An Industrial Educational Laboratory at Ducati Foundation: Narrative Approaches to Mechanics Based Upon Continuum Physics

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Abstract

This is a description of the conceptual foundations used for designing a novel learning environment for mechanics implemented as an *Industrial Educational Laboratory*–called Fisica in Moto—at the Ducati Foundation in Bologna. In this paper, we will describe the motivation for and design of the conceptual approach to mechanics used in the lab—as such, the paper is theoretical in nature. The goal of Fisica in Moto is to provide an approach to the teaching of mechanics based upon imaginative structures found in continuum physics suitable to engineering and science. We show how continuum physics creates models of mechanical phenomena by using momentum and angular momentum as primitive quantities. We analyze this approach in terms of cognitive linguistic concepts such as conceptual metaphor and narrative framing of macroscopic physical phenomena. The model discussed here has been used in the didactical design of the actual lab and raises questions for an investigation of student learning of mechanics in a narrative setting.

Keywords: momentum, angular momentum, narrative, metaphor, informal science education

1. Introduction

Learning to understand mechanics is not easy but it is crucially important at many levels of expertise in industry. This observation and social responsibility were some of the driving forces that led the Ducati Foundation to establish what we call an Industrial Educational Laboratory (IEL) for mechanics. The name Fisica in Moto (FiM) was chosen for this laboratory.[1] The original motivation was to provide a learning environment for young people that would allow them to experience, and maybe even work on, authentic applications of physics in industrial mechanics. At the urging of the foundation, a beautiful and richly outfitted laboratory for mechanics in automotive applications was built between 2006 and 2008 at the Ducati factories in Bologna, Italy. It opened its doors to groups of high school students in the academic year 2008-2009.

It was felt that the lack of authenticity of much of standard school physics made the subject removed from real life—an aspect that makes it boring and turns it into an unnecessarily difficult subject. The usual excuse is that physics is, by nature, a formal and difficult enterprise that forces us to use examples that will necessarily have to be simplified to the point of being fake; this is exacerbated by the fact that it is hard to come by experimental environments that allow access to authentic applications of (industrial) mechanics (see for example Hake, 1998; King and Richie, 2012). Still, it was clear for the members of the Foundation that simply providing young students with a well-equipped laboratory would not, by itself, alleviate the problems learners have with a science such as physics. A concerted effort at renewing the didactic approach to conceptualizations in mechanics was called for as well.

We know from physics education research of the last few decades, that there are yet other reasons for the difficulty students experience with learning physics (Clement, 1982; Halloun & Hestenes, 1985; Hestenes, Wells, & Swackhamer, 1992; McDermott, 1984; Fuchs, 1987). If we focus on dynamics, we see that there is a general confusion concerning the term *force* that is borrowed from natural (every-day) language and formalized in mechanics. For example, expressions such as *inertia is a force, force of velocity*, *force is energy* or vice versa, *active forces* and *reactive forces*, introduce nonscientific meaning of the term and contribute to the confusion. In addition, more general expressions such as *the moral force of an individual*, or the *social forces that act in a democracy*, give the term an even broader contour.

Here are examples of what might be called common sense forms of reasoning about motion that have been identified in the literature cited in the previous paragraph (see also Brookes and Etkina, 2009). Rest is the natural state of bodies and every motion needs a force that causes it (Aristotelian physics). To move an object, a force must overcome a preexisting force (weight, inertia, a force due to motion). A force is required to sustain motion. A constant force produces uniform motion, an increasing force produces an accelerated motion. When an object is thrown, the subject imparts motive force to the object, an impetus, which sustains the body's motion until it is dissipated (Buridan's physics). In a collision, the body that causes the collision exerts a force for which there is a reacting resistance force exerted by the other body; the greater of the two forces defines which wins. In general, a greater mass exerts a stronger force than a

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[1] See http://www.ducati.it/fisica_in_moto.do for a link to FiM.

smaller mass. These and many other examples known from decades of investigations of understanding of motion demonstrate that learners have a major problem with the concept of force, and in general with mechanics. In this paper, we will suggest a different approach to the conceptualization of motion—one that makes use of the idea that mechanical phenomena are the result of the storage and transfer of quantity of motion (and quantity of rotational motion for phenomena involving rotating bodies).

For these reasons, the Ducati Foundation charged one of us (F. Corni) with designing didactic elements of the IEL. Work on this started in 2008. In short, our approach integrates three major elements we learn from (1) modern cognitive science, (2) continuum physics that uses an embodied[2] perspective, and (3) dynamical systems modeling. In all, these elements have suggested to us to create an imaginative approach to the conceptualization of mechanical phenomena. Here are some details concerning these three elements.

(1) Take, for instance, aspects put into sharp focus by the model of embodied cognition (Gibbs, 2006; Shapiro, 2011; Wilson, 2002). There, we learn about the importance of imagination and figurative thought for understanding the world around us—language and thought are metaphoric and narrative, driven by imagination. We use narrative forms to make sense of much that goes on in life. Briefly put, this is because we perceive natural, social, and psychological forces[3] that are conceptualized (talked about) as agents that drive events or are driven (by other agents)—such figures of mind allow us to put our understanding in the form of stories (Fuchs, 2015). Moreover, abstraction is an early element of life (not a late one as a result of a long education). Abstract thought is made possible by our metaphoric mind and we see it reflected in natural everyday language. Taken together, these and many other aspects of the model of embodied cognition let us believe that we should not summarily reject what common-sense reasoning and the use of natural language provide to us; rather, we should see how to build formal, theoretic knowledge upon embodied forms of understanding that include natural language, metaphor, and narrative.

(2) Secondly, continuum physics (the physical science of macroscopic systems and processes; Truesdell and Toupin, 1960; Truesdell and Noll; 1965) provides us with imaginative forms of understanding of motion as well. If we inquire into these imaginative forms (Fuchs, 2014), we realize that they are largely the same as those used to make sense of the world around us in every-day life. In particular, translational and rotational motion are experienced and conceptualized as forces of nature (in the sense of what is explained in Footnote 2). In Section 3, we will see how to analyze theories in continuum

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[2] Briefly put, the idea underlying the model of an embodied mind is this. The mind of an individual is fundamentally shaped by the physical and social interactions of an organism with its physical, social, and cultural environments. Physics is considered a cultural construct that reflects, like all other cultural products, the nature of our embodied mind. Put still differently, physics is a product of our imagination, i.e., of the figurative forms our mind creates as a result of our perception of natural phenomena. (See the following paragraph, and Section 3, for much more detail concerning the issue of embodiment.)

[3] Note that in this context, the term *force* does not denote anything like a force in mechanics. Rather, it reflects human perception of agentive phenomena that are covered by a much more general meaning of the word force. There is an instance of this in the second paragraph of this Introduction: "…physics is an…enterprise that forces us to use examples…." So, here, physics is a perceived as a force of the type we mean when we refer to natural, social (cultural), or psychological forces.

physics with the help of tools developed in cognitive linguistics that reveal figurative structures in this formal science. Briefly stated, in continuum physics, momentum and angular momentum are the extensive quantities of motion that are imagined to be stored in bodies and are transferred through materials and fields and from body to body. Potential differences (differences of velocity and angular velocity) are driving forces of such transfers, and the combination of potential differences and transports of the extensive quantities gives a sense of the power of a process. A slightly less formal use of language—as is quite normal in presentations of continuum mechanics—shows that we can conceptualize momentum and angular momentum as agents whose "doings" in mechanical systems explain how to understand motion—they are the agents of (mechanical) change.

(3) Finally, modern (educational) technology does not only provide us with fancy equipment for laboratories and data acquisition but also with computer based tools for modeling of dynamical systems. If we restrict ourselves to models of (spatially) uniform dynamical systems, we may use well-known and easy to use system dynamics modeling tools for creating interesting models of even quite complex and relevant applications (Fuchs, 2002, 2010). Interestingly, these programs use a form of metaphoric graphical language that reflects basic metaphoric structures used in common-sense reasoning and that form a core element of formal physical theories as well.

We can now say why we believe that a narrative approach to mechanics is possible and what it consists of. It is made possible because we perceive motion as a force and conceptualize it and aspects of it with the help of figurative forms. It consists of a principled use of narratives for recounting embodied (kinesthetic) experience; such narratives include the seeds for an understanding of motion, they help suggest ideas for how the (mechanical) world works.[4]

In this paper, we will describe the conceptual foundations of the FiM lab at Ducati in Bologna as they relate to continuum physics, to cognitive science, and to their interaction and integration (Sections 3 and 4). To give the reader a feeling for how the IEL might work, and to prepare the development of our model of a narrative approach to mechanics, we will first present an example of a phenomenon of rotational motion and its narrative framing as it is used in the Ducati IEL (Section 2). In Section 3, we start the discussion of our model by introducing notions from cognitive science with an emphasis on modern theories of metaphor and narrative. In Section 4, we will informally describe continuum mechanics and show how we can identify imaginative structures in equations, expressions, and descriptions found in this science. Moreover, we show how dynamical models of uniform systems can be created using the same figurative structures. Following this we will make the point that mechanics may be framed narratively. We will then discuss what we see emanating from a model of a narrative approach to mechanics for the design of IELs and for the kind of learning we expect to be possible

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[4] Narratives of physical phenomena combined with embodied approaches are known to some extent from museum pedagogy (see Stevens and Hall, 1997). See also the example of an amusement park in Italy where groups of students visit the attractions and stations guided by a tour guide and collect data with sensors. They actually feel the accelerations, make measurements of physical quantities, and are encouraged to engage in discussions: http://mirabilandia.it/en/node/155).

in such environments (Section 5). Section 6 is a brief summary of the main arguments put forth in this paper.

2. An Example of Rotational Motion

In this section, we shall briefly describe an element of pedagogy as it occurs in Fisica in Moto without going into an empirical investigation of the Ducati lab. Our hope is to give the reader an impression of the real-life learning environment before we venture into describing, in some detail, the aspects underlying its design.

The FiM laboratory has existed now for a number of years and has been visited by a great number of students working on various applications of (automotive) mechanics. For this reason, we have some knowledge about how students experience mechanical phenomena at the various experimental stations in the lab. Here is a (narrative) description and explanation of a phenomenon of rotational motion at one of the stations; it is called the *Angular Momentum Carousel*.[5] In this experiment, we allow the students an opportunity to have a strong kinesthetic experience (feel the acceleration and the dizziness of spinning, the stress in the arms and body when pushing the beam) and gradually learn how to explain what is experienced in terms of good natural language.

A three-meter long horizontal steel beam that rotates with low friction around a vertical axis passing through the midpoint, a motorbike-like seat and a counterweight constitute the merry-go-round workstation (Fig.1).

Fig. 1: The *Carousel of Angular Momentum* workstation. Note the beam, seat, counterweights, and the vertical axis of rotation.

A set of numerical data taken during a typical course of events is shown in Fig.2. (The data is taken with a gyro sensor and displayed on the dashboard.) A student takes the seat on the saddle while other students push the beam from outside the carousel to start the system rotating—angular speed is going up (phase A). As soon as the students stop

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[5] The Fisica in Moto laboratory consists of 12 experimental stations. They include the Hammer Test (temporal course of impact of a hammer on a surface), Arm Wrestling (relation between forces and torques), Sliding Cubes (inertia, momentum, friction), Frictionless Chairs Ring (collisions and recoil), Carts on Tracks (collisions), Angular Momentum Carousel (pumping angular momentum, friction, change of moment of inertia), among others.

pushing, the angular speed starts going down (phase B). When the student riding the beam moves the saddle closer to the center of the beam, the angular speed goes up (phase C). Finally, without any further intervention, the angular speed decreases over a longer period of time—fast at first, more slowly later on (phase D).

The first observation is that, when accelerating the beam from outside, pushing is more effective if done at the far ends of the beam, perpendicularly to the beam itself. Here are a couple of conclusions:[6]

> *Quantity of rotational motion (angular momentum) is given to/transferred to the bar by the students. This requires effort and it is noted that, if the floor where they stand could move, it would rotate in the opposite direction of that of the bar. It is concluded that angular momentum is pumped by the students from the ground to the bar.*
>
> *Angular momentum is contained in the rotating system.*
>
> *The angular momentum in a body cannot change by itself. (First Law of dynamics for rotational motion)*

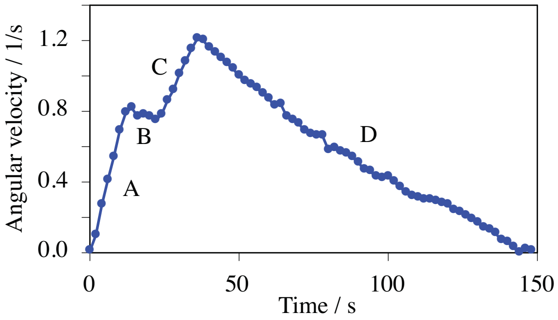

Fig. 2: Angular speed for a typical operation of the angular momentum carousel.

Once the bar reaches a certain angular velocity, the students stop pushing. The bar continues rotating while slowing down and will stop after a relatively long time.

> *The angular momentum contained in the rotating system flows into the ground as a consequence of friction between the beam and its support. This happens as long as there is a difference of angular speed between the bar and the ground. Measurement shows that the flow—the rate at which angular momentum is lost—is stronger if (difference of) angular speed is higher.*

While rotating, the experimenter can activate an electric motor that moves the saddle and the counterweight symmetrically, along the beam. When the weights move towards the axis of rotation, the angular velocity goes up, and vice versa, without any external contribution (no transfer of angular momentum). In analogy to linear momentum, no angular momentum transfer means no change in the angular momentum stored in the system. The increase in the angular velocity of the beam with the weights moving to-

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[6] Conclusions of this form are typically the result of verbal interactions between laboratory tour guides and the students visiting the lab. Note that students will have worked on examples of linear motion before this and are accustomed to use narrative forms that employ images of momentum.

ward the rotation axis is associated with a reduction of the rotational inertia (moment of inertia), the quantity analogous to inertial mass. The rotational inertia depends upon the mass of the rotating system, but also upon the spatial distribution of the elements, i.e. their distance from the rotational axis.

> *A rotating body contains angular momentum and its rotational inertia can be thought of as the capacitance of angular momentum.*
>
> *The rotational inertia increases with mass and with the distance of the mass from the axis of rotation.*

This is an example of results reached by students taking a relatively short tour of the laboratory. What we have called "conclusions" resulting from the discussions between students and tour guides are examples of narrative understanding of mechanical phenomena—this point should become clear when we outline the theoretical foundations of our laboratory design that is presented in Sections 3 and 4.

When the lab is used for a summer school for gifted Italian high school students (a year before graduation), much more is made of this example and, in particular, the explanations are formalized—put into mathematical form—by producing system dynamics models. The link between verbal form and formalized results will be described in more detail in Section 4.

3. Metaphor and Narrative Framing

In this section, we will introduce the idea of imaginative rationality and show how it is related to the figurative structures of metaphor and narrative. This requires discussing at least a little bit of background material concerning embodied cognition.

Since a description of the theory of physics we are using, i.e., continuum physics, will only be presented in Section 4, our discussion here will be concerned with perception and cognition in general and the role of metaphor and narrative in our conceptualizations of experience. However, we will already make references to our interaction with nature and to science where this is deemed necessary and useful and where we do not need the specific knowledge of the theories of macroscopic physics.

To make this clear from the outset, we take an embodied stance to questions of cognition. This is not just reflected in our ideas concerning didactics but rather makes itself felt directly in our approach to an analysis of physical science and its formal structures. We believe that it is possible to show convincingly that physics is a product of embodied minds resulting from our interaction with nature and machines. Recently, we have been able to observe a convergence of new approaches to the formulation of continuum physics and a new understanding of the workings of our mind (Section 4).

The Embodied Mind and Imagination

Concepts summarized under the title of embodied cognition have been a long time in the making. We can trace them back to critical philosophical traditions such as American Pragmatism (Dewey, 1925) and phenomenology (Merleau-Ponty, 1965). In recent decades, the philosophy of mind that has evolved from these early steps has developed into a major force in cognitive science (see Varela et al., 1992; von Foerster, 2003; Cemero, 2009).

We have been influenced by approaches to embodied cognition found in cognitive linguistics. Cognitive linguistics brings us concepts and opens new fields for research such as *image schemas* (Johnson, 1987; Lakoff, 1987; Hampe, 2005), *force dynamics* (Talmy, 2000), *conceptual metaphor* (Lakoff and Johnson, 1980, 1999), *frames* (Fillmore, 1975), *domains* (Langacker, 1987, 1991), *mental spaces* (Fauconnier, 1994), and *conceptual integration networks* (Fauconnier and Turner, 2002; Turner, 1996). The studies mentioned here and many others demonstrate how traditional views of metaphor lead us astray when considering how the human mind works—metaphors are elements of human thought and rationality, not simply poetic embellishments or, worse still, simply falsehoods that should and could be replaced by literal accounts. Figurative language reflects a figuratively and imaginatively working mind.

Expressed differently, approaches to cognition that apply notions of the embodiment of mind remind us that language or, more generally, our linguistic products, do not have a direct relationship with the world out there. Rather, words relate to conceptual structures in our mind that result from the interaction of our bodies with their physical and social environments. Assuming this philosophical stance, the above should be true of the words we speak and the equations we write in physics as well (Hestenes, 2006; Fuchs, 2006). Physics is an imaginative product of an embodied mind (Fuchs, 2015)—which does not mean that the world out there is only imagined. When we speak and write about nature, however, we should remind ourselves that we understand the world with the help of those mental resources that brought us physics in the first place.

Results in cognitive linguistics have not gone unnoticed in studies of science learning.[7] It is fair to say that these studies have shed new light upon the older question of conceptual change that has moved much of science education research for well over the last 30 years (Amin et al., 2015).

Figurative Structures and Our Understanding of Nature and Science

More specifically, studies of embodied cognition in linguistics as well as in psychology have unearthed structures of mind (such as image schemas, metaphors, and narratives) that would best be called schematic, figurative, or generally imaginative. Propositions that are supposed to be taken literally are more the exception than the rule (Gibbs, 1994).

Conceptual metaphor. We understand much of the world around us through mental devices such as (conceptual) metaphor (Lakoff and Johnson, 1980, 1999). Take an apparently innocent expression such as *his remark almost bowled me over, but I quickly found my footing*. This is simply conventional language, we do not stop and wonder what has been said; we all understand its meaning perfectly well. However, it is profoundly metaphoric and we would be hard put to find a literal form that expresses what the example actually conveys. How is this example metaphoric? Conceptual metaphors are projections of knowledge, structures, and logic from a source domain onto a target

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[7] Good introductions to the field can be found in Amin (2009) and in the Special Issue on Conceptual metaphor and embodied cognition in science learning in *IJSE* (Amin et al., 2015). See also Brookes and Etkina (2009); Jeppsson et al. (2013); Treagust and Duit (2015).

domain. Behind our example expression we see at least two metaphors, WORDS ARE A MOVING FORCE and COMPOSURE IS EQUILIBRIUM. These metaphors are (unconscious) structures of mind—however, they can be brought to our awareness and thus become tools of reasoning. The expression itself is not considered a metaphor but rather a concrete linguistic example making the metaphor(s) evident to the observer.

Quite obviously, the source domains in our two metaphors stem from physical embodied perception—here they originate from perception of physical force and equilibrium. In the example, this type of experience is projected upon the realm of social and emotional experience of an exchange between two persons and its emotional effect.

Image schemas. In common language, we find many examples of metaphoric projection where the source is (physical) perception and motor activity. The most minimal source domains are sensorimotor gestalts (schematized perceptual units). Mark Johnson and George Lakoff, whose *Metaphors We Live By* started much of conceptual metaphor theory (Lakoff and Johson, 1980, 1999) call these *image schemas* (Johnson, 1987; Lakoff, 1987; Hampe, 2005).

A partial list of image schemas contains examples such as path, verticality, equilibrium, container, process, cycle, causality, tension, or substance. If we listen and observe carefully, we notice that projections of such schemas upon other realms of physical experience are the norm. Not surprisingly, we find the typical elements of schematic and figurative thought also in the sciences (Amin, 2009; Brookes and Etkina, 2009; Fuchs, 2006, 2015; Haglund et al., 2015). Temperature or speed are high or low (example: *the temperature keeps climbing*); heat flows or can be transported (example: *in winter, we lose a lot of heat through the windows*); heat is a fluid substance (example: *There's too much heat in here, we have to make sure we can get rid of it*); electricity, water, and momentum can accumulated (example: *the car has a lot of momentum*); momentum flows more strongly if the gradient of speed is steeper; and heat has power (Sadi Carnot's *La puissance du feu*, 1824). These and countless other expressions bear witness to the fact that our imaginative mind is “all over” the physics we learn and use.

Forces of Nature. Recently, we have identified a figurative (schematic, imaginative) structure that makes its appearance in our encounters with nature, our fellow humans and their cultures, or our psyche. We are referring to the *gestalt of force* exemplified by notions of forces of nature, and social, cultural, and psychological forces (Fuchs, 2006, 2011). Examples of forces of nature are water, wind, heat, cold, motion, electricity, substances, and gravity. The concept of force—which is *not* the concept of force in mechanics (see Footnote 2)—is structured in terms of metaphors using projections from the schemas of polarity (binary opposites such as HOT <—> COLD), of FLUID SUBSTANCE, and of POWER, and others. The experiential gestalt of force leads to the creation of imaginative structures such as FORCES ARE AGENTS. It will be at the center of arguments that physical theories are structured narratively (see Section 4), which will allow us to conceptualize our approach to mechanics in the Fisica in Moto IEL.

The message we must take away from modern cognitive science is that we neglect what the mind makes available to us only at our own peril. Understanding science lies in the deeper meaning of the exemplary expressions just presented. We cannot get away with saying that the equations we use to work with in formal science represent a deeper truth or a more objective approach to reality that our metaphors cannot provide. If we want to understand, we will always have to refer results of formal manipulations and derivations back to the figures made available to us by our embodied mind.

Narrative Framing of Natural Scenes

The study of narrative in general and of stories and myths, or literature, in particular, is certainly as old as Greek philosophy. However, there has been a growing effort in narratology and in psychology to understand better how stories and the human mind interact (Ricoeur, 1984; Bruner, 1987, 1990; Herman, 2002, 2009, 2013; Dancygier, 2012).

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 (Kubli, 2001, 2005; Klassen, 2006). Where they are intrinsic, they are often limited to special cases and uses (Norris et al., 2005). However, lately, there have been attempts at creating stories of forces of nature as repositories of actual knowledge of physical processes, for the purpose of training kindergarten and primary school teachers, and for the children in these schools (Corni, 2013; Corni et al., 2014).

To extend the reach of narrative in science, a hypothesis of *narrative framing* of natural and technical scenes has been formulated (Fuchs, 2015). 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.

A particular notion of *framing*—as used in cognitive linguistics—originated in the work of Fillmore (1975); it represents one of the early important steps toward what has become known as cognitive linguistics. The earliest description of what could be meant by frame or framing is still one of the most useful for our purpose:

> I would like to say that people associate certain scenes with certain linguistic frames. I use the word scene in a maximally general sense, including not only visual scenes but also […] enactive experiences, body image, and, in general, any kind of coherent segment of human beliefs, actions, experiences or imaginings. I use the word frame for any system of linguistic choices—the easiest cases being collections of words, but also including choices of grammatical rules or linguistic categories—that can get associated with prototypical instances of scenes. (Fillmore, 1975, p.124; emphases in original.)

This statement describes most succinctly what we have mentioned above: our mind is the center of interaction of action-perception feedback loops and loops of linguistic production and reception—words are not directly linked to the world out there, linguistic meaning is indirect, tied to our (embodied) concepts.

As conceived of early in cognitive linguistics (Fillmore, 1975), the term *framing* is applied to a novel theory of word meaning. In *narrative framing of natural scenes*, we extend the notion of framing to apply as well to how our mind deals with the large-scale imaginative products we call narratives. Concrete narratives are linguistic products we use to talk about, and deal with, events that occur over longer periods of time in larger spaces and in more complex systems. Narratives are large-scale as opposed to medium-scale or small-scale linguistic products; medium-scale products appear in metaphoric networks with which we render, for example, the concept of force (in the sense described above) without resorting to a full-fledged story, and small-scale linguistic products result, for instance, from the metaphoric projection of an image schema in simple and short expressions (Fuchs, 2015; Fuchs et al., 2016).

We have suggested that complex concepts are not only structured in terms of small-scale (simpler) elements (i.e., bottom-up structuring), but are fundamentally informed by large-scale structures (top-down structuring). What we mean by force, agent, agency, time, process, cycle, etc. becomes clear through our immediate comprehension of narratives such as stories (Ricoeur, 1984; Contini, 2015). For science, we propose that this view of the role of narrative for meaning leads to a number of important issues. First, it must be possible to produce narratives (stories) that are triggers of conceptual knowledge regarding the working of agents in natural settings (Corni, 2013; Fuchs, 2015). Second, continuum physics should have a structure that contains all the elements we would require of a narrative field—indeed, we can show this to be the case by a reading of the equations of the physics of macroscopic dynamical systems that is inspired by modern cognitive science (Fuchs, 2014). Third, and most generally and maybe most importantly, we draw an analogy between the relation between story-worlds[8] and stories on the one hand and that of models and simulations of natural and technical systems, on the other (Fuchs, 2015).[9] In the same way that a story lets a listener create a story-world (a mental model), simulations (mental, analytical, or computational) suggest ideas concerning the properties of and relations between the quantities populating models and theories. Quantities (variables, initial values, and parameters) in formal scientific models are the counterparts of characters and scene descriptors in story-worlds.

These issues will be taken up in the following section of the paper that starts with a description of the structure of the physics of macroscopic systems and processes.

4. Continuum Mechanics, Dynamical Systems, and Narrative

The scientific basis of the presentation of mechanical phenomena in the FiM lab is taken from the most comprehensive form of a theory of extended materials and fields—continuum physics. Modern continuum physics started in the 1950s (Truesdell and Toupin, 1960; Truesdell and Noll, 1965). Its development carried over into extended irreversible thermodynamics of (nonlinear) processes (Truesdell, 1984; Müller, 1985; Fuchs, 2010; Jou et al., 2010) and is now a staple of advanced engineering theory and practice.

There is a simpler form of theories of macroscopic processes that preserves much of the generality of continuum physics: this is the theory of uniform dynamical systems obtained by applying the equations for continuous media and fields to uniform bodies and regions (control volumes). Examples of such approaches are the theory of uniform dy-

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[8] Narratologists make an important distinction between stories and story-worlds (Herman, 2002). Story-worlds are mental models. The relation between story and story-world has been described as “Story-worlds can be defined as the worlds evoked by narratives, and narratives can be defined in turn as blueprints for world-creation.” (Herman D.: StoryWorlds: A Journal of Narrative Studies. *Journal of Narrative Studies*, **1**, 2009, p.vii-x.)

[9] On the relation between narrative, models, and simulation in economics, see Morgan (2001, 2012), and in computational physics and chemistry, see Wise (2011).

namical models of thermal processes (Fuchs, 2010), generalized forms of engineering analysis (called systems approaches, see Richards, 2002), control engineering (Tyreus, 1999), or those that apply to motion of finite uniform bodies and materials, or to the electrodynamics of lumped circuits. Both continuum physics and the physics of uniform dynamical systems answer—from the perspective of physics and engineering—the question of why we choose momentum and angular momentum as primitives in our models of motion in FiM.

The structure of continuum physics

From a purely formal perspective, the structure of continuum physics looks as follows. In order to create a theory of continuous physical processes, we

> *[…] have to agree on which physical quantities we are going to use as the fundamental or primitive ones; on their basis other quantities are defined, and laws are expressed with their help. Second, there are the fundamental laws of balance of the quantities which are exchanged in processes, such as momentum, charge, or amount of substance; we call these quantities fluidlike. Third, we need particular laws governing the behavior of, or distinguishing between, different bodies; these laws are called constitutive relations. Last but not least, we need a means of relating different types of physical phenomena. The tool which permits us to do this is energy. We use the energy principle, i.e., the law which expresses our belief that there is a conserved quantity which appears in all phenomena, and which has a particular relationship with each of the types of processes. (Fuchs, 2010, p.9)*

Fundamental quantities. The fundamental or primitive quantities used in a theory of continuum physics are those that derive from an analysis of the gestalt of force applied to forces such as heat, electricity, substances, and motion. In the case of heat as a force of nature, these are hotness (thermal intensity), entropy (caloric: quantity of heat), conductive flux and radiative source rate of entropy, and entropy production rate. For all other phenomena, there are, theoretically but not necessarily in reality, analogous intensive and extensive quantities plus the conductive fluxes, radiative source rate, and production rate. Most important for this paper is the case of theories of motion. For linear motion, these quantities are velocity, (linear) momentum (quantity of motion), conductive flux density of momentum (stress), radiative source rate (body forces); the production rate of momentum is strictly zero.

Imaginative understanding of these quantities derives from embodied experience by projection of image schemas upon the phenomena in question. It should not come as a surprise, then, that Newton started his exposition with quantity of motion and that the most modern theories cast their basic relations in forms that make use of momentum and the other fundamental quantities from the start.

Laws of balance. Laws of balance of the fluidlike quantities[10] (entropy, charge, amount of substance, momentum and angular momentum for the forces just listed) form the

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[10] The term “fluidlike” was introduced by Fuchs (2010) to denote what has been called “substancelike” in an innovative physics course for high school (The Karlsruhe Physics Course; Herrmann 2000; Schmid

core of a theory; their mathematical structure makes use of metaphoric projections of schemas of (fluid) substance, amount, container, surface, in-out, path (source-path-goal), collection, and flow, to name the most obvious. This is attested to by examples of (natural) language use in describing what a law of balance stands for. For example, a *body* (container) *contains* a certain *amount* of momentum (fluid substance); it is *separated from the surroundings* by its surface (creating an in-out situation). As a result of an interaction, momentum *flows into or out* of the body (through the surface) going from an *initial to a final location* along a particular *path* (source-path-goal). Inflow *adds to*, outflow *subtracts from* the store of momentum *in* the body (collection; see Lakoff and Nunez (2000) for a discussion of the metaphoric basis of mathematical procedures such as addition and subtraction).

Constitutive relations. Constitutive relations make use of a large amount of schematic spatial and dynamic knowledge (Fuchs, 2014). Just consider the examples of containment (of a fluidlike quantity) and its effect upon intensity, and the conductive transport of fluidlike quantities. Collecting and storing more entropy (caloric) in a body raises the thermal level (intensity: temperature). The conductive current density of entropy depends upon (1) the local temperature gradient that is understood in terms of the metaphor of a thermal landscape with its highs and lows and steep or gentle slopes, and (2) how the nature of the path taken by entropy enables or opposes its flow (note the force dynamic schemas of letting, opposition, or resistance; see Johnson, 1987, and Talmy, 2000, for a detailed discussion of force dynamic schemas). Verticality, tension, and force dynamic schemas conspire to create an imaginative world in which we understand the constitutive equations of continuum thermodynamics and, by analogy, of mechanics.

Energy. Finally, energy makes its entrance upon the scene as the power of a force—this is Sadi Carnot's image of the waterfall explaining the notion of *la puissance du feu* (*the power of heat*: Carnot, 1824). Caloric flows from a high to a low level—the strength of the flow and the height of its fall combine to determine the power of a fall of heat (the rate at which energy is made available in the fall of caloric, called *availability* in modern engineering thermodynamics, see Bejan et al., 1996; Fuchs, 2010). This is a concrete example for the embodied knowledge that the quantity and the quality of a phenomenon conjoined create its power. The equivalent concept in mechanics is that of stress power: the rate at which energy is made available when momentum flows through a medium from a point of higher to a point of lower velocity.

In macroscopic classical physics, the notion of energy is extended to include the concepts of energy storage and transfer, allowing for a law of balance of energy to be formulated. Importantly, it is assumed that energy can neither be produced nor destroyed: there is no production term for energy in the expression for its balance.

Momentum, momentum transfer mechanisms, and forces. The following discussion concerns the relation between the notion of force in mechanics and the basic conceptualization of motion found in continuum physics. Simply put, we want to know how the well-known $F = ma$ fits with what we have said about the momentum principle in continuum mechanics.

1982, 1984; Falk et al., 1983). It denotes a subset of the extensive quantities of continuum physics for which laws of balance can be formulated.

If we rewrite the law of balance of momentum as it is formulated in continuum physics for the case of uniform systems, we obtain

$$\frac{dp}{dt} = I_{p,cond,net} + I_{p,conv,net} + \Sigma_p \qquad \text{Equ. 1}$$

(Fuchs, 2010, Chapter 3 and p.88). This is the result applicable to a typical form of control volume analysis (for the material contained in a control volume) used in many branches of engineering. As a special case, it entails the equations of balance of momentum for a body.[11] The conductive momentum current (or flux) $I_{p,cond,net}$ is the integral of the momentum current density tensor over the surface of the material (Landau and Lifshitz, 1959, p.13), whereas $I_{p,conv,net}$ is the sum of all convective momentum currents (a convective momentum current is the result of the momentum carried by the moving material across the element boundary). Σ_p denotes the volume integral of the density of the momentum source rate—it is the momentum source rate for the material under investigation.

The difference between this and the short $F = ma$ appears too great to be explained in a single step. Therefore, let us take a look at the generalized form of Newton's second law (equation of motion) useful for control volume analysis in engineering (Richards, 2002, Chapter 5; Bejan, 1993, p.220). It is usually written in a form similar to

$$\frac{d}{dt}\left(mv\right) = F_S + I_{p,conv,net} + F_B \qquad \text{Equ. 2}$$

Note that we have already inserted the capacitive relation between momentum and speed of a material, $p = mv$. Here, F_S is the net *surface force*, i.e., the integral of the stress tensor over the surface of the material. F_B is the net body (or volume) force due to interaction of a body and fields; it is the integral of the body force density over the volume of the material. $I_{p,conv,net}$ is the net convective momentum flux.

Equ.(1) and Equ.(2) are equivalent. We simply use different terms when speaking about the same imagistic concepts. We say stress tensor *or* (conductive) momentum current density tensor when we describe the surface distribution of (conductive) momentum transport across the surface of a material. Therefore, we say surface force *or* (conductive) momentum current when we mean the integral over the surface (of a material). Equivalently, we say body force *or* (radiative) momentum source rate. Interestingly, the word force is never used for convective momentum transports: convective momentum currents are convective momentum currents, period. In our approach, momentum and momentum transports form the core of the scientific and engineering conceptualizations of motion. Force in mechanics is the term for two of the three forms of momentum transfer: conductive and radiative (Fuchs, 1987).[12]

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[11] If we allow for open systems (flow systems or elements), we have to distinguish between *bodies* and *control volumes* (or the *material* contained therein). We will use the term *body* for the material of a closed system (i.e., one not allowing transport of mass into or out of the element). We will refer to open systems by the terms *control volume* or *material*.

[12] Whether or not we use the word *force*, and if so, how, is an altogether different matter having to do with choices that are anything but simple and clear cut. A particular choice will depend upon many fac-

What we learn from this is that $F = ma$ is a strongly simplified and limited version of the generalized form of Newton's second law (the equation of motion, Equ.2). It does not make explicit the distinction between surface and body forces. Importantly, it is not possible to apply $F = ma$ to open systems, it only applies to bodies—forces do not change the mass of a system. The concept of force (augmented by mass and acceleration) simply does not suffice to formulate the equation of motion as it is used in engineering and applied science.

In summary, our imaginative mind lets us think of amount of substance, entropy, charge, momentum, and angular momentum as fluid-like quantities that are stored and transported; there may be radiative forms of transport (entropy, momentum, and angular momentum) or production of the quantity (entropy and amount of substance). Energy accompanies all processes like a bookkeeper in a company who follows the physical work done. What is done and how it is done is not determined by the bookkeeper; only how much can or will be done will be controlled by the bookkeeper.

System dynamics tools for modeling systems and processes

We make use of graphical computational tools for modeling of dynamical processes known from system dynamics.[13] Here we give a brief description of the approach afforded by these tools that are important for several reasons. The graphical user interface for this form of dynamical modeling provides an additional form of metaphoric language that is used by tutors during Summer Schools (for selected high school students in Italy). Students employ such programs there for explicit dynamical computer modeling of their projects.

The notion of dynamics as the result of the storage, flow, and production of certain quantities lends itself to graphical metaphorical projection. Today, system dynamics tools provide user interfaces that make visual elements such as reservoirs (storage elements) and flows (process quantities for transports and production) available to the modeler (see Figs. 3 and 4). A combination of a reservoir and one or more flows sets up the first order differential equation expressing a law of balance (see Fig. 3). Then, feedback loops between reservoirs and process quantities lead to full-fledged dynamical models—linear or nonlinear (see Fig. 4).

A typical example dealt with in Summer School is that of two gliders with repelling magnets moving on a horizontal air track. On the left in Fig. 3 we see a diagram of a

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tors, age and sophistication of our students, goals for the physics and engineering to be learned, form of the learning environment, cognitive goals, and philosophical stance.

[13] System dynamics is an approach to dynamical systems that developed from control engineering and cybernetics in the Servomechanisms Group at MIT in the 1940s (Wiener, 1948; Forrester, 1961). It has since been used extensively in the social sciences. With the advent of graphical user interfaces, tools have been created that employ visual metaphors for reservoirs and flows (plus additional variables) for designing dynamical models (examples of such tools are *Stella* (iseesystems.com), *Berkeley Madonna* (berkeleymadonna.com), and *InsightMaker* (insightmaker.com)). Mathematically speaking, these tools allow us to produce initial value problems in ordinary differential equations and have them solved numerically for extensive simulation exercises.

preliminary version of a system dynamics model. On the right, data and simulation of the preliminary model are shown.

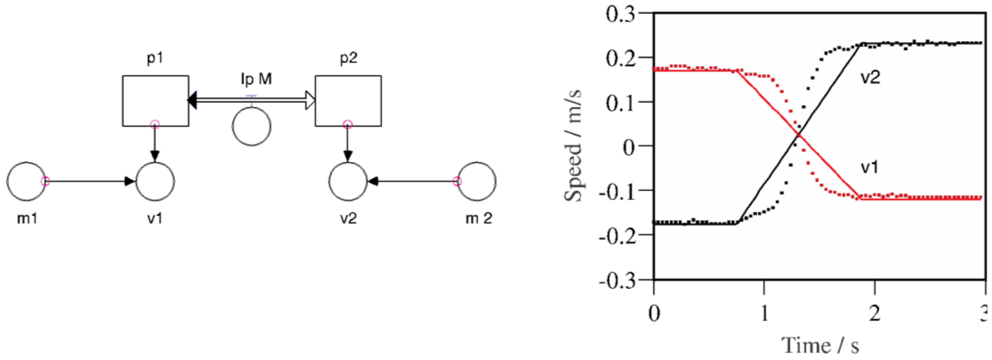

Fig. 3: First step in the creation of a dynamical model of the collision of two gliders on a horizontal track carrying repelling magnets.

Momentum (p) of the two gliders is represented by the rectangular reservoirs. Speed (v) is calculated on the basis of the instantaneous momentum and the mass (m) of a glider. The interaction between the gliders (via the magnets), represented by the flow of momentum (Ip_M), is modeled here as having constant strength during the period lasting from about 0.75 s to 1.85 s. During this period, momentum and speed change at constant rates leading to a result that is only partially satisfactory. Steps leading to a satisfactory model will involve connections that express our ideas what the strength of the momentum current might depend upon. Note that initial and final speeds are calculated correctly. The total momentum of the gliders is conserved. Note, as well, that we did not make use of the balance of energy for calculating final velocities.

Now we create a second and better version of a model of the collision. The example presented in Fig. 4 assumes that the magnitude of the force (the magnitude of the current Ip_M; M stands for magnet) is proportional to a certain power (n) of the distance between the centers of the two magnets (delta x). The interaction between carts and track were neglected—friction forces were set equal to zero in the concrete model—which proved to be more than adequate (see the fit between a simulation run and the data sets in the diagram on the right in Fig. 4).

This means that we need to calculate the positions of the two gliders that can be used to determine the distance between the magnets. The position of a glider is obtained by integrating the velocity (v = p/m) over time and adding the initial position.[14]

The parameters of the model are the power (n) of the dependence of Ip_M upon the inverse distance (delta x) and the factor of proportionality (k). Students can change these values, repeat simulations, and compare the results to their experimental data. A value of n = 5 gives the best fit for the experiment performed in this example.

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[14] In typical system dynamics tools, an integrator is created by using the elements that let us express laws of balance—reservoirs and flows. The important difference between the graphical expression for a law of balance on the one hand and a simple integrator on the other is this: in a law of balance a number of flows may appear each of which represents a particular interaction taking place; in an integrator, we only have a single rate of change that is being integrated. In Fig. 4, the rate of change is dx/dt = v.

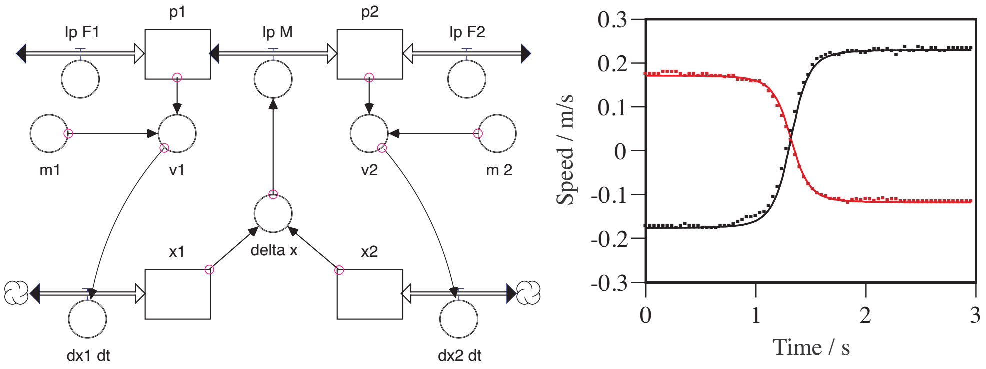

Fig. 4: Experiment and model for two carts on a horizontal track colliding with repelling magnets mounted to their fronts. Left: Diagram of dynamical model (prepared with the program Stella). Right: Speed of the carts as functions of time (data: circles; simulation: solid line).

The concrete example is rich enough in detail and of a type that may not be readily found already solved in textbooks. Students can experience a situation that requires actual creative construction of ideas whose consequences need to be tested—we have a perfect situation of inquiry where our narrative mind plays an important role.

An Imaginative Approach to Mechanics

Combining the conceptualization of motion inherent in continuum physics with narrative and other figurative forms allows us to design an imaginative approach to mechanics. Here we will briefly describe the basic ideas that have been applied to the design of mental models, explanations, and narrative forms used in FiM.

We have already outlined aspects of the conceptualization of motion afforded by continuum mechanics (Section 4): we are certainly allowed, maybe even compelled,[15] to think of momentum and angular momentum as fluid-like quantities that are stored and transported; typically, all three types of transport, conductive, convective and radiative, appear in realistic and practical applications. If we are dealing only with closed systems, we do not have convective transports and the equations of motion are a bit simpler than what we described in Section 4.

This lets us design imagistic elements to be used in mental models and explanations of concrete phenomena (i.e., for simulations of such cases). Importantly, we can imagine momentum and angular momentum to be the agents (of change) in mechanical processes.[16] They are fluid-like agents whose action and reaction in mechanical situations tells the story of what is happening. Importantly, the story has explanatory power.

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[15] Who, or what would make us think that way? There is much evidence in modern cognitive science that it is our mind that leads us in this direction. Considering this possibility—that it is quite inevitable that our mind generates these embodied structures of science for us—is an important and exciting challenge for philosophy, education, science, and technical culture.

[16] Note that we do not advocate personification of these "agents." Rather, if we make use of natural language to speak about the structures found in continuum physics (and mechanics), this language will—according to cognitive analyses—make use of figurative structures that correspond to the images we are discussing here. We cannot avoid using conceptual metaphors and larger narrative forms when speaking about motion, i.e., when we model and simulate mechanical processes. On the notion of agency in emotion and cognition, see Boyer (2007), Newman et al. (2010).

A story of a stuck truck. Consider the following example of a case of linear motion—it will give us an impression of how motion can be modeled using the approach outlined here (this is similar to examples dealing with linear motion in a couple of stations in Fisica in Moto; however, we feel that the example chosen here is better known to our readers). A passenger car pushes a stalled truck into town. (This is the situation proposed for Question 15 of the revised (1995) version of the *Force Concept Inventory* problem testing student understanding of Newton's Third Law. See Hestenes et al. (1992).) The car starts moving slowly toward the truck from behind—the engine pumps momentum from the ground for the car to raise its speed. When the car touches the truck, the parts touching are compressed and stressed somewhat—momentum begins to flow through them from the car into the truck. Briefly, the car comes to a standstill, its wheels spin. Momentum continues to be pumped but must flow back to the earth through the wheels of the truck—car and truck do not move.

Eventually, the wheels of the car grip the surface of the street and the momentum pumped by the engine flows into the car and the truck—both car and truck become faster, the momentum accumulating in them makes them move together at the same speed. As they move together, there is a lot more momentum in the truck compared to in the car. Since there is resistance between vehicles and the air and the street, momentum is continually lost. It must be continually replenished by pumping through the car's engine and it continues to flow from the car to the truck keeping the amounts of momentum in the car and the truck constant. (In this story, Newton's Third Law is implied: momentum leaving the car through the parts touching the truck enters the truck; the flow of momentum out of the car equals the flow of momentum entering the truck. Students find this conclusion a no-brainer.)

In this story, we recognize momentum both as an agent and as a patient—how it acts and suffers in the (story-)world suggests some of its properties and those of related concepts such as speed, speed difference, change of speed, mechanical stress, friction, etc. The role of energy is hinted at in the part where the engine pumps momentum from the ground to the vehicles.

Informal learning and natural language. Remember that the design is meant to allow for informal learning. This has consequences for the use and the form of language in speaking about mental models and simulations of motion. Adjectives (high-low) are used for intensity and tension, large-small (much-little) for amount, a noun for amount (agent), power (strong-weak) for causal strength. If we are aware of this in designing mental models, we gain both in understanding and in our ability to use good language for speaking naturally about what is commonly considered a formal scientific affair (Corni et al., 2014). Much of the power of good language rests in its ability to evoke appropriate and useful images.

Modeling and narrative. Now consider what the use of system dynamics modeling is telling us about the relation between mechanics (as an example of macroscopic physics) and narrative. Modeling tools that make use of system-dynamics graphical interfaces support the integration of narrative and formalism in two interesting ways. First, they give us access to metaphoric representations of relations that make up a model. Secondly, as has been pointed out by Morgan (2001, 2012) and Wise (2011) modeling and simulation are narrative activities—they differ from older forms of physical science where examples can be solved purely by analytical means. This difference is felt most strongly in fields of science where nature has a history such as in earth science, astronomy, or biology (Norris et al., 2005; Glennan, 2010), or in the science of complexity (Wise, 2004). When approached from the perspective of modern narratology, we can show that models correspond to story-worlds and simulations are stories told in these worlds (Fuchs, 2015). The combination of a problem based learning environment with system dynamics modeling lets students get a taste of a narrative approach to physical science.

5. Investigations of Learning of Mechanics in IELs

The model of learning of mechanics in an activity-based environment such as the IEL presented here should allow us to formulate questions for future investigations. How should IELs be designed—both physically and conceptually? What is the nature and quality of learning that can take place in such environments? What are particular cognitive challenges we should pay attention to? At this point, we shall primarily discuss the last of these points.

Note that the points, or challenges, we identify change if we change our vantage points: from typical school physics to continuum physics, from formal approaches to linguistics to cognitive linguistics, or from literary theory to modern narratology. Many of these changes seem to be directly related to a shift in perspective from disembodied to embodied cognition.

Understanding motion. We should not kid ourselves: understanding mechanics is difficult, no matter how we try to accomplish the task. Many aspects of this difficulty are known from previous research into science learning (Clement, 1982; Halloun & Hestenes, 1985; Hestenes, Wells, & Swackhamer, 1992, McDermott, 1984). The view commonly taken is that the form of mechanics taught in schools is a veridical version of our knowledge of the world of motion; in fact, it is the only possible version and learners should simply adapt to its formalism if they want to master the science. Whatever conceptions learners bring with them that do not agree with standard wisdom must be misconceived.

When viewed from the perspective of continuum physics, mechanics does not magically turn out to be simple. However, the questions we ask as educators about why this is so are different; the challenges we see turn out to be different (see, for example, Fuchs, 1987; Burkhard, 1987). Learners have to deal with geometrically demanding situations (motion in three dimensions); distinguish between linear and rotational motion and then join the descriptions in cases where the two forms of motion are combined; and, very importantly, find ways not to confuse the extensive mechanical quantities (momentum and angular momentum) with energy and then learn how energy relates to mechanical processes. All of these difficulties need to be overcome in an environment where the usage of natural language differs fundamentally from formal practice (Brookes and Etkina, 2009).

The main difference in answers to the challenge of mechanics (and physics) seems to be this: Traditionally, we assume that the very core concepts of novices are somehow wrong—misconceived. In our view, it appears that our embodied mind provides us with many useful concepts whose formalization and application in demanding situations pose the real problems for learners. For this reason, we suggest that research into learning and understanding of mechanics in an IEL such as the one at Ducati should concentrate upon the form and usefulness of basic embodied concepts of motion demonstrated by students. We want to know, above all, how learners form images of momentum, angular momentum, and energy in motion, and their relation. Starting from this point, we then have to research how veritable formal difficulties can be overcome so a larger proportion of young students can create a sense of achievement when confronting mechanics in school.

The role of (natural) language. No doubt, language is always important. Science educators will certainly agree with this statement but, in general, very little will be done to integrate language education with science learning. In fact, science is often seen as a realm where a student can shine even if he or she struggles with natural language. Natural language and the forms of understanding it entails can apparently be circumvented by mathematical formalisms that are assumed to carry the true message of a mathematical science such as physics.

In addition, science has created its own form of natural (non-mathematical) language that can be almost as daunting for novices as mathematical formalisms. Halliday (2004), Halliday and Martin (1993), and Lemke (1990) have analyzed the development of form and use of natural language in scientific discourse. They point out how, for instance, nominalization turns what could be natural everyday language into a forbidding form of discourse for learners—language anticipates and mimics the formalisms used in the presentation of mathematical and non-mathematical sciences alike.

In contrast to this state of affairs, a figurative and narrative (i.e., generally imaginative) approach to science has no direct need for formalizing spoken or written natural language. Rather, we want to make use of the grammatical and semantic tools provided by our languages to evoke the images upon which formalisms can be built should that be necessary. We believe that in this manner, a narrative approach can be used to bring together science and language education, particularly for young learners (Corni, 2013).

Again, more research will be needed to confirm, contradict, or qualify these statements. Lately, science education researchers have become aware of the importance and utility for learning and understanding of conceptual metaphor and other issues raised by cognitive science in general and cognitive and functional linguistics, in particular (Amin, 2009; Amin et al., 2015; Brookes and Etkina, 2009; Fuchs, 2006). This type of research points in the direction of what it means to employ natural language in science.

In a nutshell, we need to be concerned with questions of how to make use of the power of natural language for learning about mechanics in IELs, and if it makes a difference to the quality of learning if this power is harnessed.

Narrative understanding. Much research in cognitive science has gone into describing our narrative mind, what it is, how it functions (Bruner, 1987, 1990; Velleman, 2003), and how we may make the most of it in the context of science learning (Kubli, 2001, 2005; Norris et al., 2005; Metz et al., 2007; Klassen, 2006). Most of the applications of narrative in science have been concerned with stories *about* science rather than stories in which the concepts found in a science unfold.

This is perhaps not surprising. Influenced and guided by Bruner's famous distinction between narrative and paradigmatic modes of thought (Bruner, 1987, 1990), and philosophers’ insistence that stories give us emotional closure, not intellectual understanding (Velleman, 2003), we seem to be hard pressed to find a way that lets us integrate narrative modes of thought with doing science. However, recent studies have pointed us beyond the narrower view in the direction of the workings of our narrative mind in science proper (Wise, 2004, 2011; Morgan, 2001, 2012; Fuchs, 2015).

This allows us to ask questions that are particularly relevant for our purpose: what is the role of the notion of agency and agents in macroscopic physical science? How does agency relate to development of a sense of causality, or vice-versa? What is the relation between our knowledge of agents (characters) such as momentum and understanding of the story schema? How important is direct experience of macroscopic physical (mechanical) phenomena for the development of a sense of large-scale narrative schemas in our minds (Corni, 2013)? We still do not know enough about these issues and we do not have enough concrete data to assess to what extent narrative understanding supports understanding of physical phenomena such as motion in IEL learning environments.

Embodiment, perception, language, and learning. As mentioned in the first paragraphs of this section, the new questions all relate more or less directly to the hypothesis of embodied cognition. Researchers who work in this field tell us how the interaction of our organisms with our environment(s) leads to conceptual structure that can be expressed in language and other forms. Cognitive linguistics is one of the more recent research traditions that have taken up the issue of how we recognize embodiment and its consequences for understanding. Again, science education research has taken note of this in recent years (Hestenes, 2006; Fuchs, 2006; Amin, 2009; Amin et al., 2015). In our view, it is important that researchers and educators begin asking questions that are motivated by this embodied line of research in cognitive science and education.

6. Summary and Outlook

In this paper, we described the foundations of a narrative approach to mechanics in an IEL—continuum physics and system dynamics modeling on the one hand and cognitive science, linguistics, and narratology on the other. The actual use of the laboratory was described only briefly with an example of the type of investigations that can be performed there. In short, the IEL provides a learning environment that combines aspects of kinesthetic experience with mental modeling stressing imaginative forms of conceptualization of mechanical processes. The rationale for the last point is that imaginative forms of rationality connect experience and (macroscopic continuum physics) models more directly than traditional school physics does.

Obviously, the expectation expressed in this last sentence will need to be investigated in depth. The work on the IEL has progressed to a point where we can start with didactic research of the actual learning that is occurring in the lab.

To conclude, we hope that examples of learning environments such as the IEL at Ducati can encourage more teachers to try modern approaches to mechanics and embark on research in embodied cognition in science education. We need to increase the extent and depth of our experience with the challenges and opportunities encountered in the learning of mechanics, not the least for the reasons why Ducati built the lab in the first place:

to educate the next generations of young people so a technical culture may continue to live and thrive in Northern Italy.

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