, it has been taken up as a paradigm for education (see for example the Symposium on Conceptual Metaphor and Embodied Cognition in Science Learning; ESERA Conference, 2-7 September 2013, Nicosia, Cyprus).

Early cognitive linguistics has been instrumental in making us aware of the ubiquity of *force dynamic schemas* (Talmy, 2000) and *conceptual metaphor* (Lakoff and Johnson, 1980) in language, and by extension, in the human mind. Johnson (1987) and Lakoff (1987) introduced the notion of *image schemas* that proved to be an important concept for later applications of linguistics in cognitive science.[2] Image schemas are recurring patterns in our mind of sensorimotor experience; they are relatively small-scale perceptual gestalts. They become patterns of understanding and thinking through the process of metaphoric projection (or parable, see Turner, 1996).

Metaphors, and systems of metaphors, created in this manner, are conceptual structures rather than embellishments or purely rhetoric elements of language. When speaking of metaphors (at least in the conceptual metaphor theory of cognitive linguistics), it is important to distinguish between three different uses of the word *metaphor*: (1) Special *linguistic metaphoric expressions* (such as those found in the right column of Table 1), (2) *metaphors* proper (left column in Table 1) which constitute a conceptual structure (a gestalt), and (3) *metaphor* as the process of metaphoric projection (from a source to a target domain), i.e., a gestalt-structuring process (Taverniers, 2002) that creates a metaphor according to the second (proper) sense.

An important extension of cognitive linguistics has been made by Fauconnier and Turner (2002) in their theory of *blending* (conceptual integration) that shows how online creation of figurative structures (metaphors, analogies, or generally, blends) are formed.

Cognitive linguistics has found its way into science education research in general (Amin, 2009) or in special applications (Amin, 2001; Hestenes, 2006; Fuchs, 2006; Brookes and Etkina, 2007; Amin et al. 2012; Scherr et at., 2012; Jeppsson et al., 2013). In general, detailed investigations of linguistic expressions by students and laypersons demonstrate what we have long known from teaching and research into alternate conceptions or misconceptions but they cast the question of how humans understand nature in a new light. Many of the instances of misconceptions actually turn out to be valid embodied conceptualizations of the world around us and as such can lead to a reevaluation of approaches to science education. This paper is an example of this statement.

Narratology and Narrative in Science

The study of myth, story, and narrative is as important for understanding the human mind as is cognitive linguistics. Research in this vast field spans centuries and has accelerated in recent times (for myth, see Kirk, 1970, Nixon, 2010; for stories see Mandler, 1984, Egan, 1986, Bruner, 1987; for narratology in general see Ricoeur, 1984-1988, Herman, 2013). Despite their importance as a figure of mind, and despite all the interest they have generated among educators, a detailed and general model of stories is missing. We know that stories have their own structure (we may speak of a *story schema* or a *narrative structure*; Mandler, 1984; Bruner, 1987; but note that story structure in western societies is quite different from that of Native Americans; St. Clair, 2003). Also, we count myths as examples of stories, but we still cannot quite agree upon the question of what myths are and what their origins and uses are (Kirk, 1970; Nixon, 2010). For our purpose here, let me consider *stories* the *explanatory narration of events and actions unfolding over time*—meaning the narration of relatively large-scale phenomena (Fuchs, 2013c).

The story of the typical application of narrative theory to science education is told fairly quickly. There is an excellent summary of the dominant model of storytelling and narrative in science in the paper of Norris et al. (2005). The dichotomy between narrative and paradigmatic understanding expressed by Bruner (1987) has led most researchers to restrict their view to affective aspects of stories (Klassen, 2005; Kubli, 2001). Stories are used to talk about science (the *context and history of science*, the life of scientists) and to create an affectively positive environment for teaching science. The basic assumption in this dominant model is that the products of science—models and theories—cannot have a narrative structure even though a large body of research shows how scientists and children use metaphor and analogy to create and/or understand nature and science (Gentner and Gentner, 1983; Gentner et al., 1997). In the end, science and narrative are two different natural kinds (Bruner, 1987).

A more far ranging application of narrative understanding of science (*narrative explanation*) has been discussed by Norris et al. (2005). If science deals with singular, non-recurring events (such as a meteorite hitting our planet and wiping out the dinosaurs) or historical aspects of nature (biological evolution or evolution of the universe, for example), narrative explanation and corresponding understanding may be of great importance.

There is a third use of narrative in the sciences as I will demonstrate in this paper. Thermodynamics as an example of modern continuum physics is built upon figurative structures that, in their entirety, create a narrative environment. A model of this environment of figurative structures has been presented in Fuchs (2013c).

Continuum Thermodynamics and the Rediscovery of Caloric

Traditional thermodynamics is well known for its arcane and hard to understand structure. Physicists commonly try to give the unusual aspects of this theory (unusual as compared to any other physical theory, see Fuchs, 2010: Introduction) a positive twist by claiming how its universality (its system and material independent aspects) makes it a wonderful product of the human mind that will surely never have to be changed even in the face of revolutions in other fields of physics. However, all we have gotten is a formal theory limited to static conditions (Callen, 1985, p. 26)—something that would be unacceptable in any other field of physics.

Continuum thermodynamics—as a branch of continuum physics—does away with this restriction (Truesdell, 1984; Müller, 1985; Jou et al., 1996; Fuchs, 2010). Thermodynamics becomes an example of the spatially continuous dynamical models of macroscopic physical and chemical sciences—it becomes analogous to theories of fluids and electricity. As such, it can be analyzed using the same figurative structures that also apply to the other fields. This is what I will do below.

The modern structure of thermodynamics has made another development possible. It has become clear that Sadi Carnot's (1824) analogy of heat engines and waterfalls is a fruitful tool for reevaluating the figures of mind applied to this science. Calendar (1911) and Job (1972) have pointed out that Carnot's caloric (suitably extended by the assumption that caloric is created in irreversible processes) fits the formal concept of entropy. Based on this observation, Fuchs (2010) has created a version of modern continuum thermodynamics that makes direct use of figurative and narrative elements, and Mares et al. (2008) have argued for the explicit reintroduction of the caloric theory.

FIGURATIVE STRUCTURES IN THERMODYNAMICS

In this section, I will show that the language of force dynamics (Talmy, 2000), image schematic structures (Johnson, 1987; Hampe, 2005), and metaphoric projections (Lakoff and Johnson, 1980) apply to the cognitive structure of continuum physics in general and thermodynamics in particular. Since the use of natural language in continuum physics literature is fairly limited, I will apply cognitive semantic analyses to the equations and make the results transparent by introducing visual schemas and metaphors for the concepts found in these mathematical texts. [In the following, terms that correspond to schemas or metaphors will be shown in small caps.]

Take, for example, the continuum model of thermal conduction (Müller, 1985; Jou and Casas-Vasquez, 1988; Fuchs, 2010, Chapter 13) and compare it to the diffusive transport of a chemical substance. The law of *balance of caloric* (entropy) is perfectly analogous to that of chemical substance or electric charge (having terms for storage, flow, and production of a fluid substance; in the case of charge, the production term is missing).

In Fig. 1, we see the figurative elements that constitute the concept of balance of extensive quantities. A SUBSTANCE (chemical or caloric) can be stored—there is a term showing how fast the stored quantity (expressed by its density) in a CONTAINER changes (note the schema of CHANGE). The changes come about because of FLOW into or out of the container, and because of production (CREATION or destruction) of the substance—there are terms quantifying these PROCESSES in the equations of balance.

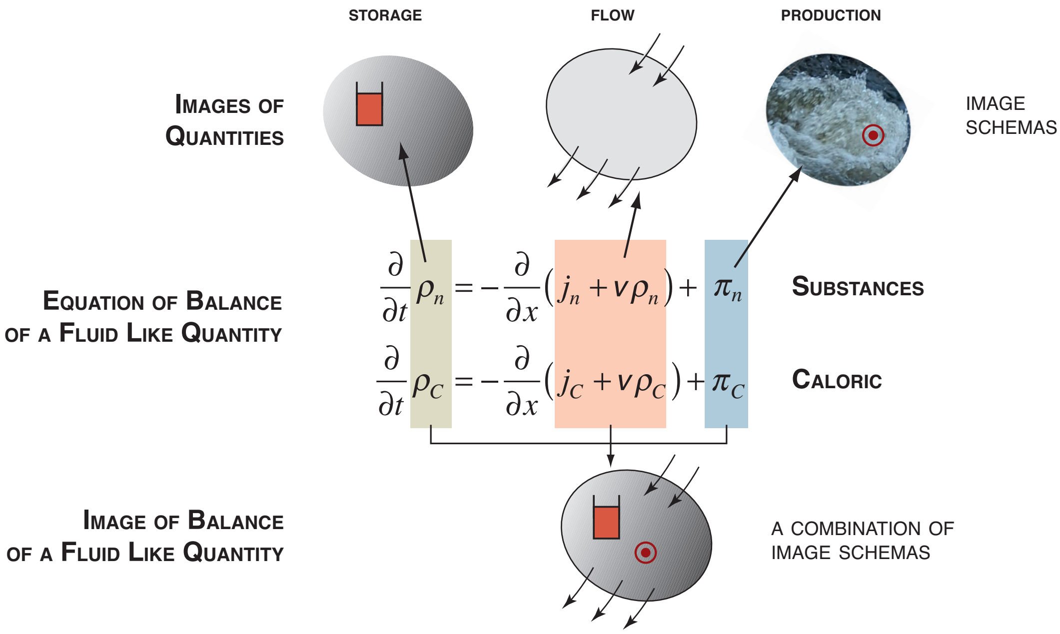

Figure 1. Basic figurative elements visible in the equations of balance of amount of substance and caloric (an explanation is given in the text).

If we ask how flow and production come about, we immediately introduce drives, i.e., potential differences that derive from the notion of a POLARITY associated with a particular phenomenon (HOT-COLD for thermal, chemically WEAK-STRONG for chemical processes). The continuum equation for a (conductive) flow of caloric, for example, makes use of the schema of VERTICALITY—a fluid substance flows from higher to lower points in a landscape (Fig. 2). There are circumstances that control the flow—OBSTRUCT it or ENABLE it (in the equations, these are quantified by the conductivities).

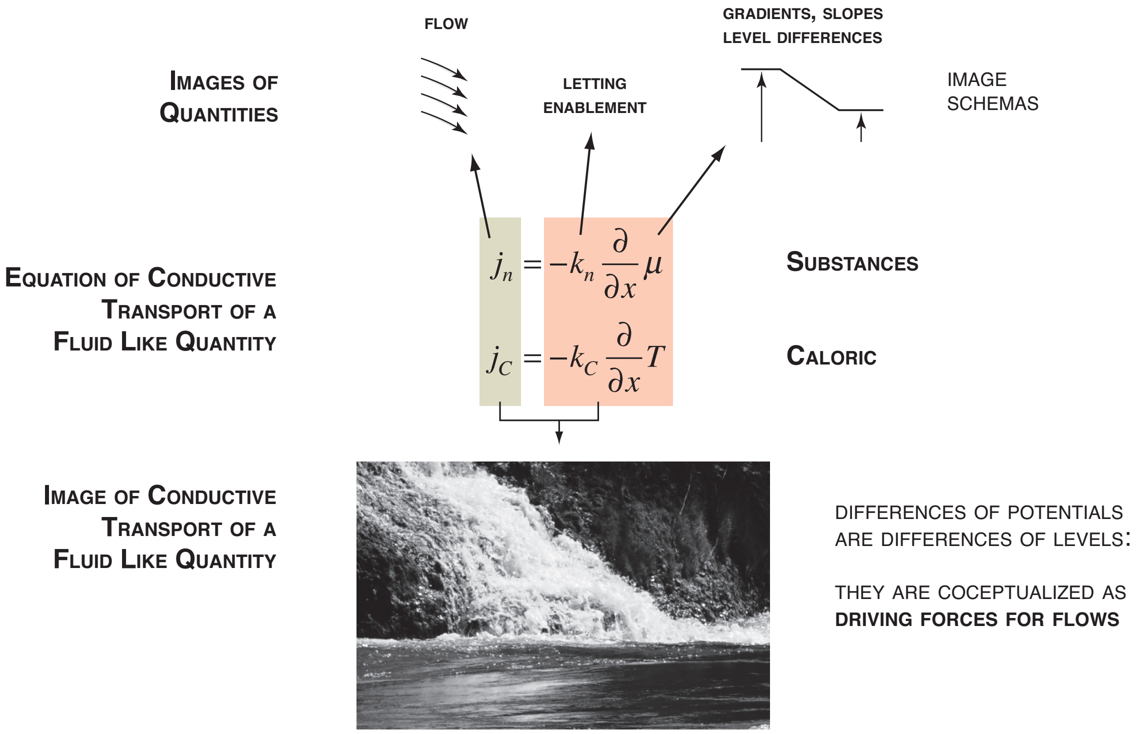

Figure 2. Equations and images for flow in continuum models of the transport of caloric and chemical substances (an explanation is given in the text).

The figures of mind do not stop here. An analysis of energy relations in a continuum model of the flow of caloric shows how the notion of POWER applies to thermal processes (Fig. 3; not all aspects of the derivation are given here; for more information, see Fuchs, 2010).

Take the equation of balance of energy for the conduction of caloric (first equation in Fig. 3), use the relation between a flow of energy and caloric (second equation; energy is carried along by caloric with a load factor equal to the local temperature), and insert all of this in the equation of balance of caloric (third equation). We obtain an equation for the spatial change of the energy flow that can be interpreted with the help of a visual metaphor (the box with arrows, lines, and levels). The visual metaphor makes use of the image schemas introduced before. Caloric flows from a higher to a lower point thereby RELEASING (making available) energy at a rate equal to the product of the flow and the change of temperature along its PATH. The second term on the right of the resulting equation shows what the energy released is used for: it is needed to produce caloric at a rate dependent upon the local temperature (this is the general expression showing the relation between dissipation and entropy production rates). In summary, the explanation is the same given by Sadi Carnot for the operation of heat engines. Caloric falls from a higher to a lower temperature thereby making energy available (Sadi Carnot's *La puissance du feu*).

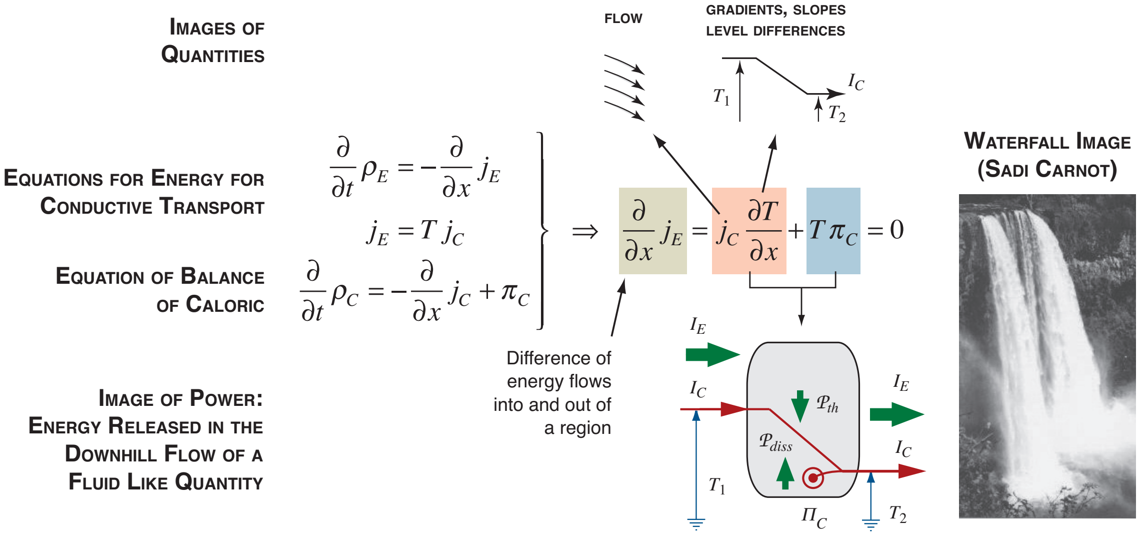

Figure 3. The origin and form of the notion of power in continuum thermodynamics (an explanation is given in the text).

What I have done here is demonstrate the elements of the model of *forces of nature* (Fuchs, 2006, 2011, 2013c). The gestalt of a force is characterized by three main schemas (size or QUANTITY, INTENSITY or quality, and force or POWER). Constitutive relations for capacitance, resistance, or induction,[3] and derived relations, make use of further schemas such as CONTAINER, PATH, LETTING and OBSTRUCTING, INERTIA, and BALANCE.

In summary, the figurative structures introduced so far add up to a number of metaphors such as HEAT IS A FLUID SUBSTANCE, TEMPERATURE IS THE MEASURE OF VERTICAL LEVELS IN A THERMAL LANDSCAPE, HEAT IS A POWERFUL AGENT, etc.. Note that these metaphors give rise to both linguistic and visual (graphical) instances.

In this view, heat is a force in the same category as music, justice, water, wind, light, and many more. [Music has been described as, but not named, a *force* by Johnson (2007, Chapter 11). There he shows how our understanding of music is characterized by three sets of metaphors: MOVING MUSIC METAPHOR, MUSICAL LANDSCAPE METAPHOR, MUSIC AS A MOVING FORCE METAPHOR. These three metaphors correspond to the ones for quantity of fluid substance, vertical level in a landscape, and power used in my account of forces of nature.] A minimal Cognitive Model visualizing the linguistic structure inherent in the equations of the dynamical continuum model of heat in conduction is shown in Fig. 4.

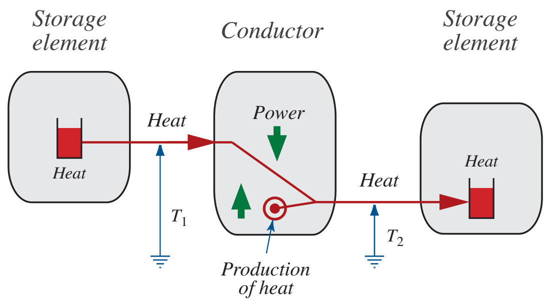

Figure 4. Minimal Cognitive Model of heat. The visual metaphor shows storage, flow, production, and power of heat such as in thermal conduction, cooling and heating.

A NARRATIVE APPROACH TO SCIENCE PEDAGOGY

Finally, we should ask how the figurative structures present in our scientific models of continuum thermodynamic processes add up to stories, i.e., to the larger scale narrative structures. The short answer is that the gestalt of forces leads to the notion of (powerful) agents. Agents are perfect elements of narrative and they fit into the general story schema (Mandler, 1984; Fuchs, 2012). This is how we end up with narrative structures in the example of science I have discussed here.

The longer answer has been given in Fuchs (2013c). Image schemas and the metaphorical projections, forces and agents, stories and collages (collections) of stories make up a vast network of figurative structures of the human mind. In a feedback model of the interaction of such a mind with the worlds of (physical and other) phenomena and linguistic products, forces and stories occupy a privileged center in human understanding of nature.

In this model, the scientific structures of *concepts*, *models*, and *theories* correspond to *metaphors*, *stories*, and *collages of stories*, respectively. Most important for a possible narrative approach to science pedagogy is the correspondence between (scientific) models and stories. We can cast important models of continuum physics and chemistry in the form of stories. Such stories can be heavy on affective elements and light on the logic of the characters of forces of nature; in such a form they are perfect tools for primary science (Corni, 2013; Corni et al., 2012, 2013). Or they can be light on affective aspects and strong on the more formal elements of the forces as when we introduce more advanced students to a field and its models. For the older students, stories can turn into more formal narratives that include elements of science we normally term *non-narrative*.

SUMMARY

In this paper, I have discussed the conjecture that the conceptual elements of our most formal products of science (such as continuum physics) are constructed from the figures of an embodied mind. Physics is not the direct representation of an outer world in our minds but rather the representation of our imagination working upon this outer world. If we take the results of cognitive linguistic analyses of the products of science as a clear sign of their figurative nature, we are led to conclude that scientific models are narrative at their core.

This opens up a new avenue for the study of narrative in science. We are no longer limited to applying narrative to the context or history of science (stories *about* science) or to stories of the history of nature. We can now construct stories of the products of science, i.e., of the models constructed in science. Such stories are useful for primary science as well as for more advanced approaches. In the case of primary science, stories of forces of nature prove to be an invaluable tool for educating and motivating teachers and for introducing children to the workings of nature reflected in a world of imagination (Egan, 2013). In more advanced science, they show teachers that natural language and narrative forms may be tools for better understanding of an often arcane subject of study.

NOTES

1. There is a second important consequence of the discovery of the figurative roots of thermodynamics in particular—not for teaching per se but for the structure adopted for the formal theory. The study of the human mind shows that we can make use of a different conceptualization than the one afforded by the traditional approach of thermodynamics. The structure of the traditional theory of thermodynamics is a twisted version of the gestalt of forces of nature (quantity and power of the gestalt are identified rather than differentiated leading to an identification of *heat* with *energy*). Based upon linguistic and cognitive analysis, we can show that a more direct approach to thermal phenomena is possible and leads to a dynamical theory of heat rather than a theory of the statics of heat (Fuchs, 2010). These forms of the theory of thermodynamics demonstrate how the quantity of *heat* corresponds to *caloric* or *entropy*, making possible a direct caloric approach to thermal phenomena (Mares, 2008) and thermal design optimization in engineering (Bejan, 1996).
2. Talmy's (2000) force dynamic schemas are basically image schemas appearing in the long list of basic schemas that have since been identified (Hampe, 2005).
3. Thermal induction (inertia) has been introduced by Jou and Casas-Vázqzez (1988), Fuchs (2010, Chapter 13) and is a general element of extended irreversible thermodynamics (Müller, 1985; Jou et al., 1996).

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