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From Stories to Scientific Models and Back: Narrative framing in modern macroscopic physics

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Narrative in science learning has become an important field of inquiry. Most applications of narrative are extrinsic to science—such as when they are used for creating affect and context. Where they are intrinsic, they are often limited to special cases and uses. To extend the reach of narrative in science, a hypothesis of narrative framing of natural and technical scenes is formulated. The term narrative framing is used in a double sense, to represent (1) the enlisting of narrative intelligence in the perception of phenomena and (2) the telling of stories that contain conceptual elements used in the creation of scientific models of these phenomena. The concrete case for narrative framing is made by conceptual analyses of simple stories of natural phenomena and of products related to modern continuum thermodynamics that reveal particular figurative structures. Importantly, there is evidence for a medium-scale perceptual gestalt called FORCE OF NATURE that is structured metaphorically and narratively. The resulting figurative conceptual structure gives rise to the notion of natural agents acting and suffering in storyworlds. In order to show that formal scientific models are deeply related to these storyworlds, a link between using (i.e. simulating) models and storytelling is employed. This link has recently been postulated in studies of narrative in computational science and economics.

Keywords: *Narrative framing; Perceptual gestalts; Modeling; Science education*

Introduction

The investigation described here grew out of a number of questions all centrally related to how humans understand nature and (natural) science. Along the way, a unified approach to the physics of dynamical systems and a theory of uniform thermal dynamical processes—all based upon modern continuum physics—were

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developed (Dumont, Fuchs, Maurer, & Venturini, 2014; Fuchs, 2010); cognitive linguistics has been employed to study the conceptual structures embedded in macroscopic physical science; stories of forces of nature have been produced and used for application in teacher training and in a novel primary school curriculum in Italy; and lately, the question has been taken up of how small-scale embodied conceptual structures (such as conceptual metaphor) relate to the large-scale structures of story and storyworld.

In the course of these studies, a number of points have become clear. Different fields of continuum physics[1] and the physics of macroscopic physical science all make use of the same few basic figurative structures allowing us to write theories and models in strongly analogous forms. It is possible to summarize these structures as a network of (small-scale) figures of mind[2] that lead to the conceptualization of a (medium-scale) perceptual gestalt I call FORCE OF NATURE.[3] The perception of concrete forces of nature (wind, water, light, ice and fire, electricity, motion, food, or soil, to name but a few) leads us to construct this conceptual network as a matter of everyday life—the figures of mind used to understand folk physics are also those that structure modern macroscopic physical science.

These observations lead me to propose a hypothesis regarding the relation between narrative and science. The perception of forces of nature in large-scale events (a winter storm) lets us construct the figure of *natural agents* central to stories (this is a process of *narrative perception*). This, in turn, allows us to tell stories about forces of nature (as an act of *narrative production*). On the other hand, recipients of such stories can build storyworlds having a certain form in which natural agents act and suffer according to certain rules (this is again an act of *narrative perception*).

So far, this should not come as a surprise—the particular way it is phrased may sound novel but it is simply a description of humans interacting with the world and creating semiotic products of folk science. My question is how this relates to formal science. Remember that the cognitive model of FORCE OF NATURE can be shown to be fundamentally the same in formal macroscopic physics and in folk science. Therefore, we can conjecture that narrative perception and narrative production also apply to the products of formal science—if only indirectly. We will see in this paper that the relation between the simulation of formal models and the act of storytelling will help us create a link between the roles of narrative in everyday understanding of the natural world (folk science) and science.

In this paper, I will refer to the various processes and acts of narrative perception and narrative production as the *narrative framing* of natural scenes.[4] We can understand this term as referring to two different but intimately related senses of the use of narrative: (1) enlisting of narrative intelligence in the perception of phenomena[5] (we perceive living through a winter storm as a story, and when we hear stories or are exposed to formal models and their simulations, we also bring narrative perception to bear upon the understanding of the semiotic products) and (2) producing and telling stories that contain conceptual elements used in creating formal models of these phenomena (we narrate stories about the winter storm using language that contains the seeds of the concepts of which formal scientific models are made). The former is equivalent to saying that we have a narrative mind, a point that can only be inferred indirectly by evidence gained from our behavior as observers of nature and recipients and creators of stories. The latter is accessible to direct observation: we can study semiotic products used both in everyday life and in science and make the case for the narrative nature of our concepts in folk science and in formal science (and show that they are closely related).

This paper is structured as follows. In the next section, some background material will be outlined (mainly relating to issues such as conceptual metaphor and narrative). Then, in order to introduce the reader to the range of semiotic phenomena available to us, three examples will be presented—a Winter Story for small children, Sadi Carnot's narrative introducing and motivating his model of the power of heat, and a formal model of electrical heating of water in a teakettle. A reading of these examples reveals conceptual metaphoric and narrative structures, most importantly those used to give form to the *gestalt of force of nature*.

These first parts of the paper prepare the ground for a more general discussion of narrative framing in the light of narratology (as cognitive science) and recent studies of narrative in science—computational science and economics, to be precise. We will find it useful to compare the relationship between simulations and models to that between stories and *storyworlds*. There we will see how models (a major component of scientific work) relate to storyworlds (the cognitive models created by the perception of narratives).

Research into the subject dealt with in this paper has greatly profited from cognitive science in general and cognitive linguistics in particular. Therefore, in the Conclusion, I will return to the wider concern of research in embodied cognition in science and discuss how the present paper may add to this endeavor. Moreover, reference to work in the field of narrative in science education will be made and we will see how the idea of narrative framing relates to studies of the use of narrative in the science classroom. Finally, some applications of the extended use of narrative being conducted at present will be mentioned as a view to the future of research in this field.

Metaphors and Narratives

In order to prepare the reader for some of the terminology used, we will first take a brief look at conceptual metaphor theory and the postulate of embodied cognition, and a modern theory of narrative.

Embodied Cognition and Conceptual Metaphor

The tools used in the analyses presented in this paper have been developed in cognitive science, particularly in cognitive linguistics and in work revolving around the model of an embodied mind. A leading model in the science of the human mind, the one I adopt here, has evolved from an integral view of the interaction of human organisms with their natural, social, and psychological environments. The embodied mind is assumed to be a product of this interaction (Chemero, 2009; Dewey, 1925; Gibbs, 2006; Gibson, 1966, 1979; James, 1890/1983; Johnson, 1987; Lakoff and Johnson, 1999; Noë, 2004). Simply put, in a dynamical systems view of embodied cognition (Thelen and Smith, 1994), the nervous system of the organism resonates with its body in its interactions with the environment, leading to dynamical patterns which can variously be described as basins of attraction or, more usefully for us, shapes or gestalts (Arnheim, 1969; Johnson, 1987). As constructs of perception, such shapes are projected to lead to new structures, that is, figures of mind such as conceptual metaphor (see the later text). Our representations of the outside world are not direct reflections but rather representations of the figures given to us by perception and imagination.

The assumption of an *embodied mind* has important consequences for the form and meaning of our linguistic creations. What is often seen as literal language is, on scrutiny, often found to be implicitly figurative—mirroring a figurative mind. Cognitive linguistics has become a tool for investigating the human mind as it is reflected in our language. For example, metaphoric expressions are no longer viewed as embellishments of language but rather as expressing deep-rooted forms of understanding of the world (Gibbs, 1994; Johnson, 1987; Lakoff, 1987; Lakoff and Johnson, 1980, 1999; Lakoff & Núñez, 2000; Talmy, 2000a, 2000b).

Cognitive linguistics and the model of an embodied mind have also been the starting point for identifying image schemas as gestalts abstracted from recurring experience of bodily interactions with the environment (Hampe, 2005; Johnson, 1987; Lakoff, 1987; and see Arnheim, 1969, whose discussion of the 'intelligence' of visual perception leads to a similar point). Among image schemas, we find CONTAINER, PATH, (FLUID) SUBSTANCE, SCALE, BALANCE, PROCESS, and the schemas identified in force dynamics and spatial relations by Talmy (2000a) and Langacker (1987, 1991). Many of the most basic forms of conceptualizations used and reflected in language are based upon metaphoric projections of these types of schemas, such as when we say that 'heat has been collecting in the room' (note the schemas of CONTAINER and FLUID SUBSTANCE in this example).

Conceptual metaphor theory, as a branch of cognitive linguistics, makes an important distinction between CONCEPTUAL METAPHOR and metaphoric linguistic expression. The latter is what we hear or read when somebody uses a metaphor, the former is a figure of mind—we might say it is the actual concept. For example, 'heat flows through the walls of the building' is an example of an expression for the underlying metaphor HEAT IS A FLUID SUBSTANCE. Metaphors are the result of the (metaphoric) projection (Turner, 1996) of structure from a source domain onto conceptual structure in a target domain. A primary form of metaphor can result if structure from an image schema is projected—such as in the examples used in the previous paragraph. Primary metaphors can be combined into complex metaphors by conceptual blending (Lakoff and Johnson, 1999).

Theory of Narrative: Stories and Storyworlds

In this section, I provide a brief description of a couple of elements from recent research in narratology. The points raised are somewhat different from discussions of narrative and storytelling in science and science education (see Norris, Guilbert, Smith, Hakimelahi, & Phillips, 2005, for an important contribution to the latter). The goal is to understand enough of the theory of narrative for us to discuss the role of 'good' stories in the model of narrative framing.

A model of narrative. In this paper, I will use a model of narrative as a *radial category* (Herman, 2009). It allows us to consider different forms of narrative as belonging to the same category; at the same time it tells us more clearly what we mean by *story*. According to a modern theory of categorization (Lakoff, 1987; Rosch, 1973), a radial category is one that has central or prototypical members (the categories exhibit prototype effects) and members that do not share that status—they are less prototypical and more peripheral. An example is the category of chair, with a typical dining room chair as a central member and a beanbag chair as a rather untypical one.

Herman calls *story* the prototypical member of the *category of narrative*. There are non-central members that relate to the categories of *description* and *explanation*, so-called narrativized descriptions and descriptivized narrations, or explanatory narratives and narrativized explanations. Briefly, narrativized descriptions and descriptivized narrations are (text) types between description and (prototypical) narrative; explanatory narratives and narrativized explanations are (text) types between prototypical narrative and explanation with varying degrees of emphasis on either narrative or explanation (see Herman, 2009, pp. 89–100, for more details). According to Herman (2009), four elements constitute the central member of the category of narrative. I will recount his list in slightly different words. Stories are narratives that include *all of the following elements*: (1) *events*; (2) (conscious) *experiencing of events* by *agents*; (3) *tension for creating events*; and (4) reason or *occasion for telling* by a narrator. Herman argues strongly for the roles of intentionality and author in stories (Herman, 2013).

Stories and storyworlds. The distinction between stories and storyworlds will prove important in the following. Stories are concrete narratives, whereas storyworlds are the mental models we construct when we are exposed to stories—stories transport us into storyworlds.

In *Story logic*, Herman (2002) defines storyworlds as follows: '[. . .] storyworlds [are construed] as mental models [. . .] supporting narrative understanding.' (p. 17). He writes that:

> [i]n trying to make sense of a narrative, interpreters attempt to reconstruct not just what happened—who did what to or with whom, for how long, how often and in what order—but also the surrounding context or environment embedding existents, their attributes, and the actions and events in which they are more or less centrally involved. [. . .] storyworld points to a way interpreters of narrative reconstruct a sequence of states, events, and actions not just additively or incrementally but integratively or 'ecologically' . . . (pp. 13–14)

To put this more simply and directly for our purpose, a story recounts the *what* of events and the storyworld we construct informs us about the *why*. Applying this distinction to the relation between narrative and science, we will be able to refer to stories as simulations and storyworlds as the models simulated (see the later text).

A Winter Story and Carnot's Power of Heat

Can scientific narratives be proper stories? Can such stories help us understand nature and build scientific models? Can we use narrative intelligence to understand scientific models? To discuss these and related questions, I will describe three examples constructed for widely different applications—a story for primary science for small children and a word model of the operation of heat in steam engines by Sadi Carnot (this section), and a dynamical model of electric heating of water in a teakettle that uses the uniform dynamical models version of continuum thermodynamics (the following section).

A Winter Story

Here is a shortened version of a story that was originally written to investigate questions relating to narrative and science learning (Fuchs, 2011, 2013a) and has since been used in the training of teachers and in early elementary school (Corni, 2013; Corni, Giliberti, & Fuchs, 2013). The story narrates how cold holds a wintry town in its grip.

> A small town called Little Hollow lay in a hollow surrounded by a high plain. As the last of the warmth of late fall left the plain surrounding Little Hollow, the cold of winter found its way into the area and spread out. So it was not all that cold up there. Even in the midst of winter, the sun managed to send some warming rays onto the plain. The snow that fell on the plain was not so cold either, but it was plenty, and the people of Little Hollow loved to go up to the plain for cross country skiing.
> But in Little Hollow, things were different. The cold of winter knew a good place where it could do its job of making everything and everybody cold much more easily. It could flow into the hollow where the town had been built. It could collect there and it knew it would not be driven out so easily by a little bit of wind as could happen on the plain. More and more cold could collect in Little Hollow, and it got colder and colder as the winter grew stronger. The temperature fell and fell.
> The people of Little Hollow knew that the cold would find its way into their homes if they were not careful to close windows and doors. The cold could even sneak in through tiny cracks between walls and windows, so the people had learned to build their homes well to make it hard for cold to flow in. At times when much cold had collected in their town, when it had become terribly cold and the temperature was very, very low, the fires in the furnaces had to work very hard to fight the cold. The people in their homes made sure that the heat produced by the furnaces would always balance the cold so that their homes felt comfortably warm.
> For the children of Little Hollow, the cold of winter was not so bad. They dressed warmly and played hard when they were outside. But even for them, the thick cold of winter had mischief in mind. It went into the snow lying on the ground to make it very cold as well and this made the snow drier and harder to work with. The children could not form

snowballs, and it was much more difficult to build snowmen. They had to wait until winter had grown somewhat tired, and the cold was slowly driven out of Little Hollow. When that happened the cold of winter knew its time had come. The warmth of early spring would grow stronger and drive the cold out of the hollow. The cold knew it had to accept its defeat but it also knew very well it would be back . . .

If a story should be prototypically narrative, it must make use of and be shaped by agents, tension, events and processes, causation/power, and connection to emotional understanding (Herman, 2009, 2013). If it is to contribute to scientific thinking, it must also contain the small-scale conceptual structuring of storyworld and agents that make scientific formal reasoning possible. Such structuring can be provided by metaphoric projection of schemas (Johnson, 1987; Turner, 1996). Our story appears to meet both criteria.

Analysis of the Winter Story

The Winter Story creates a storyworld: it describes a scene relative to which natural agents (cold and heat) are profiled (their characters are outlined). Moreover, by being embedded in a story, cold is given a character with emotional aspects[6] (related to the generating polarity, i.e. COLD ↔ HOT) causing and being subject to processes that unfold over time. The agents act and suffer in accordance with their properties (characters), and the story narrates a particular course of events in this storyworld.

The storyworld receives structure from the conceptualization of its elements—in particular, the agents appearing in it—in terms of figures of mind. We can identify a list of *image schematic elements* whose *metaphoric projection* leads to the fleshing out of a character or *agent* called *cold* (see a selection of expressions from the story in Table 1). Table 1 lists the types of conceptual metaphors that characterize forces (of nature): the THERMAL LANDSCAPE metaphor, the MOVING COLD metaphor, and the COLD AS A MOVING FORCE metaphor (I am using names analogous to Johnson's three metaphors in his analysis of music; Johnson, 2007, pp. 248–254). These metaphors reflect our figurative understanding of the major properties of forces (of nature). To be more specific, the story creates partial models of cold (such as when the cold outside tries to sneak into a home through the walls) and allows for their mental simulation. Models and simulations are guided by the logic of the figurative structures (for example, when a material is a container for cold, elements of the story must follow the logic of the CONTAINER schema).

Overall, the story suggests that there is a *force of nature* (made vivid as an agent) having properties of *quantity* (size), *intensity* (coldness, temperature), and *power*. (Originally, the idea of a simple basic gestalt of the type I call FORCE was suggested by macroscopic physical science; see Fuchs (2006, 2007, 2011) for more details.[7]) Cold can accumulate, it can flow, it can be hindered, it causes other phenomena, and it can be balanced (fought) by heat; imbalance between the intensity of cold in different places lets cold flow. Accumulation of cold makes a given material colder.

Table 1. Metaphors for cold in a Winter Story

Metaphors	Linguistic metaphoric expressions
COLD IS A THERMAL LANDSCAPE	And it got colder and colder as the winter grew stronger. The temperature *fell* and fell. When it had become terribly cold and the temperature was very, *very low* …
COLD IS A (FLUID) (MOVING) SUBSTANCE/OBJECT	The cold of winter *found its way into* the area and *spread out*. It could *flow* into the hollow … it could *collect* there … The cold could *sneak* in through tiny cracks between walls and windows …
COLD IS A POWERFUL AGENT (MOVING FORCE)	The cold of winter knew a good place where *it could do its job of making everything and everybody cold* … It went into the snow lying on the ground to *make it very cold* as well and this made the snow drier and harder to work with. The fires in the furnaces *had to work very hard to fight* the cold.

Clearly, our story frames a scene. The question remains how properly scientific this framing can be seen to be. Sadi Carnot's verbal rendering of his idea of the role of heat in steam engines will now be used to show that the conceptual structure in the Winter Story is fundamentally the same as that found in his scientific text (Fuchs, 2010).

Carnot's Power of Heat

Carnot's model of the power of heat serves as a prime example of the kind of metaphoric structures that are common to our perception of forces of nature. Carnot described the operation of a heat engine as follows (Carnot, 1824):

> Everyone knows that heat can produce motion. That it possesses vast motive-power no one can doubt, in these days when the steam-engine is everywhere so well known. (p. 3) The production of motive power is then due in steam-engines not to an actual consumption of caloric, but to its transportation from a warm body to a cold body […] (p. 7) According to established principles at the present time, we can compare with sufficient accuracy the motive power of heat to that of a fall of water […]. The motive power of a fall of water depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used, and on what may be termed, on what in fact we will call, the height of its fall, that is to say, the difference of temperature of the bodies between which the exchange of caloric is made. (p. 15)

This linguistically beautiful example reflects in a compact manner, the figures of mind we have seen operating in the Winter Story—heat is a force of nature in the sense described earlier. Nature or machines create a thermal tension (temperature difference) that lets quantities of heat (caloric) flow like water in a waterfall. As it turns out, the power of heat, that is, the measure of its causative force, results from the measures of tension and quantity[8] combined:

$$\text{Power of heat} = \text{Flow of caloric} \cdot \text{Thermal tension.}$$

The conceptualization of the gestalt of heat in terms of intensity (tension: understood metaphorically by the projection of the SCALE schema), quantity (a FLUID SUBSTANCE metaphor is used to conceptualize such quantities), and power (metaphoric projection of the gestalt of direct manipulation, see Lakoff and Johnson, 1980) is the starting point for the construction of modern (continuum) thermodynamics (Fuchs, 1996/2010). Naturally, we recruit additional schematic and metaphoric structures to understand the properties of a force such as heat. Aspects of fluid substance use projections of schemas such as FLOW, CREATION, and CONTAINER, whereas flow uses ENABLING or RESISTANCE. Clearly, there are a fair number of fine-grained elements of a metaphoric network to be found in our conceptualization of forces.

Summary

Carnot's text is a non-central member of the narrative category (even though the first paragraph quoted above hints at a possible full story): it basically recounts the bottom-up view of the force of nature called *heat*. We may think of the passage as a narrativized explanation (a text type intended as an explanation but written in a form that includes elements of narrative; see the earlier text). Still, it is an example of narrative framing of natural (and technical) scenes: it supports narrative perception (the enlisting of narrative intelligence). It conjures up images of the agent called heat. No matter how short the description, it transports us into a storyworld where the character of the force of heat is described clearly while semi-formally.

Our Winter Story, on the other hand, comes very close to what we call a central member of the category of narrative according to the four requirements listed earlier (Herman, 2009). It embeds natural agents in a story, frames a natural scene, and describes how the agents act or suffer in this world. Importantly, agents' characters are described metaphorically in terms of the same conceptual structures that are found again in corresponding scientific accounts. Heat (rather than cold) is a quantity that flows and can be stored; temperature is its potential; and the flow of heat from higher to lower potential drives other processes (remember Carnot's text and note the case of a formal model to be presented in the next section).

However, an important part of the argument that the Winter Story is a prototypical narrative rests upon our willingness to give the natural agents a character similar to sentient intentional beings. Conversely, this means that we, as interpreters, must be touched emotionally by such natural characters; in other words, it means that we must be able to get to know forces of nature emotionally (both through stories and direct natural experience) and ground our intellectual understanding in such an emotional foundation (see Endnote 6 for a brief discussion of what is involved in this issue). We will have proper stories not only due to the appearance of human (or human like) intentional agents but also when we recount the adventures of forces of nature. The argument can be summarized as follows: our encounters with nature become narratable just as our encounters with other humans do.

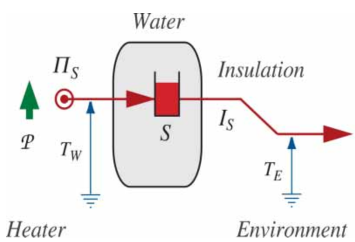
In short, although they have radically different origins, both examples discussed here stimulate *narrative perception* of natural scenes—they prompt the creation of natural storyworlds (remember that narrative perception is one of the senses of narrative framing). Importantly, since they have the same narrative elements (both conjure up scenes with forces of nature as agents), the storyworlds are of the *same* type (put more formally, they suggest the same scientific concepts). Conversely, this means that we can write proper stories such as the Winter Story that can be scientifically relevant (this is the sense of *narrative production* alluded to in the definition of narrative framing given in the Introduction).

Narrative Framing in a Formal Model and Its Simulation

The notion of narrative framing is not solely dependent upon our being able to produce prototypical narratives, that is, stories for scientific purposes. The first of the senses mentioned in the description of framing presented earlier—enlisting of narrative intelligence in the perception of nature and semiotic products—will still be at work even if we have a formal text that is not at all story-like. In order to demonstrate this, I will discuss the example of a formal mathematical model of electric heating of water in a teakettle (see Figure 1) and its simulation(s). To simplify matters, it will be presented in the uniform dynamical systems version of a continuum physics model (Endnote 1). In contrast to an example presented in everyday language, we have here the opportunity to read figures of mind from the form of equations (remember that I am claiming that narrative perception can still work in the case of a mathematical text).[9]

The Model

Imagine some water in an electric teakettle. When the electricity is turned on, the water will get hotter over time and, because of the loss of heat through the kettle



$$(1) \quad \dot{S} = \Pi_S - I_S$$

$$(2) \quad \dot{S} = K_S \dot{T}_W$$

$$(3) \quad I_S = G_S \left(T_W - T_E \right)$$

$$(4) \quad \Pi_S = \frac{1}{T_W} \mathcal{P}$$

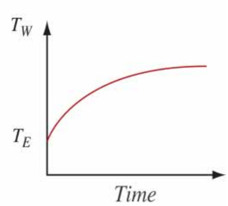


Figure 1. Process diagram (left), equations, and simulation of a dynamical model of the heating of water in a teakettle. The quantities shown are (electric and thermal) power ($\mathcal{P}$), entropy (S), flow of entropy (I_S), production rate of entropy (Π_S), temperature of water (T_W), temperature of environment (T_E), entropy capacitance of water (K_S) and conductance for flow of entropy through the wall of the kettle (G_S).

wall, its temperature will reach a steady state at a level that depends upon the power of heating (Figure 1, right). The mathematical model (Figure 1, center) makes use of the law of balance of entropy for heater and water (entropy is produced in the heater and communicated to the water; the water stores entropy and emits it to the environment; Figure 1, Equation (1)); the constitutive relation between entropy stored and water temperature (Equation (2)); the constitutive relation between entropy loss to the environment and temperature difference between water and environment (Equation (3)); and the relation between electric power, entropy production rate, and water temperature (Equation (4)). In addition, an initial condition for the entropy of the body of water, electric power, and constitutive quantities (capacitance and conductance) need to be specified (not shown here).

Simulation

Stripped to its bare bones, a model such as the one presented earlier is a system of equations (expressions or statements). A simulation leads to quite a different semiotic product—it is both an activity and a result that has lately been related to storytelling and stories (see the later text).

Importantly, time only makes its proper appearance in a simulation. Even though time is written in the equations of dynamical models (see Figure 1), only a simulation involves evolution (tracing paths) through time. Only a simulation shows the full meaning and importance of the variables that are related by the equations of the model. Simulations show us the full range of possibilities of behavior (in the virtual world) inherent in the model.

Furthermore, the model does not specify every single one of the elements necessary for its simulation. In particular, initial values and parameters are not given (prescribed) by the model. Specifying them involves using the model for particular purposes, an act that cannot be defined as part of a theory to which the model belongs. To create this definition, a practitioner has to embed the model in the world. This act involves a mental attitude that goes beyond what a particular theory provides to us: it is a narrative act (see Morgan, 2001, 2012; and in the following).

Metaphoric and Narrative Interpretation of Model and Simulation

When we read the equations we can get a feeling for the figures of mind they reflect.[10] Equation (1) is the law of balance of entropy. It suggests that entropy is imagined as a *fluid quantity* that is contained in bodies and whose amount can change (dS/dt) due to flow (I_S) and production (Π_S).[11] When the amount of entropy in the water changes, the temperature of the water (T_W) changes in parallel according to the properties of the container (K_S: the entropy capacitance of the water; see Equation (2)). Equation (3) tells us that entropy flows due to the *thermal tension* between the hotter (water) and colder (air) bodies. Temperature is a *level* (potential) whose difference is felt as a tension. The insulation of the kettle lets entropy through (or obstructs the flow; G_S is the conductance for the flow of entropy from water to air).

Finally, we make use of the notion of *power* of a force of nature. This calls into existence at least one more force of nature, in this case electricity (see the left of the diagram in Figure 1). Electricity is the agent responsible for the production of entropy (the patient). Power is the measure of their interaction: the first agent (electricity) makes energy available at a certain rate; the energy is used to produce entropy in the electric heater. The measure of power of the first agent is equal to the causative power influencing the patient that is equal to the measures of the thermal tension in this process (difference of temperatures between heater and absolute zero) and quantity of entropy conjoined.

When we (mentally) simulate the model, or if we recount a simulation in natural language, we are setting up a concrete scenario in the world of the figures of mind (in the storyworld) of the model and then follow the agent(s) through a sequence of events.

Summary

Clearly, however they present themselves, a mathematical model and a graphical or tabular representation of a simulation are not stories, not even a more peripheral version of a narrative. The process diagram on the left in Figure 1—while representing concepts in the form of visual metaphors—is not a story either.

Nevertheless, narrative framing can (and should) still happen even though neither a story nor forces of nature nor metaphors may be directly visible in the semiotic product.[12] The argument rests upon the assumption that we, as readers and learners, can *perceive* narrative structures in the model and its use—we enlist narrative (and metaphoric) understanding in interpreting the model. Clearly, we have a very similar network of embodied conceptual relations as in the example of the Winter Story. Heat is a force of nature structured in terms of metaphors like the ones used before, and it is understood in terms of its role in simulations of the model. The model itself represents a characterization of a storyworld (including a specification of the character of the agents), and a simulation is like telling a particular story with this model.[13]

Narrative Framing: Stories and Storyworlds, Simulations and Models

Two lines of research concerning science and narrative in the fields of computational science and economics will be seen as greatly enhancing our investigation of narrative as a central component of the production and reception of science. In the previous sections, I have referred to a relation between scientific models and storyworlds. This point will now be discussed in more detail leading us to a model of the relation between embodied conceptual structures and semiotic products and acts in the realm of science (see Figure 2 for a graphical representation of the model).[14]

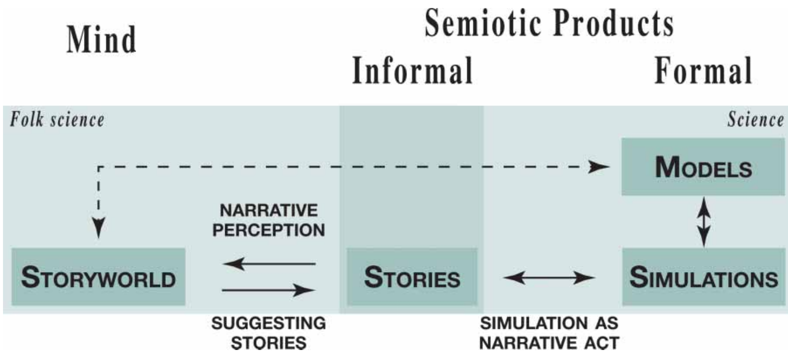


Figure 2. A model of the relation between formal models and storyworlds. The relation is mediated by simulating-as-storytelling-with-models and stories-transporting-us-into-storyworlds. Note that the relation between models and storyworlds is indirect—it emerges from the other relations.

Growing Solutions in Computational Science as Storytelling

A particularly interesting case of *science as historicizing narrative* has been described by Wise (2011). Wise contrasts the traditional mode of explanation as deduction from differential equations with explanation through simulation. He argues that narratives that accompany simulations are historical in kind: they (the narratives) *explain* natural phenomena by growing (developing) them rather than by referring them to general laws. This is a phenomenon well known to those working in computational fields of science: explanations (of the behavior of systems) grow from many simulations; a picture emerges from a vast number of trajectories followed rather than from a single analytic solution of a set of equations.

Narrative Embedding

The following application of narrative in social science has been described by Morgan (2001). I consider this paper on economic modeling one of the most important (not the least for the natural sciences) for showing how far the theory of narrative in science has come (for an extended and more recent discussion, see Morgan, 2012). Morgan demonstrates that *using models* and relating them to the world is a *narrative activity*. How to make use of a model or what to look for in a simulation are aspects that are not covered by the model or its underlying theory. Posing questions that lead to the definition of parameters and initial values for subsequent simulation is a narrative act.

Both Morgan's and Wise's investigations point to a strong and rather direct relation between narrative and simulation (Morgan: telling stories with models)—this will prove central to my model of the role of narrative framing presented in the later text. Note that researchers seem to draw a line when it comes to using narrative for helping frame natural and technical scenes in the sense discussed in the previous sections. It is not assumed that narratives frame scenes in a manner that would lead us to formulate concepts and models. Models are derived from theory in a classical manner and theory is given—it exists prior to modeling and the subsequent narrative act of embedding models in the world. Storytelling does not lead to theory.

Stories Suggest Concepts and Models

This is clearly too narrow an interpretation of the research cited (Morgan, 2001; Wise, 2011)—it would be strange if there were no feedback from the act of simulating as storytelling to the construction of models. Since 2001, Morgan has extended her work on narrative and modeling (see Morgan, 2012). She writes that:

> after my initial paper on stories (2001) [. . .] I tried to push further the ideas about narrative in the way that economists work with models. I came to distinguish between two things. One was the way stories form the identity of a model—the stories that can be told by working with a model (in simulations [. . .]) are the way that economists fully understand what kind of a model it is. Second, there are stories that are developed to map/match those models onto features of the world. (Private communication, 2014)

By using the notion of storyworld, we can explain how stories lead to the construction of scientific models and how such models can be read narratively (meaning that they lead to the construction of storyworlds; see Figure 2); note that the interaction between models and storyworlds is assumed to be indirect. I accept Morgan's (and Wise's) idea that simulating models means telling stories (with these models) as a central feature of my proposal. If we further accept that scientific stories (such as the Winter Story or Carnot's text) let us create scientific storyworlds—that is, conceptual structures (frames) that contain the seeds of scientific ideas—we can consider models the formal counterparts of storyworlds. In other words, stories of forces of nature relate to storyworlds as do simulations to models. Stories that frame natural scenes transport us into (natural) storyworlds where we create (narrative) understanding of forces of nature.

This closes the circle: models suggest stories and stories suggest models (via their storyworlds). Stories have the power to propose concepts and models and, therefore, elements of theory.[15] The stories recounting our encounters with nature contain the elements that become building blocks of theoretical knowledge. Framing of natural scenes originates in narrative perception of nature whose products find their way into our formal scientific models and theories.

Conclusion: Narrative Framing and Science Education Research

The notion of narrative framing of natural and technical scenes suggests a number of consequences for science, science learning, and science education research. In the practice of modeling and simulation, narrative is seen as a methodological tool that helps with conceptualizing new situations. Science learning, on the other hand, can profit from an application of narrative that goes beyond creating affect and historical and social background and even beyond using narrative for explaining particular natural–historical events. In order to better understand novel uses of narrative in science learning, previous research in this field will be described briefly in the later text.

As for science education research, the present study suggests that there is more than just a superficial link between everyday and scientific forms of thought—we can expect linguistic studies to shed fresh light upon questions in conceptual change research (see Amin, 2009). Finally, if we accept that scientific thinking is deeply embedded in some forms of narratives (such as stories of forces of nature), we can extend applications of cognitive linguistics and the concept of embodied cognition to semiotic products that are larger than single utterances—we can probe students' understanding of science in situations that involve more than a single concept. It will become possible to investigate large-scale modeling activities in science learning (Fuchs, 2006; Hestenes, 2006).

The discussion in this paper has been based upon developments in modern continuum physics, investigations of narrative in computational science and economics, and modern narratology, all of which lie somewhat outside the scope of current research in science education. Therefore, it is time to embed the theme of this paper into wider concerns, particularly those of studies of narrative in science learning and of conceptual metaphor and embodied cognition. Finally, I will give a view to research into applications of narrative framing.

Narrative in Science Education

Storytelling in science classrooms has attracted considerable interest in recent years. We are confident that stories can be used to create affective environments for social–historical contexts of science to engage and motivate learners; here, storytelling remains *extrinsic* to science. Some applications, discussed under the heading of *narrative explanation*, introduce the concept of narratives *intrinsic* to science (the distinction between extrinsic and intrinsic forms of narratives has been made by Norris et al., 2005).

How does the idea of narrative framing fit in with previous work on narrative in science and science education? Since narrative understanding is most easily associated with the non-paradigmatic (see Bruner, 1987, 1990, who seems to assume that there is a dichotomy between narrative and paradigmatic modes of understanding), it is not surprising that applications of narrative in science have been studied mostly for *extrinsic* cases. For instance, there is the grand narrative of meaning of science and of scientific knowledge (Lyotard, 1979/1984; science has a meaning for understanding human culture and the human condition). Then, there are less grand examples such as when we say that the claims of science or a part thereof (such as of thermodynamics) are a 'story.' Arnold and Millar (1996, p. 251) tell us that:

> [t]he scientific 'story' about thermal phenomena then says that, if two objects at different temperatures are placed in thermal contact, heat will spontaneously flow from the one at higher temperature to the one at lower temperature. [. . .] the 'story' must be accepted *as a piece*; it only makes sense as a complete 'story'.

So, there is a ‘scientific story’ as opposed to a possibly non-scientific one, and it is a story because it connects conceptual elements into a whole rather than leaving them as a more or less loosely packed conglomerate of statements (laws, etc.).

Stories *about* science have been created and investigated for a range of applications. An important goal of authors of such stories is to create affect (Egan, 1986); Spoel, Goforth, Cheu and Pearson (2008) discuss an example of apocalyptic narrative explanation in the field of climate change meant to engage citizens. Kubli (2001, 2005) shows how storytelling can be employed very generally for creating an environment conducive to learning about science. Stories about science and technology can create historical and social context (Klassen, 2006; Levinson, 2006; Metz, Klassen, McMillan, Clough, & Olson, 2007). Learning of science is supported by creating reading materials where expository texts are blended with narrative elements (Avraamidou and Osborn, 2009). Finally, narrative has been investigated for promoting conceptual change (Klassen, 2010), and providing background for learning about the process of science (Bruner, 1996, p. 126).

In their study of intrinsic uses of narrative, Norris et al. (2005) present a thorough discussion of the concept of *narrative explanation*. With regard to the phenomenon of explanation, the authors argue against a narrow reading of *explanation* only in terms of the *deductive* or *deductive-nomological model* (the covering law model; see, for example, Hempel and Oppenheim, 1948). Briefly stated, according to this model, an explanation of a phenomenon refers to the general laws and initial condition from which a solution can be derived that reflects the observations. (In this sense, the initial value problem formulated in Figure 1 is an explanation of the phenomenon of electric heating of water in the teakettle.) Norris et al. (2005) show how the deductive reading of explanation cannot do justice to a vast range of science. Where science treats either *singular events* (a meteorite striking the Earth 65 million years ago) or *historical events in nature* (stellar evolution, the development of a particular ecosystem), strict deduction fails. In the end, only narratives of the (special, singular, historical) events can be produced. Such stories properly and sufficiently *explain* what we want to know.

Actually, this use of stories is related to simulating models as explained earlier. Assuming that there is a model behind it, telling a story of the demise of the dinosaurs (Norris et al., 2005) is similar to how economists tell stories in their use of models (Morgan, 2001, 2012). So, there is a direct link between some of the research in narrative in science learning and the present theme. And even though extrinsic uses of narrative seem to be far from what I have discussed in this paper, note how important its concern with basic aspects of narrative—such as the elicitation of emotion and affect—is for our subject here (see earlier and Endnote 6).

Embodied Cognition in Science Learning

Much of the present paper has been motivated by cognitive linguistics and the concept of embodied cognition (see, for example, the characterization of forces of nature in terms of an embodied conceptual network described earlier). In science education, conceptual metaphor theory has been employed to inform us about common sense conceptualizations used by learners and professional scientists alike (Amin, 2001, 2009; Amin, Jeppsson, Haglund, & Stromdahl, 2012; Brookes and Etkina, 2007; Fuchs, 2006, 2007; Jeppsson, Haglund, Amin, & Stromdahl, 2013; Lancor, 2014a, 2014b). Linguistic investigations motivated by the concept of embodied cognition help us understand students' reasoning in science and cast light upon figurative structures of the human mind at the same time. We become more sensitive to everyday forms of reasoning that should help us become better teachers. Moreover, we understand better in what way common sense reasoning is a productive resource in learning.

Language is an agent of active learning and conceptual change, not just a tool for probing the mind. A quote from Amin (2009, p. 166) neatly summarizes the role of feedback from language and semiotic products to the mind: 'It is suggested that the appropriation of construals implicit in language and the metaphorical nature of our understanding of many concepts pervasively reflected in language, together, are likely to constitute important sources of conceptual change.' This parallels the discussion of narrative framing presented with the examples in earlier sections. I consider narrative perception of natural scenes prompted by texts (or more generally, semiotic products) as a process analogous to what Amin calls 'the appropriation of construals'; this indicates that such texts should be seen as important sources of learning, including learning how to use language for understanding.

An early investigation by Andersson (1986) shows how cognitive linguistics and the theory of conceptual metaphor (Lakoff and Johnson, 1980) can be used to unify observations of preconceptions of learners in science. Furthermore, Bliss (2008) has come up with suggestions for understanding student reasoning as based upon the role of (image) schemas formed by our perception of the natural world. Her proposal is also an attempt at unifying observations of everyday understanding of macroscopic physical phenomena. Andersson's discussion of the *experiential gestalt of causation* and Bliss' schemas are important components of my concept of forces of nature. As I have discussed earlier, the conceptual structure of forces is made of metaphoric projections of image schemas many of which bear resemblance with Bliss' schemas. Moreover, the aspect of power is structured very similar to what we learn from the gestalt of causation.

Embedding these various lines of research into investigations related to narratology widens the field of inquiry. This paper is an attempt at bringing together cognitive narratology with cognitive linguistics and its applications in science learning.

Outlook: Researching Applications of Narrative Framing

Narrative framing has been explored, and continues to be explored, for a number of applications. The theory of uniform dynamical thermal systems has been produced explicitly upon framing thermal phenomena in terms of forces of nature (Fuchs, 1996/2010). A course on physics as a systems science for engineering students using this approach has been taught for over 10 years (Dumont et al., 2014). A story approach to mechanics is being developed and investigated in an Industrial Educational Laboratory at Ducati in Bologna, Italy (Ascari, Corni, Corridoni, Anna, &

Savino, 2013). An art student at Zurich University of the Arts has produced an animated movie for her bachelor's thesis that transforms stories of forces of nature into an animation creating and using visual metaphors (Deichmann, 2014). Based on her approach, plays are designed for workshops on science and technology taught at VW's Autostadt campus. Most importantly, stories of forces of nature have been written by Fuchs (2011–2014, Private communication) and Fuchs (2013a, 2013b) for inclusion in a narratively shaped primary school curriculum and teacher training in Italy (Corni, 2013, 2014; Corni et al., 2013); here, the entire curriculum takes a cue from narrative science education.

Much research remains to be done on narrative framing for applications in science, not just regarding details but fundamental questions as well. Implicit in my arguments is a model of embodied conceptual structures (including narrative) created by organisms interacting with their environment that still needs to be worked out. We need to research what it means when student teachers learn science in a narrative approach and we want to understand better what happens when children are exposed to stories of forces of nature and directly to nature—what storyworlds do they construct, what are the results of direct perception of events in nature corresponding in scale to what we may call stories, and how do these results relate to storyworlds? Forces of nature and narrative framing are expected to be important in this endeavor.

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Notes

1. As far as science is concerned, the present analysis is limited to macroscopic physical science—essentially in the form of continuum physics and its simple derivative of spatially uniform dynamical systems. While the literature on continuum physics is vast, it is by nature very technical. Some of the books on continuum physics in general (Eringen, 1971–1976; Truesdell & Noll, 1965; Truesdell & Toupin, 1960) and on continuum thermodynamics in particular (Jou, Casas-Vazquez, Lebon, 1996; Müller, 1985; Truesdell, 1984) may be of use for those interested in an overview and technical aspects. The most accessible of these may be a text on a modern dynamical theory of heat (Fuchs, 2010). Here is a brief description of the basic structure of continuum physics (Fuchs, 2010, p. 9). Modern continuum physics presents us with a unified approach to macroscopic physical systems and processes taking the following form. First, we have to agree upon which physical quantities we are going to use as the fundamental or *primitive* ones. On their basis, other quantities are defined and laws expressed. Second, there are the fundamental *laws of balance* of the quantities that are exchanged or created in processes, such as momentum, charge, entropy, or amount of substance; I call these quantities *fluidlike*. Third,

there are potentials or potential differences that are visualized as driving forces for the processes undergone by the fluidlike quantities. Fourth, we need particular laws governing the behavior of, or distinguishing between, different bodies; these laws are called *constitutive relations*. Constitutive laws relate the basic fluidlike quantities to potentials or potential differences. Last but not least, we need a means of relating different types of physical phenomena to each other. The tool that permits us to do this is energy. We use the *energy principle*, that is, the law that expresses our belief that there is a conserved quantity appearing in all phenomena that has a particular relationship with each type of processes.

2. Figures of mind: objects of (in) mind created by figurative thought (e.g. a metaphor) or by perception (a perceptual gestalt or shape). Short for *figurative structures of mind*; to be distinguished from figurative structures outside of mind and structures of mind that are not figurative. (On the notion of figurative thought and related concepts, see Gibbs, 1994.) In using the term figure of mind, I take a cue from *figure of speech*. Traditionally, such as in rhetoric, examples of figures of speech are metaphor, simile, hyperbole, synechdoche, etc. Since cognitive linguistics insists that figurative language reflects a deeper (i.e. mental) phenomenon, the term *figure of mind* is introduced as the (mental, cognitive) counterpart of figure of speech. It relates not to semiotic products but to mental products, objects, or structures. Sometimes I use the term more broadly to include the (direct) products of perception, that is, *gestalts* or *shapes* (the latter term is from Arnheim, 1969). Arnheim's notion of 'visual thinking' suggests that (visual) perception is a form of thinking leading to structures of (figurative) thought. When the distinction between shapes or gestalts and the products of projection of structure from such gestalts onto target domains (as in metaphor) is important, I will use figures of mind only for the latter objects. See Section 2.1 for further details.
3. Note that I use the term *force* not in the sense of mechanics proper but in its primitive sense of phenomena that are endowed with power. Heat, wind, justice, language, pain, love, electricity, music, the market, etc. are forces or powers in this sense (music has been described as, but not named, a force by Johnson, 2007, Chap. 11). Macroscopic physical science grows from the notion of forces of nature (Fuchs, 2010).
4. Framing is used in a sense originally suggested by Fillmore's (2006) frame semantics: if we hear an utterance we construct—or, if it has been constructed before—invoke a frame, that is, a conceptual structure for understanding that utterance. The latter is said to be 'about a scene', so we can speak of framing scenes (or situations or scenarios; see also Cienki, 2007).
5. In cognitive science, it is quite common to assume that humans have a narrative mind, meaning that they understand the world narratively (see, for example, Bruner's concept of narrative construction of reality, Bruner, 1991; this is again a theme in modern narratology as a branch of cognitive science; Herman, 2013). Building on this concept, I assume that our narrative mind allows for *intelligent narrative perception*: we do not just perceive small-scale stuff as units from which larger-scale things are built but also large-scale processes and events that resemble (long) stories. This argument parallels Rudolf Arnheim's concept of the intelligence of visual perception (Arnheim, 1969) and may be recognized again in the idea of the narrativity of perception (Carr, 1991).
6. The question of emotional perception in a story of natural forces is quite central to the entire issue of using narrative in a more than peripheral (extrinsic: Norris et al., 2005) form in science and science learning. On the one hand, it has been argued quite convincingly that story and emotion go hand in hand. At the end of a good story, we should know how to feel about the events and characters (Egan, 1986). Stories give us emotional closure, not intellectual understanding (Velleman, 2003). Stories are opposed to paradigmatic thought; they are repositories of folk psychology (Bruner, 1987, 1990). On the other hand, emotion may well be the root of reason (Johnson, 2007). Therefore, accepting that a good story (a central member of the category of narrative) must make emotional perception possible and that a good scientific story must make narrative framing of forces of nature possible, we need to admit that science stories

have to open emotional access to these forces. The question of how stories of forces of nature lead to their emotional perception and, eventually, to their scientific framing, will have to be investigated in much more depth in the future. Clearly, this is just one example of the quest for understanding the relation between emotion and reason.

7. I would like to suggest that the concept of a gestalt of force and its figurative structuring goes well beyond natural phenomena. Indeed, forces are ubiquitous creatures of the human mind; we perceive social and psychological forces in addition to forces of nature. A beautiful example of the metaphoric analysis of our understanding of music (Johnson, 2007, Chap. 11) shows not only that there are other forces, it demonstrates a particularly useful form of analysis of a phenomenon that is perceived as what I call force. Johnson shows that there are three main conceptual metaphors we use in our understanding of music: (1) music as a moving object, (2) music as a landscape in which we move, and (3) music as a moving force (the identification of these metaphors parallels the structure of substance, intensity, and power I use to conceptualize forces of nature). Another example is the perception of justice where the full conceptual structure of a force is reflected in everyday utterances (Fuchs, 2011).
8. The power of a process is always equal to the product of a potential difference (tension) and the flow of a fluidlike quantity through this potential difference. In fluids: $P_{\text{fluid}} = \Delta p \cdot I_V$ (p: pressure, I_V: volume current); in electricity: $P_{\text{electric}} = \Delta\phi \cdot I_Q$ (ϕ: electric potential, I_Q: current of electric charge); in thermodynamics: $P_{\text{thermal}} = \Delta T \cdot I_S$ (T: temperature, I_S: current of caloric (entropy)); in chemistry: $P_{\text{chemical}} = \Delta\mu \cdot I_n$ (μ: chemical potential, I_n: current of amount of substance). All these equations can be represented in terms of visual metaphors, so-called process diagrams (Figure 1; Fuchs, 2010, Chap. 2; see also Falk, Herrmann, & Schmid, 1983).
9. It is certainly possible to argue, as many scientists would, that equations do not invoke images. On the other hand, if we assume that our concepts are grounded in embodied cognition, we cannot escape the conclusion that we *must* find figures of mind in the equations of a model. For an important argument that equations are more than purely formal representations, see Sherin (2001). Extending the depth and details of Sherin's work to the present case is beyond the scope of this paper. For a more detailed description of the figurative structure of the partial differential equations of continuum thermodynamics, see Fuchs (2013c). See also Endnote 11.
10. For a more sophisticated example of continuum thermodynamics (thermoelectricity), see Fuchs (2014). We find the same figurative conceptual structures there as in our simpler example. The ease with which a supposedly complicated case is modeled is a witness to the power of the storyworld that is the result of a narrative approach to thermodynamics.
11. In modern (non-equilibrium and continuum) thermodynamics, the law of balance of entropy is conceptualized as the formal equivalent of the embodied notion of the balance of a fluidlike quantity analogous to charge, momentum, or amount of substance (Fuchs, 1996/2010: Introduction). Unlike charge or momentum, entropy satisfies only half a conservation law, and amount of substance none at all. Entropy satisfies the embodied notion of caloric suitably extended by the requirement that caloric is generated in irreversible processes. On the concept of caloric in the modern theories of thermodynamics, see Callendar (1911), Job (1972), Falk (1985), Fuchs (1986, 1987a, 1987b, 1996/2010) and Mareš et al. (2008). For a contribution to the debate of historical issues, see Kuhn (1955). Let me stress here that I personally believe that changing the use of terminology from entropy to caloric would be essential on two important grounds. First, psychologically speaking, the word entropy does not convey any useful embodied image, certainly not for macroscopic models of thermal processes. This word will serve no other purpose than to confuse a child and send an adult layperson onto a search into esoteric land or for microscopic disorder. Second, for scientific reasons, it is paramount that we understand the difference between macroscopic and microscopic models (and accept that microscopic models do not ground macroscopic ones). Using two terms, caloric

and (logarithm of) number of possible configurations or states, for macroscopic and microscopic models, respectively, can make this distinction plain. I have refrained in this section from using the term caloric in order to conform to the tradition.

12. Note that we could easily construct a word model for the situation analyzed here. Its form will depend upon the audience this is intended for (engineering students or young children, for instance). Depending upon the circumstances, the semiotic product could be a peripheral member of the category of narrative (a narrativized description or an explanatory narrative) or a central member, that is, a proper story (see Section 'Theory of narrative').
13. Few practitioners and teachers of science will spontaneously interpret the mathematical model and its simulation in terms of narrative and story (in economics and in computational science, the practice seems to be different, though; see Section 'Narrative Framing'). However, this does not change the validity of what has been said. Rather, it compels us to rethink education in science. If we are not taught so, we will not develop a 'narrative eye' for what we see and do. We will simply follow the tradition and accept a system of equations as the only true and objective but otherwise meaningless collection of signs reflecting nature directly 'as it is'.
14. In this model, the relation between mind and (natural) world is missing. In this paper, I have made use of an assumption regarding this relation in the form of the claim that enlisting narrative intelligence (or the act of narrative perception) also refers to our perception of nature (see Section Introduction and Endnote 5).
15. Here is an example for how narrative thinking influences (the production of) science. Note how important figures of mind are for the construction of a theory. In continuum physics, the basic structure of the gestalt of forces guides the choice of *primitive quantities* (Endnote 1). In all fields (fluids, electricity and magnetism, heat, chemical substances, translational and rotational motion), this choice takes the same form: primitive quantities for a theory are (1) the potential and (2) a fluidlike quantity, and directly related quantities such as stored amount, current, production rate, and potential difference. The primitives of modern thermodynamics are temperature and temperature difference, entropy (caloric), current and production rate of entropy. This choice is fundamentally important (Fuchs, 1986, 1987a, 1987b, 2010, pp. 1–13).

References

Amin, T. G. (2001). A cognitive linguistics approach to the layperson's understanding of thermal phenomena. In A. Cienki, B. J. Luka, & M. B. Smith (Eds.), *Conceptual and discourse factors in linguistic structure* (pp. 27–44). Stanford, CA: CSLI Publications.

Amin, T. G. (2009). Conceptual metaphor meets conceptual change. *Human Development*, *52*(3), 165–197.

Amin, T. G., Jeppsson, F., Haglund, J., & Strömdahl, H. (2012). Arrow of time: Metaphorical construals of entropy and the second law of thermodynamics. *Science Education*, *95*(5), 818–848.

Andersson, B. (1986). The experiential gestalt of causation: A common core to pupils' preconceptions in science. *European Journal of Science Education*, *8*(2), 155–171.

Arnheim, R. (1969). *Visual thinking*. Berkeley, CA: University of California Press.

Arnold, M., & Millar, R. (1996). Learning the scientific 'story': A case study in the teaching and learning of elementary thermodynamics. *Science Education*, *80*(3), 249–281.

Ascari, A., Corni, F., Corridoni, T., D'Anna, M., & Savino, G. (2013, September). New perspective on rotation: experiments, modelling and analogies based on angular momentum as an extensive quantity. *Proceedings of the ESERA conference*, Nicosia, Cyprus.

Avraamidou, L., & Osborn, J. (2009). The role of narrative in communicating science. *International Journal of Science Education*, *31*(12), 1683–1707.

Bliss, J. (2008). Commonsense reasoning about the physical world. *Studies in Science Education*, *44*(2), 123–155.

Brookes, D. T., & Etkina, E. (2007). Using conceptual metaphor and functional grammar to explore how language used in physics affects student learning. *Physical Review Special Topics—Physics Education Research*, *3*(010109), 1–16.
Bruner, J. (1987). *Actual minds, possible worlds*. Cambridge, MA: Harvard University Press.
Bruner, J. (1990). *Acts of meaning*. Cambridge, MA: Harvard University Press.
Bruner, J. (1991). The narrative construction of reality. *Critical Inquiry*, *18*(1), 1–21.
Bruner, J. (1996). *The culture of education*. Cambridge, MA: Harvard University Press.
Callendar, H. L. (1911). The caloric theory of heat and Carnot's principle. *Proceedings of the Physical Society of London*, *23*(1), 153–189.
Carnot, S. (1824). Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance (R. H. Thurston, Trans. and edited. Peter Smith, Gloucester, MA, 1977). Paris: Bachelier.
Carr, D. (1991). *Time, narrative, and history*. Bloomington, IN: Indiana University Press.
Chemero, A. (2009). *Radical embodied cognitive science*. Cambridge, MA: The MIT Press.
Cienki, A. (2007). Frames, idealized cognitive models, and domains. In D. Geeraerts, & H. Cuyckens (Eds.), *The oxford handbook of cognitive linguistics* (pp. 170–187). Oxford, UK: Oxford University Press.
Corni, F. (Ed.) (2013). *Le scienze nella prima educazione. Un approccio narrativo a un curricolo interdisciplinare*. Trento: Erickson.
Corni, F. (2014). Stories in physics education. In S. Burra, M. Michelini, & L. Santi (Eds.), *Frontiers of fundamental physics and physics education research* (pp. 385–396). Milano: Springer.
Corni, F., Giliberti, E., & Fuchs, H. U. (2013). Student teachers writing science stories: A case study. *Proceedings of the ESERA conference*, Cyprus.
Deichmann, M. (2014). *Im übertragenen Sinne. Metaphern und Bildvergleiche in der Wissernschaft* (Bachelor thesis). Zürcher Hochschule der Künste, Zürich. Movie to be found at http://vimeo.com/98311515
Dewey, J. (1925). Experience and nature. In J. A. Boydston (Ed.), *The later works* (pp. 1925–1953, *Vol. 1*). Carbondale, IL: Southern Illinois University Press.
Dumont, E., Fuchs, H. U., Maurer, W., & Venturini, F. (2014, August). From forces of nature to the physics of *dynamical systems. The 9th international conference on conceptual change*, Bologna, Italy.
Egan, K. (1986). *Teaching as story telling*. Chicago, IL: University of Chicago Press.
Eringen, A. C. (1971–1976). *Continuum physics* (*Vols. I–IV)*. New York: Academic Press.
Falk, G. (1985). Entropy, a resurrection of caloric—A look at the history of thermodynamics. *European Journal of Physics*, *6*(2), 108–115.
Falk, G., Herrmann, F., & Schmid, G. B. (1983). Energy forms or energy carriers? *American Journal of Physics*, *51*(12), 1074–1077.
Fillmore, C. (2006). Frame semantics. In D. Geeraerts (Ed.), *Cognitive linguistics: Basic readings* (pp. 373–400). Berlin: Mouton de Gruyter.
Fuchs, H. U. (1986). A surrealistic tale of electricity. *American Journal of Physics*, *54*(10), 907–909.
Fuchs, H. U. (1987a). Thermodynamics—A 'misconceived' theory. In J. D. Novak (Ed.), *Proceedings of the second international seminar on misconceptions in science and mathematics* (Vols. I–III, pp. 160–167). Ithaca, New York: Cornell University.
Fuchs, H. U. (1987b). Entropy in the teaching of introductory thermodynamics. *American Journal of Physics*, *55*(3), 215–219.
Fuchs, H. U. (2006). From image schemas to dynamical models in fluids, electricity, heat, and motion. Examples, practical experience, and philosophy. *Proceedings of the 2006 GIREP conference*. University of Amsterdam.
Fuchs, H. U. (2007). *From image schemas to models in fluids, electricity, heat, and motion. An essay on physics education research*. ZHAW, Institute of Applied Mathematics and Physics www.zhaw.ch/~fusa/LITERATURE/Literature.html

Fuchs, H. U. (2010). *The dynamics of heat (2nd ed.). Graduate texts in physics*. New York: Springer (first edition: Springer, New York, 1996).

Fuchs, H. U. (2011). Force Dynamic Gestalt, metafora e pensiero scientifico. Atti del Convegno '*Innovazione nella didattica delle scienze nella scuola primaria: al crocevia fra discipline scientifiche e umanistiche*', Modena, Italy: Artestampa. English version: Force Dynamic Gestalt, Metaphor, and Scientific Thought. ZHAW, Institute of Applied Mathematics and Physics www.zhaw.ch/~fusa/LITERATURE/Literature.html

Fuchs, H. U. (2013a). Il significato in natura. In F. Corni (Ed.), *Le scienze nella prima educazione. Un approccio narrativo a un curricolo interdisciplinare* [Meaning in nature—From schematic to narrative structures of science], Erickson, Trento, Italy. ZHAW, Institute of Applied Mathematics and Physics. www.zhaw.ch/~fusa/LITERATURE/Literature.html

Fuchs, H. U. (2013b). Costruire e utilizzare storie sulle forze della natura per la comprensione primaria della scienza. In F. Corni (Ed.), *Le scienze nella prima educazione. Un approccio narrativo a un curricolo interdisciplinare* [Designing and using stories of forces of nature for primary understanding in science] Trento, Italy: Erickson. ZHAW, Institute of Applied Mathematics and Physics. www.zhaw.ch/~fusa/LITERATURE/Literature.html

Fuchs, H. U. (2013c). The narrative structure of continuum thermodynamics. *Proceedings of the ESERA conference 2013*, Cyprus.

Fuchs, H. U. (2014). A direct entropic approach to uniform and spatially continuous dynamical models of thermoelectric devices. *Energy Harvesting Systems*, *1*(3–4), 253–265.

Gibbs, R. W. (1994). *The poetics of mind. Figurative thought, language, and understanding*. Cambridge: Cambridge University Press.

Gibbs, R. W. (2006). *Embodiment and cognitive science*. Cambridge: Cambridge University Press.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston, MA: Houghton-Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton-Mifflin.

Hampe, B. (2005). *From perception to meaning. Image schemas in cognitive linguistics*. Berlin: Mouton de Gruyter.

Hempel, C. G., & Oppenheim, P. (1948). Studies in the logic of explanation. *Philosophy of Science*, *15*(2), 135–175.

Herman, D. (2002). *Story logic*. Lincoln, NE: University of Nebraska Press.

Herman, D. (2009). *Basic elements of narrative*. Chichester: Wiley-Blackwell.

Herman, D. (2013). *Storytelling and the sciences of mind*. Cambridge, MA: The MIT Press.

Hestenes, D. (2006). Notes for a modeling theory of science, cognition and instruction. *Proceedings of the 2006 GIREP conference*, University of Amsterdam.

James, W. (1890/1983). *The principles of psychology*. Cambridge, MA: Harvard University Press.

Jeppsson, F., Haglund, J., Amin, T. G., & Strömdahl, H. (2013). Exploring the use of conceptual metaphor in solving problems on entropy. *Journal of the Learning Sciences*, *22*(1), 70–120.

Job, G. (1972). *Neudarstellung der Wärmelehre: Die Entropie als Wärme*. Frankfurt: Akademische Verlagsgesellschaft.

Johnson, M. (1987). *The body in the mind*. Chicago, IL: University of Chicago Press.

Johnson, M. (2007). *The meaning of the body*. Chicago, IL: University of Chicago Press.

Jou, D., Casas-Vazquez, J., & Lebon, G. (1996). *Extended irreversible thermodynamics* (2nd ed.). Berlin, Germany: Springer.

Klassen, S. (2006). A theoretical framework for contextual science teaching. *Interchange*, *37*(1–2), 31–62.

Klassen, S. (2010). The relation of story structure to a model of conceptual change in science learning. *Science & Education*, *19*(3), 305–317.

Kubli, F. (2001). Can the theory of narratives help science teachers be better storytellers? *Science & Education*, *10*(6), 595–599.

Kubli, F. (2005). Science teaching as a dialogue—Bakhtin, Vygotsky and some applications in the classroom. *Science & Education*, *14*(6), 501–534.

Kuhn, T. S. (1955). Carnot's version of Carnot's cycle. *American Journal of Physics*, *23*(2), 91–95.
Lakoff, G. (1987). *Women, fire, and dangerous things*. Chicago, IL: University of Chicago Press.
Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago, IL: University of Chicago Press.
Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh*. New York, NY: Basic Books.
Lakoff, G., & Núñez, R. E. (2000). *Where mathematics comes from*. New York, NY: Basic Books.
Lancor, R. A. (2014a). Using metaphor theory to examine conceptions of energy in biology, chemistry, and physics. *Science & Education*, *23*(6), 1245–1267.
Lancor, R. A. (2014b). Using student-generated analogies to investigate conceptions of energy: A multidisciplinary study. *International Journal of Science Education*, *36*(1), 1–23.
Langacker, R. W. (1987). *Foundations of cognitive grammar, Volume I, Theoretical prerequisites*. Stanford, CA: Stanford University Press.
Langacker, R. W. (1991). *Foundations of cognitive grammar, Volume II, Descriptive application*. Stanford, CA: Stanford University Press.
Levinson, R. (2006). The use of narrative in supporting the teaching of socio-scientific issues: A study of teachers' reflections. *Interacções*, *2*(4), 24–41.
Lyotard, J.-F. (1984). *The postmodern condition: A report on knowledge*. Manchester: Manchester University Press (original published in 1979).
Mareš, J. J., Hubík, P., Šesták, J., Špička, V., Krištofik, J., & Stávek, J. (2008). Phenomenological approach to the caloric theory of heat. *Thermochimica Acta*, *474*(1–2), 16–24.
Metz, D., Klassen, S. McMillan, B., Clough, M., & Olson, J. (2007). Building a foundation for the use of historical narratives. *Science and Education*, *16*(3–5), 313–334.
Morgan, M. S. (2001). Models, stories, and the economic world. *Journal of Economic Methodology*, *8*(3), 361–384.
Morgan, M. S. (2012). *The world in the model. How economists work and think*. Cambridge: Cambridge University Press.
Müller, I. (1985). *Thermodynamics*. Boston, MA: Pitman.
Noë, A. (2004). *Action in perception*. Cambridge, MA: MIT Press.
Norris, S. P., Guilbert, S. M., Smith, M. L., Hakimelahi, S., & Phillips, L. M. (2005). A theoretical framework for narrative explanation in science. *Science Education*, *89*(4), 535–563.
Rosch, E. (1973). Natural categories. *Cognitive Psychology*, *4*(3), 328–50.
Sherin, B. L. (2001). How students understand physics equations. *Cognition and Instruction*, *19*(4), 479–541.
Spoel, P., Goforth, D., Cheu, H., & Pearson, D. (2008). Public communication of climate change science: Engaging citizens through apocalyptic narrative explanation. *Technical Communication Quarterly*, *18*(1), 49–81.
Talmy, L. (2000a). *Toward a cognitive semantics* (*Vol. I*). Cambridge, MA: MIT Press.
Talmy, L. (2000b). *Toward a cognitive semantics* (*Vol. II*). Cambridge, MA: MIT Press.
Thelen, E., & Smith, L. (1994). *A dynamic system approach to the development of cognition and action*. Cambridge, MA: MIT Press.
Truesdell, C. A. (1984). *Rational thermodynamics*. New York: Springer.
Truesdell, C. A., & Noll, W. (1965). The non-linear field theories of mechanics. In S. Flügge (Ed.), *Encyclopedia of physics* (v. III/3). Berlin: Springer.
Truesdell, C. A., & Toupin, R. A. (1960). The classical field theories. In S. Flügge (Ed.), *Encyclopedia of physics* (v. III/1). Berlin: Springer.
Turner, M. (1996). *The literary mind. The origins of thought and language*. New York: Oxford University Press.
Velleman, J. D. (2003). Narrative explanation. *Philosophical Review*, *112*(1), 1–25.
Wise, M. N. (2011). Science as (historical) narrative. *Erkenntnis*, *75*(3), 349–376.