
From Image Schemas to Dynamical Models in Fluids, Electricity, Heat, and Motion

An Essay on Physics Education Research

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Abstract

The fields of cognitive linguistics, evolution of the human mind, and modeling in physics instruction are brought together in an attempt to create a new agenda for Physics Education Research for all stages of education.

According to modern cognitive science, human understanding is based on embodied figurative thought. Application of cognitive linguistics to continuum physics and to a recent theory of the dynamics of heat uncover some pervasive imaginative structures which are used to conceptualize physical processes. The most important structure emerging is that of a weakly differentiated force-dynamic gestalt of physical processes having the aspects of quantity (substance), quality (intensity), and force or power. These aspects are conceptualized by metaphorically projecting a few image schemas onto different phenomena. I will argue here that this cognitive process creates similarities between different fields of physics which allow us to apply analogical reasoning to theories of fluids, electricity, heat, chemical substances, and motion. For students, the challenge is how to learn to differentiate the aspects of the force-dynamic gestalts rather than to go through conceptual change (as advocated by mainstream physics education research).

Evolutionary theories of the human mind suggest that the imaginative concepts identified in this essay originate in mythic culture. Mythic oral cultures provide a set of cognitive tools to which methods of formal theoretic (or philosophic) thought have been added in later stages of the development of human cognition. Very likely, individuals go through similar stages in their growing up years. An extended theory of inquiry is presented here that makes use of the integration of cognitive tools acquired by individuals during their years of learning—from early childhood, through adolescence, to adulthood. The theory—which I call the Four-Cycle—extends the notion of learning cycles.

Interestingly, the figurative structures discussed here are similar to ones found in systems science. If we combine our knowledge of the conceptual structure of physical processes with the methodology of system dynamics modeling, we will be able to construct a pedagogy of active engagement and inquiry in the field of (physical) dynamical systems. The approach created in this manner is a concrete application of modeling theories of physics instruction.

In the last section of the essay I will present an overview of questions and suggestions for research which deal, among other things, with the origin and development of figurative thought in children; the differentiation of the aspects of the gestalt of physical processes during early school years to prepare for the learning of a formal science; the development of software tools that implement the gestalt of physical processes; the integration of introductory physics in a general (systems) science curriculum and application of physics in applied fields ranging from medicine to ecology; and the integration of a dynamical theory of heat in physics instruction.

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INTRODUCTION

In this essay I would like to bring three new elements to bear upon the question of how we can learn and understand basic physics. They are a theory and methodology of physics as a systems science (including the modeling of dynamical systems), an investigation of its figurative—i.e., image-schematic, metaphoric, analogical, and narrative—structure, and a generalized theory of learning making use of a view of the evolution of the human mind. In this introduction, I will outline the theme and present short accounts of the works of others which have influenced my own ideas (and, at the same time, collect some important and interesting literature).

1.1 MOTIVATION AND GOALS

Understanding physics—or any other science—has become somewhat of a holy grail in theoretical and practical studies of science learning. Researchers and teachers are no longer satisfied with just presenting a science to their students. We want our students to *understand*. This is where the problem starts. What does understanding mean? And—assuming we knew what it means—how would we go about creating subject matter and learning environments that help students develop this understanding?

The study of didactic problems and corresponding suggestions for solutions has grown steadily over the last few decades. I would like to focus on an aspect that has received little or no attention in the debate over how to learn physics. It is the question of grounding of our understanding of basic natural processes in image schemas and their metaphoric projections. It appears that there are basic bodily mechanisms of understanding that create the foundations of our view of nature and its operations. These mechanisms—made concrete in image schemas—are elaborated metaphorically and projected onto our explanations of physical processes. Researchers in cognitive science, linguistics, and philosophy have suggested that this is how understanding is constructed. If this is true, we have to strengthen figurative elements of human thinking during education rather than trying to replace them early by purely formal thought.

This aspect of understanding is an element of a more encompassing theory of learning. It helps

us understand how ideas for hypotheses might be formed in the course of scientific investigations or the learning of a science. The capacity to form ideas and hypotheses is one of the cognitive tools or “sense-making capacities” humans developed in the course of their history, and which individuals develop in the course of childhood and adolescence. In evolutionary theories, metaphoric thinking is associated with the phase of mythic oral cultures. Later developments include theoretic thinking based on literacy and tools such as modern (electronic) media. The best of these tools can be combined into a generalized approach to thinking and learning.

The figurative conceptual structure created for understanding different physical processes is best described as a small collection of (similar or analogous) force-dynamic gestalts. Causal thinking takes the form of a search for the force or power of a phenomenon and is intrinsically dynamical—we want to know what causes the processes of change observed in nature. This is particularly apparent in the origins of the science of heat as constructed by researchers during the time from the Accademia del Cimento to Sadi Carnot who expressly searched for the power of heat. (As is well known, thermodynamics was later turned into a theory of the equilibrium of heat—a development from which it did not recover until late into the 20th century.) While it may have been difficult if not impossible in the past to let dynamics be the cornerstone of an introduction to physics for novice learners, modern tools make the modeling of dynamical systems accessible to even the very young. We are now in a position to create a pedagogy of active involvement and inquiry based upon methodologies of system dynamics modeling.

Together the three subjects outlined here are an example of an approach with a more optimistic attitude toward common sense reasoning than has been customary in traditional physics education research. Newer developments take a similar positive view. We acknowledge the difficulties students have with learning physics, but we believe that an understanding of a formal science can and must be constructed with the help of the cognitive tools available to all of us.

1.2 COGNITIVE LINGUISTICS AND STRUCTURES OF FIGURATIVE THOUGHT

My interest in metaphors and related matters grew from questions concerning the origin of ideas and hypotheses for the models we create when we describe and predict physical dynamical processes. Furthermore, in my teaching I have always relied upon the use of analogies and mental images to suggest ideas for models. In the course of time, supported by the structure of physics as a systems science, analogies became a foundational element of this approach. This finally led to the question of how analogies arise, and how they are related to mental images and metaphors. Here, I would like to describe research in cognitive linguistics and on the conceptual structure of physical processes in uniform dynamical systems (Section 1.3) that serves as the basis of the theory of force-dynamic gestalts of physical phenomena outlined in Section 2. The following lines of research figure prominently in these fields.

The embodied nature of human thought. Human concepts are embodied, and semantic structure reflects conceptual structure (Evans and Green, 2006, Chapter 6). In other words, language reflects embodied understanding of the world. Continuing this line of thought, it becomes clear that understanding is rooted in imagination—it does not build simply on language having propositional structure. Rather, words get their meaning because they reflect the imaginative and figurative roots of understanding—they are not literal representations of an objectively given world (Rorty, 1981; see Fig.1).

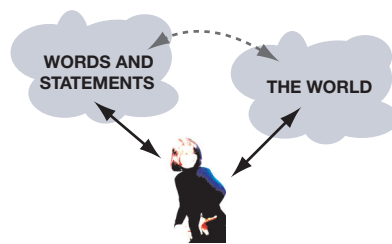


Figure 1: Words do not directly relate to the world. They do so through the human mind. Put differently, words relate to the models of the mind. Fuchs (2005).

Two lines of research that changed our view of cognition are exemplified by the work of Mark Johnson on image schemas and that of Leonard Talmy on schematic systems in language (Johnson, 1987; Talmy, 2000a,b). The former basically developed the notion of the embodied foundations of human thought whereas the latter introduced the study of embodied schematic systems in semantics.

Briefly stated, Johnson’s research established the notion of image schemas as the basic building blocks of human understanding (Johnson, 1987). Image schemas are abstract patterns (gestalts) formed by recurrent experience in every-day life. Our sensorimotor system provides us with these schemas in the first few months and years of our life. They are simple yet have enough internal structure so that more elaborate mental structures can be built upon them. In other words, they make reasoning possible. Some of the image schemas identified by cognitive scientists and linguists are those of verticality (up-down), substance and object, path, scale, container, near-far, center-periphery, and balance, to name just a few.

Talmy showed that languages use a small number of schematic structuring systems for semantics (Talmy, 2000a, Chapter 7; and Talmy, 2005; in fact, his work on how language structures space was influential for the early development of cognitive linguistics). These are the systems of attention, perspective, configuration, and force-dynamics.¹ Here, I will only mention the last of the four in more detail. In contrast to the others (which derive mostly from vision) it derives from kinaesthesia and somesthesia. This system has to do with how we conceive of the world

of interactions, and it may very well be the abstract source (in the form of the schemas or *gestalts*) of our notions of causation. It contains such elements as agonist and antagonist, causing, letting, balance, resistance, etc. The system gave rise to notions of a class of image schemas of force discussed by Johnson (1987, Chapter 3).

The upshot of this research and of much that has been done since on these issues² is this: Human reasoning appears to be grounded in some abstract schemas that are provided by the sensorimotor system. It seems that most if not all basic schemas are universal and independent of culture. If these schemas actually are what they are claimed to be, we should find them in every field of human activity and reasoning, including the formal sciences. I maintain that this is the case (see Section 2). Naturally, to make sense in other fields, the schemas must be projected onto other experiences, otherwise they remain restricted to the phenomena of direct sensorimotor experience. Metaphor is a process that provides this important transfer (see below).

Cognitive development. Jean Mandler (2004) adds the dimension of individual development in early childhood to research on cognition in general and on image schemas in particular. She and her co-workers have demonstrated over the years how conceptual systems start forming long before a child develops a language, and that concepts grow out of the very first image schemas that are built up in the child. Importantly, Mandler argues that early concepts are general, encompassing, and abstract, rather than specialized, detailed, or concrete.

A similar message comes from Rudolf Arnheim. Though not concerned with developmental issues, he showed how visual perception is “intelligent” and leads to the formation of simple, abstract shapes which are used in thinking (Arnheim, 1969). Abstraction comes first, and detail is added later, as demonstrated by the abstract nature of children’s drawings.

These results—and what we can learn from a theory of cognitive tools which we discuss in Section 1.4 and Section 3—contrast quite sharply with how we normally interpret Piaget’s view of child development (Piaget, 1951, 1952, 1954; Piaget and Inhelder, 1971). This will prove important for my view of what physics education research can contribute to the schooling of young children.

Metaphorical projections. We commonly think of metaphor as a figure of speech which we might use to express a point more vividly for learners or for informal purposes, but that cannot contribute to a formal theory of nature such as physics. We think that metaphor is used by poets,

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1. Croft and Cruse (2004, Chapter 3, p.46) have worked out a somewhat more elaborate system based on the one by Talmy and others.
 2. An extensive description of figurative thought and embodiment has been provided by Gibbs (1994, 2006). See also the general texts on cognitive linguistics (Evans and Green, 2006; Croft and Cruse, 2004; Ungerer and Schmid, 2006). More specialized investigations of interest to us are those on image schema research (Grady, 2005; Clausner and Croft, 1999; Turner, 1991; see in particular the anthology edited by Hampe, 2005).

not by scientists. The cognitive linguistic theory of metaphor, however, paints a different picture of this form of figurative language. Criticism of objectivist philosophy and associated theories of language developed slowly for over a century until an important breakthrough for cognitive linguistics finally came in the form of Lakoff's and Johnson's theory of conceptual metaphor (Lakoff and Johnson, 1980). Since then, the field has taken off strongly with work ranging from linguistics to the sciences.³ We now see much of language as metaphorical, to the point where we might say that the human mind is metaphorical through and through.

Metaphor is the projection of knowledge and structure of a domain (source domain) onto a new and different one (target domain). Take as a simple example expressions such as "the pharaoh has a high status in society."⁴ Here we project the domain of verticality (up-down) onto social status. While the expression is completely conventionalized, it is an example of a conceptualization—it is a linguistic expression for an actual conceptual metaphor which shows how we think about social status. Note that the projection is one-sided (asymmetric, i.e., it cannot be reversed), and it is used essentially unconsciously. Moreover, in this particular case, the source is an image schema. For a more complex example, take "Two roads diverged in a wood, and I—I took the one less traveled by" (Robert Frost) which is a linguistic expression for the metaphor LIFE IS A JOURNEY. While the particular expression is novel and was created consciously, the underlying metaphor is conventionalized and unconscious.

Language and thought are full of metaphors, simple to complex ones, that often build entire networks.⁵ An interesting theory of the structure of metaphors is that of primary metaphors (Grady, 1997) or of basic metaphors (Lakoff and Johnson, 1999). Metaphoric projections of image schemas will prove to be especially important to us (Section 2).

Analogical reasoning. Before I discuss research on analogy, let me quickly introduce an issue that is equally important to metaphor and to analogical reasoning. This is the notion of similarity. Traditionally, both metaphor and analogy have been assumed to express some underlying (objective) similarity between source (base) and target. However, this assumption was challenged early on in modern metaphor research. Roughly said, we assume that metaphors create

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3. For more information on conceptual metaphor see Ortony (1993), Chiappe (2003), Gibbs (1994), Grady (1997), Glucksberg (2001), Jäkel (2003), Keysar et al. (2000), Kövecses (2002), Lakoff (1990, 1993), Lakoff and Johnson (1999), Lakoff and Nunez (2000), Turner (1991, 1996); on visual metaphor see St. Clair (2000); on conceptual integration see Fauconnier (1994, 1997), Fauconnier and Turner (2002); on metaphor and analogy see Gentner (1982); on metaphor in science see Brown (2003).
 4. This type of metaphor is actually found in the hieroglyphic Egyptian language where the same word that is used for the level of the water in the Nile is used for social status (R. Fuchs, 2004).
 5. Here are two interesting and important observations. (1) The same source domain is often applied to different targets, which I propose can be the source of created similarity (which is then used in analogy). (2) The same target can be metaphorically structured by more than one source domain—in fact, often by quite a few; this could account for the observation that we have many different explanations for the same phenomenon.

similarity rather than build upon it (Black, 1962, p. 83). The same is true of categorization which is demonstrated by an example of how infants group objects. Bird models with outstretched wings are grouped with models of other animals rather than with models of toy airplanes (Mandler, 2004, p. 179). In analogy research, the criticism of classical views was influential in that it led scholars to propose that analogies project (or categorize) structure rather than use surface similarities. The question of the construction of similarity will be discussed in more detail in my theory of force-dynamic gestalts of physical processes (Section 2).

Possibly the most influential research on analogy has been that of Dedre Gentner and her colleagues who work in psychology and artificial intelligence (Gentner 1983, Gentner, Holyoke and Kokinov, 2001).⁶ They developed the structure mapping theory of analogy which stresses the mapping of elements and relations between elements from a base domain to a target domain.

The structure mapping theory is quite successful in explaining established analogies, but it falls short in demonstrating how we spontaneously generate analogies, and why we generate particular analogies. To account for such important features, Atkins (2004) proposes a theory of analogy as a categorization phenomenon. She bases her ideas on observations in the physics and science classroom, on categorization in cognitive linguistics (Lakoff, 1987) and on a theory of metaphor as categorization (Glucksberg, 2001; Glucksberg et al., 1997).

What is the relation between analogy and metaphor? Metaphor theorists hardly ever mention analogy, but the question has been discussed by Gentner (1982) and by Gentner et al. (2001). Basically, analogy and metaphor are considered the same which is also obvious in the work of Atkins (2004). In the theory of force-dynamics gestalts of physical processes, however, I will make a clear distinction between metaphoric and analogical projections—at least for the cases considered (see Section 2).

1.3 THE STRUCTURE OF THE PHYSICS OF UNIFORM DYNAMICAL SYSTEMS

In this section, I would like to outline research on the structure of physics as a systems science. Looked upon from this perspective, processes, systems, and system behavior are stressed rather than many of the aspects commonly treated in physics classrooms. The processes dealt with are those of fluids, electricity, heat, chemical substances, and motion, and the perspective is one of dynamics rather than statics.

The theories that serve as the foundation of this approach are those of continuum physics. They

6. More on analogy: Falkenhainer, Forbus, and Gentner (1989), Gentner (1989, 1998), Gentner and Gentner (1983), Gentner and Markman (1997), Gentner et al. (1997), Holyoak and Thagard (1995).

have received much attention during the second half of the 20th century (Truesdell and Toupin, 1960; Truesdell and Noll, 1965) and have led to advances such as a dynamical theory of heat (Truesdell, 1984; Müller, 1985; Fuchs, 1996; Jou et al., 1996). An important aspect for our purpose is the application of analogy to the various fields which lets us recognize a particularly fundamental as well as simple conceptual structure. This structure will be found to be the same as that used in much of human reasoning concerning force-dynamic causal phenomena—not only in physics but also in psychological and social situations.

In the following paragraphs, I will describe aspects of macroscopic physics that were developed with the intent of creating a systematic exposition of physical processes. I call the exposition a uniform dynamical systems approach to physics, with an outlook to spatially continuous processes (see Fuchs, 1996).

Fluid-like quantities and energy carriers in physical processes. Starting from the vantage point of Gibb's thermodynamics, Falk, Herrmann, Job, and Schmid developed an approach to physics teaching that stresses the use of what they call substance-like quantities (Falk and Ruppel, 1973, 1976; Falk, Herrmann and Schmid, 1983; Herrmann and Job, 1996; Job, 1972; Job and Herrmann, 2006; Schmid, 1982, 1984; see also Burkhardt, 1987). For reasons that will become clear later, I prefer the term fluid-like or fluid-substance-like. Job (1972) demonstrated how Sadi Carnot's thermodynamics could be made use of for introducing entropy as the every-day concept of heat (see also Callendar, 1911). Based on this approach, a physics course for high school was developed at the University of Karlsruhe (Herrmann, 1989-1999). Briefly stated, the approach is a vivid interpretation of the Gibbs Fundamental Form

$$dE = TdS - pdV + \mu dn + \dots \quad (1)$$

It relates changes of extensive quantities of a system to the change of its energy. If we now change differentials to flows of the quantities,⁷ we obtain

$$I_E = TI_S - pI_V + \mu I_n + \dots \quad (2)$$

This is interpreted as follows. An energy current I_E is, in general, composed of terms that are products of the currents of the extensive fluid-like quantities entropy (S), volume (V), or amount of substance (n) plus others and their respective potentials (temperature T , pressure p , or chem-

7. The GFF shows its origin in a theory of the statics of heat (a theory of thermal equilibrium, Callen 1985, p. 26). First, we have to "dynamicize" the relation by introducing rates of change of the extensive quantities. Then we apply laws of balance to replace rates of change by flows. However, it is clear that this does not work in general; there is no direct way from the GFF to Eq.(2). This can be seen if we use the law of balance of entropy that contains a production term, or the balance of amount of substance that contains production and destruction terms. So, the proper approach would take the reverse path: Use laws of balance plus constitutive laws for a particular material, and then derive the GFF for this material (see Fuchs, 1996).

ical potential μ). This is re-described vividly by saying that the fluid-like (extensive) quantities function as energy carriers, and that an energy current is composed of terms where each represents a part carried by a different energy carrier. This image can be used to create process (flow) diagrams of energy carriers and associated energy currents (Fig.2).

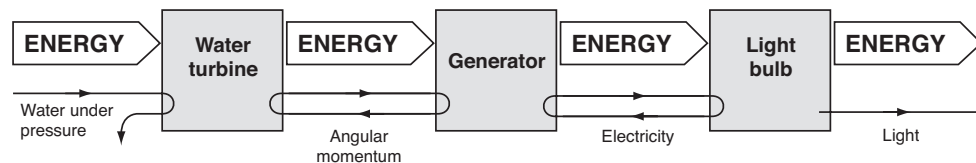


Figure 2: Process or energy flow diagram of a chain of processes. Energy enters a device with an energy carrier (here the carriers are named informally) where it is unloaded and then loaded upon a second carrier. After this, the energy leaves the device with the second carrier. From Herrmann (1989-1999).

The authors have created courses of high internal consistency ranging in level from middle school (secondary school) to university, always applying the same concepts. They even produced a book using the same approach in a purely qualitative form for primary school (this was called *The Energy Book*, Falk and Herrmann, 1981).

Clearly, such an approach calls for the application of analogies across diverse fields of physics (see Table 1). There is a fluid-like quantity with an associated potential in every category of phenomena (the categories I use are fluids, electricity, heat, transfer and reaction of substances, gravity, rotational and translational motion). Expressions for the power of a process or for a conductive energy flow are the same in every area, and we commonly have the same structures of constitutive relations (capacitive, resistive, inductive) everywhere.⁸ As a result, introducing thermodynamics or chemical physics based on concepts such as entropy and the chemical potential, respectively, becomes simple and natural. Georg Job's contention that Sadi Carnot's heat (caloric) can serve as the modern concept of entropy, and that the chemical potential is best understood in analogy to temperature or pressure, bears fruit (Job, 1972; Job and Herrmann, 2006).

In the last few years, the course has been used successfully with thousands of high school students in Baden Württemberg, and the part written for junior high school (middle school) has

8. There are some exceptions such as a lack of inductive thermal processes in every-day phenomena (but see Fuchs, 1996, p. 648-654 for a discussion of thermal waves). Also, some other properties of the fluid-like quantities are different (in contrast to charge, momentum, and angular momentum, entropy, amount of substance, and volume are not conserved; momentum and angular momentum are vectorial quantities; mass and charge create fields). Further, only some of the quantities admit radiative type transfers, and expressions for convective currents depend on particular circumstances.

been translated into English, Spanish, Italian, Russian, and Chinese.⁹ Whatever benefits we might associate with such an approach to physics, there is one rather unexpected result. Investigations show that girls in particular like this course much better than a standard one, and students read the text to an extent unheard of in standard courses (Starauschek, 2001).

Table 1 Analogical quantities in fluids, electricity, heat, substances, and motion

Phenomena	Fluid-like quantity	Potential	Production	Radiative source term
Fluids	Volume	Pressure	Positive/negative	
Electricity	Charge	Electric potential		
Heat	Entropy	Temperature	Non-negative	Yes
Substances	Amount of substance	Chemical potential	Positive/negative	
Gravity	Gravitational mass	Gravitational potential		
Rotation	Angular momentum	Angular speed		Yes
Translation	Momentum	Velocity		Yes

The role of energy in physical processes. Two problems emerge from an oversimplified use of the Gibbs Fundamental Form as the basis of structuring physical theories as described above (Eq.(1) and Eq.(2)). One has to do with an interpretation of the role of energy in physical processes which is too limited in an important respect. The second (discussed further below) concerns the fact that the structure is not truly dynamical and lacks means for the inclusion of radiative and convective transports (in other words, it lacks the breadth of continuum physics which is particularly apparent in thermodynamics). I shall deal with the first point here.

Energy has three important properties relevant for our purpose, two of which are commonly represented in physics: Energy is transferred and it is stored (see Fig.2). However, if we want to understand the simple process of the conduction of entropy and energy through a body, we need the notion of energy released in a process (Fig.3, left).

In conduction, entropy enters a thermal resistor together with an associated flow of energy. The energy current out of the resistor is equal to the one going in, and its magnitude is of no partic-

9. See the Website of the Department of Physics Didactics at the University of Karlsruhe (<http://www.physik-didaktik.uni-karlsruhe.de/>). Most of the translations of the Karlsruhe Physics Course are available online as pdf files.

ular importance for understanding what is going on in the slab conducting entropy. To calculate the rate of production of entropy due to conduction, we need to know the rate at which energy is released by the fall of entropy from higher to lower temperature (Fig.3, left). This rate will be called power.

Fuchs and Maurer generalized the concept of energy by introducing the notion of power as the rate at which energy is released or used in physical processes (Fuchs, 1987a, 1996; Maurer, 1990; Borer et al., 2005; for an example see Fig.3, right).¹⁰ This is a direct interpretation of Carnot's concept of the power of heat (Carnot, 1824) and can be made vivid and graphic in terms of the waterfall metaphor of physical processes (Fig.4). The energy released each second in a process is calculated by the product of the current of a fluid-like quantity going through a potential difference, and that potential difference.

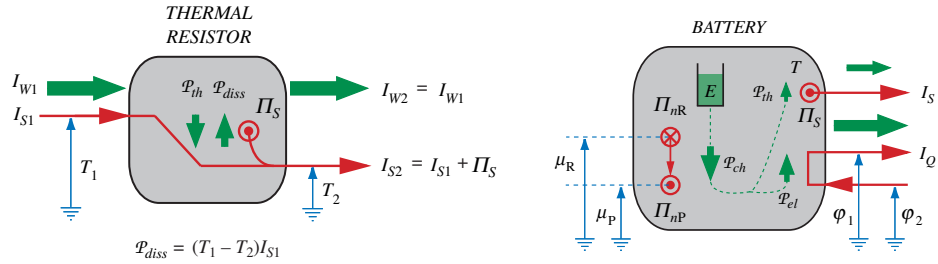


Figure 3: Process diagrams of conductive entropy transfer (left) and of a battery (right). In addition to the fluid-like quantities, their potentials, and energy flows and storage, these diagrams introduce rates at which energy is released or used in physical processes (vertical fat arrows inside the rectangles that denote the systems under consideration). A circle with a dot denotes a production rate (source) whereas a circle with a cross symbolizes a sink. For more examples on process diagrams see Fuchs (1996), Borer et al. (2005), Fuchs (2006b).

A theory of the dynamics of heat. I used the forgoing developments to produce a unified approach to a dynamical theory of heat (Fuchs, 1996). It is essentially a uniform dynamical systems version of modern continuum thermodynamics (Truesdell, 1984; Müller, 1985). It uses Carnot's metaphor of thermal processes (see Section 2) and describes thermal phenomena as a theory of the storage, flow, and production of entropy (balance of entropy) along with proper constitutive laws for particular materials. The energy principle is used for additional constraints on constitutive relations (Fuchs, 1996, p.2). In this manner we arrive at a theory of thermal pro-

10. One might be tempted to think of this aspect as that of the “conversion” of energy from one form into another. However, the example of conduction discussed here shows that this does not work. There is no “conversion” of “heat energy” into more “heat energy” as energy and entropy are conducted through a body.

cesses featuring initial value problems in analogy to theories of fluids, electricity, or motion. Irreversible thermodynamics is a natural part of such an approach and allows us to treat examples such as thermoelectricity (Fuchs, 2002b) and optimization problems (Fuchs, 1999a,b) from the start. Furthermore, all types of transport processes (radiation and convection along with conduction) are included. Put simply, the fields we normally distinguish as thermodynamics and heat transfer are now unified into a single description. The dynamical theory of heat has been used in university physics courses (Ansermet, 2006) and for a new theory of control engineering (Tyreus, 1999).

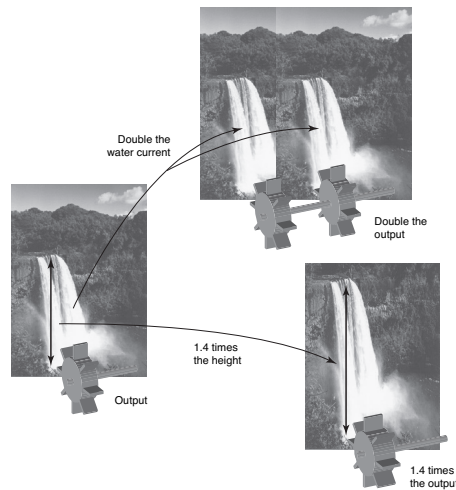


Figure 4: The waterfall metaphor of physical processes: The power of a fall of water is proportional to the flow of water and to the height through which the water falls.

We now have representations of phenomena in fluids, electricity, heat, chemical substances, and motion (rotation and translation) that make use of a set of consistent metaphors which allows us to apply analogical reasoning across the board. For a brief description of this unified structure see Fuchs (1996, Prologue) and Borer et al. (2005).

1.4 DEVELOPMENT OF THE HUMAN MIND AND COGNITIVE TOOLS

The use of image schematic structures in theories of embodied understanding, and of metaphor in cognitive science and in accounts of the development of the human mind, indicate that we can profit from considering an evolutionary model of embodied cognition. I want to suggest that bringing together research into image-schematic and metaphoric structures of our under-

standing of basic physical processes with investigations of the development of the human mind can produce an evolutionary theory—having both biological and cultural aspects—of how we might best learn some physics. The theory is useful in defining questions in physics didactics that should be addressed in the future.

We readily accept that science grows from an interplay of modeling and experimentation (Fig.5). When we conceptualize and operationalize the processes underlying these activities it becomes clear that the account is unsatisfactory on at least two counts. First, how do we get our motivation for studying a certain field, or more precisely, how do we come up with good questions to be answered, and, second, how do we arrive at ideas for possible answers to these questions? A proposal—called the Four-Cycle—that integrates all these aspects (formation of questions, creation of hypotheses, experimentation, and formal modeling) will be described in Section 3. It can be looked upon as a generalization of learning cycle theories.

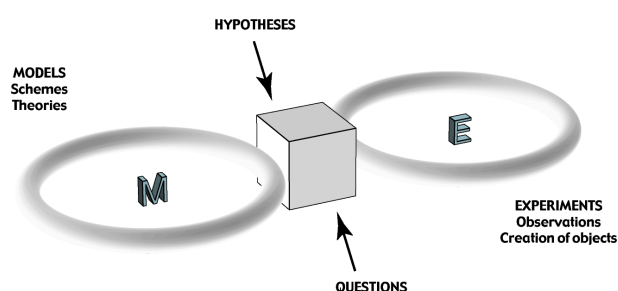


Figure 5: The Bi-Cycle of modeling (M) and experimentation (E), as a symbolic representation of the modern scientific method. Each cycle represents certain concrete steps that are normally taken when we construct and execute experiments or build and simulate models. The steps might be described as analysis, model building and simulation for the M-cycle. The E-cycle consists of steps such as planning, building, and data acquisition. The cube at the center symbolizes the confluence of the results of the two cycles where we compare results and decide on how to proceed. Hypotheses and Questions point to two aspects that are commonly left out of descriptions of the scientific method.

The ideas that led to the construction of the Four-Cycle have been strongly influenced by accounts of the development of the human mind and the growth of cognitive tools in culture and in individuals. Scholars in this field come up with four to five successive phases of thinking or understanding, starting with bodily origins, going through mimetic (using face and hands to “talk”) to mythic (spoken language based) stages, and ending with more recent forms of understanding based upon literacy and newer symbolic techniques of representing and handling knowledge (from books to computers to movies). In these accounts it is common to associate the mythic period with an active phase of the development of figurative understanding, while other stages lead to additional sense-making capacities or cognitive tools.

The development of the human mind. Of the many theories concerning the evolution of the human mind I mention only the one by Merlin Donald (1991). It goes with models of the development of language and is most in line with the theory of individual growth (Egan, 1997) discussed below. Basically, this is a story of the change of the human mind through stages of episodic, mimetic, mythic, and theoretic understanding and cultures. Episodic understanding is that of more highly developed mammals—it provides the individual with a set of capabilities that allow it to perform bodily functions at a high level. There is no language, no form of representation of the actual episodic life in consciousness. The mimetic stage introduces the first means of representation of the previous phase with the help of body, hand, and face (the capacity of representation rests on the mapping and awareness of these parts of the body in the brain). Early humans (and possibly primates) possess this ability. Simply stated, mimesis allows hominids to begin to tell stories (Fig.6, see the path from E:episodic to M:mimetic).¹¹

The development of spoken language leads us into mythic culture with its own set of cognitive and cultural tools. Language is used to represent the previous two stages—mimesis and episodic life (Fig.6, L:linguistic). If we add visual symbolic means to our representations (Donald, 1991, p. 296-305; see Fig.6), we arrive at written languages with the tools of literacy and theoretic culture (Ong, 1982; McLuhan, 1962, 1964). This phase creates and uses external symbolic storage systems ranging from paper to computer storage to film.

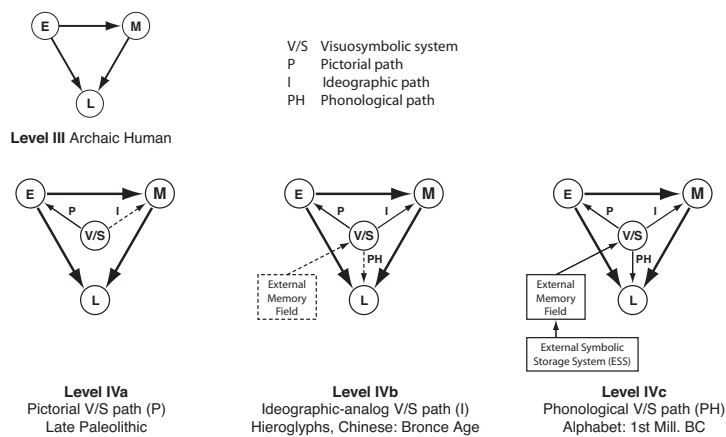


Figure 6: The development of mimesis, spoken language, and literacy as forms of representation (modeling) of an older form of understanding with the help of new tools. According to Donald (1991, p. 305).

11. Recently, Donald's theory of mimesis has been used to introduce the concept of mimetic schemas alongside (or as a replacement of?) image schemas for understanding the origin and development of spoken language. See Zlatev (2005). See also Donald (1998).

The system of reference to, or representation of, an earlier capacity with the help of a newer one may very well be the source of the metaphoric human mind. Quite clearly, Donald's theory is one of the embodied mind.

Individual development and cognitive tools. Kieran Egan (1997) worked out a detailed theory of individual development and of sense-making capacities or cognitive tools that parallels ideas of how the human mind developed. While he does not have much to say about pre-lingual stages (see Mandler, 2004, for this phase), he is eloquent about stages of the acquisition of spoken language, i.e., the mythic phase (ages 4-8, Egan, 1988) and of early literacy which he calls the romantic stage (ages 8-15, Egan, 1990). The romantic phase heralds the philosophic or theoretic stage of the full use of formal, symbolic thought. Here is a quote about mythic understanding from Egan (2001):

[Mythic understanding...] is a product of learning to use an oral language. [...] Universally, in all human cultures, the development of oral language involves a set of cognitive tools, such as the use of stories to give shape and affective meaning to events, the use of binary oppositions to provide an initial grasp on phenomena, an engagement with fantasy, [...] So I will consider what stories are and why they engage children so powerfully, why children are so attracted to fantasy, why they enjoy rhythmic language, why forming their own images from words is so important, why emotionally charged binary oppositions¹² are so prominent in their imaginative lives (security/anxiety, courage/cowardice, love/hate, etc.)...

These lines speak of things that are important in how children, and by extension, we all, learn to understand the world around us. I have come to believe that the truth of these words does not diminish with us getting older or getting a formal education in a formal science. The analysis of metaphors in physics will reveal that we use mythic understanding to structure our concepts of physical processes (Section 2).

What has been very important to me is the detailed description of the cognitive tools that come with the use of spoken and written language. Egan gives lists of such tools that he says should be used and strengthened during childhood education (Egan, 2005), and he provides examples for how to develop these tools. I will use these lists to operationalize two of the four cycles in

12. Binary oppositions (I prefer the term 'polarities') are a prominent element of mythic thought. For example, this element represents much of ancient Egyptian thought and culture, both in situations of every-day life and of spiritual affairs. In Egyptian and Babylonian cosmologies, the world is created by differentiation from undifferentiated chaos, by the sky separating from the Earth. Life continues as long as the tension between the two is maintained. In Egypt, it was the god Shu (air) that supports Nut (heavens) from falling to Geb (Earth). In Babylonian mythology, it was the wind that separated heaven and earth. Dynamics is rooted in the tension between the poles of the polarities that govern nature and society.

my representation of inquiry based learning (see Section 3). The close association of cognitive tools with forms of language development and use parallels Donald's theory of the growth of the human mind (see Table 2, and Donald, 1991).

Table 2 Comparison of developmental phases

Donald	Egan	Language	External Media and Tools	Age
Episodic	Somatic	Reaction to events		6 Ma
Mimetic		Body language		2 Ma
Mythic	Mythic	Spoken language		100 ka
Theoretic	Romantic	Written language	Stone, Paper	10 ka
	Philosophic realism	Written language, Formal languages	Paper, Film, Computer, RAM, HD, DVD, Experiment	1 ka 100 a

Learning cycles. The cycles in Fig.5 and the Four-Cycle presented in Section 3 remind me of theories of learning cycles. I will use research done by Anton Lawson (1995) in this brief exposition of an approach that I find important for any development of activity and inquiry based curricula. Lawson describes C. A. Lawson's ideas of how (scientific) learning proceeds in steps (Lawson, 1967). They can be described as a sequence of

- attention to some undifferentiated "whole"
- the differentiation of the whole through the identification of its parts
- the invention of a pattern by which the parts are interrelated
- testing the invented pattern to see if it applies
- use of the new pattern in other similar instances

(see Lawson, 1995, p. 160). Lawson expresses it as "The mind creates from sensory data and then imagines the creation to be true to allow the generation of an expectation, which is then tested in the external world..." (see Lawson, 1995, p. 2). This can be cast into the form of a cycle: "...the process of scientific 'discovery' is really a cyclic constructive process that consists of the *exploration* of novel phenomena, the *invention* of novel conceptions, and the *application* of the newly invented conceptions to the interpretation of old and new phenomena alike." (p.34) This is a fairly straight-forward description of what is known as the hypothetico-deductive model of the scientific method. However, if we analyze this process more carefully, we see that its topology is more like that of the Bi-Cycle presented in Fig.5 than a single cycle. This is also observed in descriptions of (industrial) design as in Fig.7.

Inquiry based learning. Maybe a few words on inquiry based pedagogy are in place at this point. No matter what researchers in (science) education think about particulars of how thinking and learning work, they all seem to agree on one thing: Learning should be active and if possible inquiry based.¹³ With the following theme—modeling in physics education—I will add to the discussion of active forms of learning in specially designed learning environments.

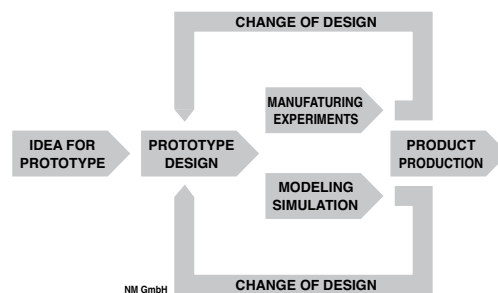


Figure 7: A description of modern methods in industrial design. Engineers move through two interacting cycles in prototype development, i.e., the construction of a prototype and its modeling and simulation. The figure is from Numerical Modeling GmbH in Zurich. <http://www.nmtec.ch/>.

1.5 DYNAMICAL SYSTEMS, SYSTEMS SCIENCE, AND EXPLICIT MODELING

Physics as a systems science is a subset of continuum physics. It treats phenomena as resulting from the storage, flow, and production of certain easily visualized quantities, such as fluids, electricity, heat, and motion. In this form, it leads to a theory of the dynamics of spatially uniform objects. If we combine models of such objects into larger aggregates, we arrive at more or less complex systems whose behavior is of prime interest in many of the applied sciences, in engineering, medicine, and ecology.

The methodology of system dynamics modeling has turned into a prime tool for realizing the potential of the physics of uniform dynamical systems for activity and inquiry based curricula. I shall briefly describe resources for system dynamics modeling and then turn to a modeling theory of physics instruction that has been very influential in physics education research.

System dynamics modeling. Based on experience with control systems, Jay Forrester developed an approach to the modeling of industrial and social feedback systems that has since come to be known as systems thinking and system dynamics modeling, or simply system dynamics

13. For resources, see AAAS (<http://www.aaas.org/>, and search for Inquiry).

(Forrester, 1961, 1968, 1969). Since then, SD has been applied in a variety of fields ranging from management, to ecology, to biological systems, to name just some of the prominent ones.¹⁴

Software tools were developed that allowed increasingly simple access to practical modeling. Whereas Forrester used the concept of rates of change and levels to represent processes of change, Barry Richmond (Richmond, 1997; Richmond et al., 1987) introduced the notion of stocks and flows in his program Stella.¹⁵ Stocks and flows are what we need to model laws of balance in uniform dynamical systems. In other words, with Richmond's innovation, system dynamics modeling and our approach to (physical) dynamical systems have become parallel metaphors. The work on uniform dynamical systems in physics has inspired the development of the generalized methodology of laws of balance that has been documented in my book on SD modeling (Fuchs, 2002a Chapter 3).

A further initiative worth mentioning is the System Dynamics in Education Project led by Jay Forrester at MIT (SDEP).¹⁶ The members of this project have developed many very useful resources (such as Roadmaps) for teaching systems thinking and system dynamics modeling to even the very young.

A modeling theory of physics instruction. Already in the 1970s, David Hestenes and co-workers started a project in physics education research based on a modeling approach (for a general overview, see Hestenes, 2006).¹⁷ The modeling theory of physics instruction deals with the following important aspects. Firstly, it accepts that doing physics means creating models, and it applies this insight directly to the classroom (modeling instruction); secondly, it extends modeling to the creation of a coherent base for physics education research. Since Hestenes uses modern cognitive science and linguistics to inform the models for PER, there should also be an influence of physics teaching on cognitive science. The models created by physicists to understand nature can become material and inspiration for models of cognition.¹⁸ Hestenes' insights into modeling and teaching and their feedbacks to PER and cognitive science are most noteworthy. Many of his suggestions for research and development parallel those I will make later

14. Richardson (1991), Roberts et al. (1994), Ruth and Hannon (1997), Hannon and Ruth (2001), Sterman (2000), Deaton and Winebrake (1999), McGarvey and Hannon (2004), Costanza and Voinov (2003), Hargrove (1998), Meadows, Randers, and Meadows (2004), Robinson (2001).

15. SD program Stella: isee-systems (www.iseesystems.com). A program featuring stronger mathematical methods is Berkeley Madonna (www.berkeleymadonna.com).

16. SDEP: <http://sysdyn.clexchange.org/sdep.html>.

17. See also Hestenes (1987, 1992, 1996, 1997), Hestenes, Wells, and Swackhamer (1992), Halloun and Hestenes (1985, 1987), Wells, Hestenes, Swackhamer (1995).

18. "If cognition in science is an extension of common sense, then the structure of models in science should reflect structure of cognition in general" (Hestenes, 2006).

in this essay (see Section 8 and 9 of his 2006 paper, and Section 5 of the current essay).

Maybe the most important insight from cognitive science into PER is what I mentioned briefly at the beginning of the essay: Words get their meaning because they reflect the imaginative and figurative roots of understanding—they are not literal representations of an objectively given world. Expressed differently, there is no direct relationship between words and the world (see Fig.1). Hestenes’ representation of this insight is more detailed and formal (Fig.8): We have to distinguish between the conceptual models of a science (our words) and the mental models in our mind.¹⁹

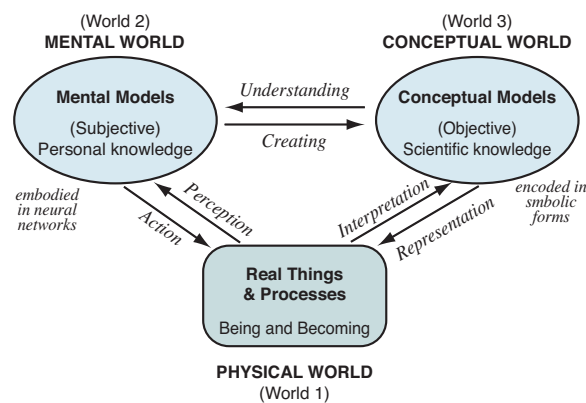


Figure 8: Models in the mind are not the formal models of science (from Hestenes, 2006). Note the correspondences with Fig.1: Person = Mental Models, Words = Conceptual Models, World = Physical World.

1.6 PHYSICS EDUCATION RESEARCH

Physics education research is relatively young, still it has developed a multitude of approaches and outlooks which cannot all be described here.²⁰ I shall make a selection of a few lines of research which are interesting in regard to the themes I am developing here. Certainly, the work done in Karlsruhe (Herrmann), in Arizona (Hestenes), and in Winterthur (Fuchs and Maurer) belongs in this list—it has already been discussed above in Section 1.3 and Section 1.5.

Misconceptions and conceptual change. An important part of PER has been dealing with so-

19. “Mental models are private constructions in the mind of an individual. They can be elevated to conceptual models by encoding model structure in symbols that activate the individual’s mental model and corresponding mental models in other minds. Just as Modeling Theory characterizes science as construction and use of shared conceptual models, I propose to characterize cognition as construction and manipulation of private mental models.” (Hestenes, 2006)

20. For an overview of resources relating to PER, see McDermott and Redish (1999).

called misconceptions. In the 1970s and 1980s, researchers realized that instruction in mechanics fails spectacularly (see Section 2 of Hestenes, 2006, for a vivid discussion). Students simply do not seem to learn much in an introductory physics course. When given conceptual questions, their reasoning is about as non-newtonian when they leave a course as when they enter it. Hestenes concluded that misconceptions were not addressed by conventional instruction; students systematically misinterpreted much that happened in the course.²¹ Similar problems were found in other subject areas ranging from electricity and optics to quantum physics. Physics education research was buzzing with investigations of misconceptions, and several international conferences devoted to just this area of research were held in the 1980s (see, for example, Novak, 1987). Eventually, misconceptions were renamed alternate, intuitive, or every-day conceptions, to give the field a somewhat more positive bent and outlook. Today, the approach is called conceptual change research to stress the point that—if they are to be successful in learning physics—students will somehow have to change their concepts about nature.²²

Some years into the misconceptions research, Smith, diSessa, and Roschelle (1994) argued for a more positive approach. They based this on diSessa's ideas concerning the origin of learners' concepts (diSessa, 1993, see below). Here is a quote from their Abstract:

“...to articulate a constructivist view of learning in which student conceptions play productive roles in the acquisition of expertise. We acknowledge and build on the empirical results of misconceptions research but question accompanying views of the character, origins, and growth of students' conceptions. Students have often been viewed as holding flawed ideas that are strongly held, that interfere with learning, and that instruction must confront and replace. We argue that this view over-emphasizes the discontinuity between students and expert scientists and mathematicians, making the acquisition of expertise difficult to conceptualize.”

On what to do about physics instruction, they say

“...This theoretical perspective aims to characterize the interrelationships among diverse knowledge elements rather than identify particular flawed conceptions; it emphasizes knowledge refinement and reorganization, rather than replacement, as primary metaphors for learning.”

21. A popular example of a “misconception” is the notion that it takes a force for a body to be moving at constant speed. Because of this, students are often said to be aristotelian thinkers.

22. “In order to understand the advanced, scientific concepts of the various disciplines, students cannot rely on the simple memorization of facts. They must learn how to restructure their naive, intuitive theories based on everyday experience and lay culture. In other words, they must undergo profound conceptual change.” From the Abstract to Vosniadou (2007).

Still earlier, at the Cornell conference in 1987 (Novak, 1987), I argued that—at least in thermodynamics—it is the physical theories that were misconceived rather than students' notions (Fuchs, 1987 b,c). This makes an even stronger point regarding the productive nature of common sense concepts, and calls into question research that aims at changing students minds to conform with outdated representations of physical knowledge, particularly in thermodynamics (Fuchs, 1996). Before we do not know more about the fundamental structure of embodied notions of physical processes, we should be careful about what changes we want to induce.

In the following paragraphs, I will discuss some examples of how physics education researchers see the origin of students' conceptual difficulties, and what could be done for better conceptual learning to occur.

Ontological structure and conceptual change. An interesting notion is that students' misconceptions are “alternate” in a fundamental manner, that they represent a fundamentally different way of thinking based on a different ontology. This idea is best exemplified by the paper by Reiner et al. (2000). The title “Naive Physics Reasoning: A Commitment to Substance-Based Conceptions,” is program. Students (or humans in general) think of light, electricity, heat, etc., as substances, a notion which is naive and has to be overcome.²³ Thinking of heat as a substance demonstrates adherence to a particular ontology which has to be replaced by a different one, namely the ontology of processes: heat (light, electricity...) is a process. Crossing ontological boundaries is thought to be difficult for learners which explains why students' conceptions are resistant to (standard) instruction. If we want to achieve conceptual change we need to induce ontological change.

Wiser and Amin (2001)²⁴ discuss the question of whether conceptual change is revolutionary (requires the replacement of naive conceptions by science) or evolutionary (leads to the accretion of additional knowledge to pre-existing intuitive notions). They describe a pedagogy that relies upon integration of common sense and scientific views—resulting in both evolutionary and revolutionary change. The integration of views relies on making students aware of their differences: “...unknown to students (and some teachers), students and teachers speak different languages, which correspond to different conceptualizations of a domain. [...] That key words (e.g. force, heat) are part of both languages, with different meanings, and that they partially share referents renders communication all the more difficult. Accordingly, our curriculum includes making students aware of the existence of the two languages, and contrasting explicitly the two conceptual frameworks they reflect. [...] Once students are aware of the two languages/

23. For more on this issue, see Chi (1992), Chi (2005), Chi (in press), Chi, de Leeuw, Chiu, LaVancher (1994), Chi and Slotta (1993), Chi, Slotta and de Leeuw (1994), Chi and VanLehn (1991), Slotta, Chi, and Joram (1995).

24. See also Wiser (1988), Wiser (1995), Wiser and Amin (2002), Wiser and Carey (1983).

conceptualizations, they can approach learning as an interpretative and constructive task [...] rather than adding to their pre-existing concepts, i.e. as restructuring rather than enrichment.”

Independent of the particular approach to or view of conceptual and ontological change, it is assumed that common sense conceptions need to be restructured.

Phenomenological primitives, cognitive structure, and the FCI. Needless to say, I see the issue of conceptual change in a different light. We have to probe the human mind more deeply and more carefully for its notions concerning how nature works before we say how the mind is supposed to be changed. We have to take into account what we have learned in cognitive science and linguistics (Section 1.2), on evolutionary theories of cognition (Section 1.4), and on the structure of theories of physical processes (Section 1.3).

In this respect, the lines of work of diSessa (1993; see also Smith, diSessa, and Roschelle, 1994) and of Hestenes (2006, Section 1.5) are especially important. diSessa (1993) has identified what he calls phenomenological primitives (p-prims):

“The name, phenomenological primitive, is meant to capture several of the most important characteristics of these objects. They are phenomenological in the sense that they often originate in nearly superficial interpretations of experienced reality. They are also phenomenological in the sense that, once established, p-prims constitute a rich vocabulary through which people remember and interpret their experience. They are ready schemata in terms of which one sees and explains the world. There are also two senses of primitiveness involved. P-prims are often self-explanatory and are used as if they needed no justification. But also, primitive is meant to imply that these objects are primitive elements of cognitive mechanism—nearly minimal memory elements, evoked as a whole, and they are perhaps as atomic and isolated a mental structure as one can find.”

In their simplest form, these p-prims are similar to image schemas (see Section 1.2). Importantly, they correspond closely to common sense concepts identified by Hestenes and co-workers (Halloun and Hestenes, 1985) who used the taxonomy of concepts or schemas to construct the famous Force Concept Inventory (Hestenes, Wells, and Swackhamer, 1992). This FCI has by now been used to test conceptual understanding of mechanics of thousands of students. Often, it is used to gauge the effectiveness of forms of instruction. Hestenes claims that the success of the FCI as a tool is the result of its design which rests on our knowledge of the fundamental conceptual structure of humans in the field of motion phenomena (“The questions are based on a detailed taxonomy of common sense (CS) concepts of force and motion derived from research,” Hestenes, 2006).

Why are there no concept inventories for other domains to speak of? Hestenes’ answer is in-

structive and speaks of the importance of knowing cognitive structures before we embark on such a task (Hestenes, 2006):

I am often asked how the FCI might be emulated to assess student understanding in domains outside of mechanics, such as electrodynamics, thermodynamics, quantum mechanics and even mathematics. Indeed, many have tried to do it themselves, but the result has invariably been something like an ordinary subject matter test. The reason for failure is insufficient attention to cognitive facts and theory that went into FCI design, which I now hope are more fully elucidated by Modeling Theory. The primary mistake is to think that the FCI is basically about detecting misconceptions in mechanics. Rather, as we have seen, it is about comparing CS (common sense) causal concepts to Newtonian concepts. The p-prims and image schemas underlying the CS concepts are not peculiar to mechanics, they are basic cognitive structures for reasoning in any domain. Therefore, the primary problem is to investigate how these structures are adapted to other domains. Then we can see whether reasoning in those domains requires other p-prims that have been overlooked.”

In other words, the success of the FCI and modeling instruction (Hestenes, 2006) is the result of the explicit identification of the schemas upon which explanations and understanding are built. The theme discussed here demonstrates that physics education research is increasingly making use of the basic structures of human thought identified in cognitive science in general, and in cognitive linguistics in particular.

The variability and dynamical nature of explanations. So far, with the exception of a remark in Footnote 5, I have not discussed a phenomenon that has been receiving more and more attention in cognitive science and in PER. When we carefully listen to someone explaining phenomena and concepts, we do not find strongly systematic answers. In other words, it appears that we do not have (in the strong sense of “possess”) single, unified concepts or conceptual structures in our mind—common sense or otherwise. Rather, we use many different ways of explaining one and the same circumstance, and we change these explanations on the fly, typically dependent on the context in which we think or are asked about some subject.

diSessa (1988, 1993) already pointed this out when he coined the phrase “knowledge in pieces.” The idea is that to the extent that we “have” conceptual (or pre-conceptual) structures, they are small rather than large, and there are relatively many of them. We make use of them based on context when we explain phenomena.²⁵

In an interesting line of research, Atkins (2004) has applied this view of cognition in her work

25. Further readings: Hammer (1994, 1995, 1996a, 1996b, 2004), Hammer, Elby., Scherr, and Redish (2004), diSessa, Gillespie, and Esterly (2004).

on analogical reasoning in school settings. She investigated dynamic, online production of analogies or metaphors and concludes that the phenomenon is best explained by a manifold rather than by a unitary view of the structure of the human mind. Analogy is a process of categorization rather than of structure mapping. Structure mapping theory is too static. In her words: “As such, mapping the structure of a concept in an analogy must first entail *creating* a representation that can be mapped, a process that structure-mapping does not explicate.” This dynamic process of the creation of structure is a theme in an investigations by Russ (2006) who studied the production of causal reasoning in classroom situation. Causal reasoning about natural and psychological phenomena will be an important aspect of the conceptual structures I will discuss in Section 2.

What we have learned in cognitive linguistics (Section 1.2) supports these ideas. The basic elements of meaning creation and understanding are image schemas from which we build our explanations by metaphoric projection (Johnson, 1987; and Section 2 of this essay). As I have remarked in Footnote 5, two phenomena associated with metaphor may well be the reason for aspects of analogical reasoning and for the variability, multiplicity, and dynamic nature of explanations. In metaphoric systems, we often project the same source domain to different phenomena. This creates a measure of similarity which is used in the form of analogical reasoning applied to relatively well structured theories of fluids, electricity, heat, and motion (Section 2). To what extent it is also responsible for the dynamic aspects of analogy investigated by Atkins (2004) is not clear yet.

The second phenomenon in metaphor mentioned above in Footnote 5 is the application of more than one source domain to reason about the same phenomenon (love is understood as a journey, as an enterprise, as a force-dynamic gestalt, etc.). This testifies to the fluidity of the human mind and supports the observations made concerning the variability of explanations used by students when confronted with a phenomenon or concept. It appears that we have many (small pieces of) resources at our disposal which we draw upon when called upon to perform a task. Unitary, stable, and large cognitive structures in a field of inquiry may very well only be the result of a cultural effort involving the tools of literacy. It appears rather unlikely, that humans could entertain these single large structures in their brains only, without recourse to externalizing the results of dynamic processes of thought (see Section 1.4).

Activity based physics instruction and studios. It is one thing to notice student difficulties in learning a science, but it is an entirely different affair to do something about it. We have seen that researchers disagree as to what is the deep rooted cause of the problem. On the other hand, most agree to one possible remedy—namely, activity based learning. Just about all approaches to PER include some form of learning environment that is quite different from what we have been doing in the past.

The realization that learning does not simply happen by information being conveyed and then

digested, leads one to consider new forms conducive to the actual process of learning which is rather more constructive than passive. The view from cognitive linguistics (in particular, research into image schemas and metaphor) is but one element of recent developments that has convinced us of the reality of the constructive nature of meaning, understanding, and learning. Here I will mention a few examples of inquiry based learning, particularly those that have been related to developments in physics education research. A few good examples have been combined in the project Activity Based Physics (ABP, 2007), a multi-institutional effort. At the project website, we can find access to materials that have been developed for different formats of activity based learning in physics. Physics by Inquiry (McDermott, 1996) was one of the first efforts to design materials for activity based physics, soon followed by Workshop Physics (Laws, 2004). They are examples of studio teaching, a format of instruction made famous by Jack Wilson at RPI (Wilson, 1994). A studio is a (real) learning environment where basically all types of activities and forms of teaching can take place—we do not need to divide a physics course into lecture, lab, and recitation, any longer.²⁶

A more recent effort is Tutorials in Introductory Physics (McDermott and Shaffer, 2002). While it is not studio-based, it still retains the active component and is, like much in the ABP project, informed by detailed research into student learning and understanding.²⁷

An important part of activity based learning has been made possible by the development of computer technology for the lab²⁸ and for modeling and simulation (see Section 4). Two parts of the ABP project are RealTime Physics (Sokoloff, Thornton, and Laws, 2004) and Interactive Lecture Demonstrations (Sokoloff and Thornton).

Let me mention the project dealing with thermal physics for middle schools guided by Marcia Linn. Much of the particular project has been detailed in the book *Computers, Teachers, Peers* by Linn and Hsi (2000). It is a fascinating combination of curriculum research and development, research into student understanding of thermal phenomena, and the use of computers in activity based learning environments.

Last, but not least, there is Modeling Instruction (Hestenes, <http://modeling.asu.edu>). It differs from other inquiry approaches by its explicit emphasis on models and modeling in all phases of the course.

26. By now, physics studios can be found at many institutions. Notable ones are those at RPI (www.rpi.edu/dept/phys/research/educ_physics.html) and MIT (web.mit.edu/edtech/casestudies/teal.html).

27. For some of the literature, see McDermott (1984, 1991, 2001), McDermott, Rosenquist, and van Zee (1987), Rosenquist and McDermott (1987), McDermott and Shaffer (1992), Shaffer and McDermott (1992), McDermott, Shaffer, and Constantinou (2000), Loverude, Kautz, and Heron (2002), Loverude, Kautz, and Heron (2003), Heron, Loverude, Shaffer, and McDermott (2003), Heron (2004a,b), Kautz, Heron, Loverude, and McDermott (2005), Kautz, Heron, Shaffer, and McDermott (2005), Cochran and Heron (2006).

28. See, for example, the data acquisition equipment by Vernier (www.vernier.com).

2

A FORCE-DYNAMIC GESTALT OF PHYSICAL PROCESSES

When humans talk and reason about phenomena that may be termed a force or power (anger, justice, heat, fluids, markets...), they use a number of—partly interrelated—metaphors that create different structures. One such structure appears to center around what I call the force-dynamic gestalt of these phenomena. One way the phenomena are conceptualized is through a construct having the aspects of substance (quantity), intensity (quality), and force or power—plus associated schemas such as those known from force-dynamics in linguistics, and the image schema of balance.

I borrow the term *force-dynamic* from linguistics to give a name to the structured gestalt I am going to identify in processes described in (continuum) physics and in totally unrelated areas such as emotions and social processes. I am aware that what I am describing here is somewhat different from the standard theory of force-dynamics, but it includes force-dynamics as a part of the complete structure. Furthermore, the best descriptor I can come up with to classify the type of phenomena I am considering here has to do with the notion of force or power and the resulting dynamics of processes and events.

In this section, I will outline research into figurative structures of continuum physics and the physics of uniform dynamical systems. In particular, I will sketch the structure of a force-dynamic gestalt I have recently identified, and its relation to cognitive linguistics will be described. Consequences for PER will be discussed in Section 5. Much detailed research has yet to be carried out, but the outlines of the theory are fairly clear.

2.1 SNOWMEN AND DRAGONS

To begin with, and to show the power of imagination even—or particularly—in the young, I will start with a story told by a little boy. On a winter day, when he was five years old, Alex came home from kindergarten. He talked to his grandmother about how the teacher had told them they should close the door or cold would come in. His grandmother wanted to know from Alex what cold was. He said that cold was a snowman. A snowman was very cold and if he

hugged Alex, the boy would get cold too and could get sick. Alex and his grandmother were outside and decided to build a snowman. When his grandmother wanted to build a big one, Alex said that a big snowman would be so cold it could even kill young Alex. Alex thought it would be better to build a small snowman.

Now his grandmother wanted to know what he thought heat was. Alex said, heat was a man of fire, or maybe a dragon. Alex could play with little dragons, they were not so hot and dangerous, but a really big dragon would be so hot and strong, its fire could kill the boy.

Alex' grandmother, Elena Sassi (Sassi, 2006), told me this story when I presented the idea of force-dynamic experiential gestalts of physical processes having three aspects. Clearly, quantity (size), intensity, and power are intertwined in Alex' description of the properties of snowmen and dragons. When I saw that we create the same gestalt in conceptualizing phenomena such as justice or pain, I became convinced that Alex' story was more than just an offspring of an unchecked imagination of a little boy, an imagination that has to be reigned in later in life if the child is to succeed in school. It testifies to a structure of figurative thought that is foundational to human understanding of nature. In terms of modern cognitive science, what we see here is an experiential gestalt whose aspects are structured through metaphoric projections of just a few image schemas.

2.2 GESTALT AND ASPECTS OF THERMAL PROCESSES

Thermal processes serve as the prime example for outlining the structure of force-dynamic gestalts in the physics of continua and of uniform dynamical processes. In this section I will mention a few pieces of evidence that show how widespread this structure is in common sense models and in science. This gives us a chance to take a brief look at the development of conceptions of heat and thermal processes. Then, I will describe some elements of the cognitive structure of a modern dynamical theory of heat.

From the Accademia del Cimento to Sadi Carnot. If we take linguistic form as evidence of cognitive structure, we can see a relatively direct line of figurative thought going from early science to the thermodynamics of Sadi Carnot. Basically, reasoning about thermal processes was directed toward determining the force or power of heat. Wiser and Carey (1983) found that the Experimenters of the Accademia del Cimento (Magalotti, 1667) tried to determine the force of heat and cold by performing a range of investigations. Wiser and Carey describe the concept of heat developed by the Experimenters as having three aspects, "substance (particles), quality (hotness), and force." They determined that the investigators of that time did not distinguish clearly between hotness and heat.

That distinction was developed in some detail almost one hundred years after the work of the

Accademia by Joseph Black, a Scottish chemist and medical doctor. He introduced the notions of specific heat and of latent heat as the factors that describe how much heat is needed to change the temperature of a material, or how much heat melts a quantity of a substance.²⁹ Finally, Sadi Carnot added a hypothesis of how heat and hotness are related to the force or power of heat. He expressed this relation in terms of the (visual) metaphor of the waterfall (Carnot, 1824):

D'après les notions établies jusqu'à présent, on peut comparer avec assez de justesse la puissance motrice de la chaleur à celle d'une chute d'eau [...]. La puissance motrice d'une chute d'eau dépend de sa hauteur et de la quantité du liquide; la puissance motrice de la chaleur dépend aussi de la quantité de calorique employé, et de ce qu'on pourrait nommer, de ce que nous appellerons en effet la hauteur de sa chute, c'est-à-dire de la différence de température des corps entre lesquels se fait l'échange du calorique.

We can say that Carnot achieved a clear differentiation of the three aspects—quantity, intensity, and power—of the gestalt of heat.³⁰

Heat in every-day language. Amin (2001) did a cognitive linguistic investigation of laypersons understanding of thermal phenomena. From that he concluded that the everyday concept of heat has the following minimal cognitive structure: “The suggestion here is that the lexical items heat (as verb and noun) and temperature designate different aspects of this model. The verb heat designates the whole model. The noun heat may designate the spatially localized entity that is the causal source of hotness, or occasionally the state of hotness itself. Temperature designates the degree of hotness, conceptualized as a location along a vertical scale.” In my terms, we might say that heat as a verb designates the gestalt of heat, heat as a (mass) noun is

29. The notion of heat was formulated in terms of the caloric theory. The ideas of specific and latent heats of air is well put by Ivory (1827): “The absolute heat which causes a given rise of temperature, or a given dilatation, is resolvable into two distinct parts; of which one is capable of producing the given rise of temperature, when the volume of the air remains constant; and the other enters into the air, and somehow unites with it while it is expanding The first may be called the heat of temperature; and the second might very properly be named the heat of expansion; but I shall use the well known term, latent heat, understanding by it the heat that accumulates in a mass of air when the volume increases, and is again extricated from it when the volume decreases.” See also Truesdell (1980).

30. It is well known that in the later development of thermodynamics at the hands of Thomson (Kelvin) and Clausius around 1850, the idea of heat as a fluid (or fluid-like) quantity was abandoned. Clausius’ words in one of his papers (1850) demonstrate how difficult the distinction between heat and the power of heat must be: “Since heat was first used as a motive power in the steam engine, thereby suggesting from practice that a certain quantity of work may be treated as equivalent to the heat needed to produce it...” Children and laypersons do not commonly distinguish between the quantity and the intensity of heat, Clausius does not distinguish between the quantity and the force or power. An investigation of the metaphoric base of the gestalt of heat (Section 2.3) shows that its aspects are not easily kept apart in common sense reasoning. This indicates that one of the most important goals of education must be to achieve the differentiation of aspects (Section 5).

an un-individuated entity occupying an extended region of space, and the intensity of heat (hotness) is designated by temperature which is conceptualized by a position along a vertical dimension (high or low).

For several years I gave students from engineering and applied linguistics the task of rating short expressions using the words heat and temperature according to whether or not they made spontaneous sense (Fuchs, 2005). I used expressions that would classify temperature as (1) a quantity that is described as high or low, or (2) a term denoting an un-individuated entity occupying regions of space, or (3) as the cause of a process. Other expressions did the same for heat. The result was not unexpected. Expressions in which heat was described as an entity or a cause and temperature as a vertical measure were deemed reasonable.³¹ Using heat as a vertical measure or temperature as an entity or a cause led to expressions that were considered unreasonable.³² This study seems to support the notion of the force-dynamic gestalt I have described here.³³

Considering that we do not commonly distinguish clearly between heat, temperature, and the force or power of the phenomenon of heat in every-day life, these results are interesting. They testify to unconscious cognitive structures of a weakly differentiated gestalt having (at least) the aspects of quantity, intensity, and power or force.³⁴ Similar results are obtained when students are asked to write about their conception of heat (Fuchs, 1987c). That we use this fundamental (unconscious) structure for reasoning seems to be supported by a qualitative study in which I gave a group of students Carnot's text (see above) to read. Another group had a descrip-

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31. Both Amin (2001) and I speak cautiously of an entity. There are indications that humans consider heat to be a substance (substance-like?) or even a "material" substance in common sense reasoning. Amin ascribes such stronger notions to the process of conceptual integration or blending. Whether or not this and notions such as the flow and the production of heat should be ascribed to the minimal gestalt or to blending will be discussed below in Section 2.4.
 32. There are some interesting variations in the answers that deviate from the general result. The lowest overall positive rating was given to expressions that use the concept of heat as an entity (some things we say could happen with heat are not considered intuitive; others, such as the production of heat appear intuitive). Engineering students are more likely to let temperature flow than are linguistics students.
 33. An element or aspect of the gestalt, namely balance or equilibrium, was not investigated either by Amin or by myself. We do know, however, that humans have an intuitive sense of balance of heat or hotness (and of cold), and they do express this under various circumstances. A more formal investigation of every-day language and of the work of the Experimenters of the Accademia del Cimento (Magalotti, 1667) might be interesting. Used to thermodynamics as it is commonly taught, we tend to criticize these investigations as lacking the notion of equilibrium (Wiser and Carey, 1983). I suggest that balance is inherent in the conceptions of the Experimenters. Moreover, equilibrium does not nearly have the same importance in a dynamical theory as in a static theory of heat (Fuchs, 1996).
 34. Persons trained in the sciences or engineering use very similar language indicating that their basic conceptions are no different, and they demonstrate difficulty with explaining every-day phenomena (Linn and Hsi, 2000). This contradicts the structure of the theory they learned which forbids heat to be considered an entity distributed in space (heat in the mechanical theory of heat is not extensive, it is not a state function).

tion of basic thermodynamics theory of heat engines drawn from Wikipedia. Both groups were asked the same questions: What happens to the power of the engine when the supply of heat is doubled; and what happens if the temperature difference is doubled? The quality of answers of the group using Carnot's description was considerably higher than that of the other group.

Still other aspects that are inherent in common sense descriptions of thermal phenomena have not yet been investigated from a linguistic perspective. These concern the straight-forward force-dynamic structures having to do with letting or obstructing (Talmy, 2000) as in the flow of heat (see, however, a remark by Amin (2001) concerning the inclusion of force-dynamic aspects in blending operations), or questions such as the production and possible destruction of heat.³⁵

Cognitive structure of a dynamical theory of heat. If we now turn to dynamical theories of heat either in continuum physics or in uniform processes form (Fuchs, 1996) we see a structure emerging that is in accord with the force-dynamic gestalt of thermal processes, and that closely resembles common sense notions.

From the work of Callendar (1911), Job (1972), Falk, Herrmann, Schmid and others (1973, 1976, 1981, 1983) and Fuchs (1996), "it clear that the entropy is the fundamental property that is transported in thermal processes (what in lay terms would be called "heat"), and that the temperature is the corresponding potential. The resulting theory of the creation, flow, and balance of entropy provides the foundation of a truly dynamical theory of heat that unites thermodynamics and heat transfer into a single subject." (Fuchs, 1996)

What are the elements of this description of thermal phenomena? In continuous processes, we introduce a density of the entropy, a current density, and a production rate density with which we formulate the law of balance of entropy ("heat"):

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial j_s}{\partial x} = \pi_s \quad (3)$$

This is clearly the representation of an un-individuated entity that is contained in regions of space, can flow, and can be produced (the production rate is strictly non-negative).

Temperature is introduced as the thermal potential. The density of the power of a thermal process is calculated by

$$p_{th} = j_s \frac{dT}{dx} \quad (4)$$

35. In an essay, a first year engineering student wrote—before receiving any formal instruction—that "Heat can be created, but it cannot be destroyed anymore; all we can do is distribute it in colder places." See Fuchs (1987c).

and, in conduction, the entropy current density and the associated energy current density are related by

$$j_E = Tj_S \quad (5)$$

As a result, there is a term $j_S dT/dx$ in the divergence of the energy current density (used in the balance of energy for conduction) which, according to Eq.(4), corresponds to the power of the fall of entropy in conduction (see the fat vertical arrow inside the box in Fig.3, left). It is analogous to what is termed stress power in mechanics.

Conceptually, this reflects the gestalt of thermal processes. Heat (entropy) is an un-individuated entity, temperature is the thermal potential or a measure of hotness (measured on a vertical scale), temperature differences are driving forces of thermal processes.³⁶ Moreover, heat is like an agent of the gestalt of direct manipulation which conceptualizes the notion of causality (Lakoff and Johnson, 1980). The agent influences patients by giving them energy; the agent is the source, the patient is the recipient of the energy.

2.3 ELEMENTS OF THE COGNITIVE LINGUISTIC STRUCTURE

The structure of the gestalt that has been laid out is apparent in a multitude of phenomena such as arguments or ideas, justice, the (economic) market, water, heat, or electricity, just to name a few. They all seem to have this in common: At a deep level they are forces or powers, concepts that are introduced to explain how things happen and how one thing influences another.³⁷ Here I would like to describe the structure somewhat more formally, using ideas from cognitive linguistics. As I mentioned before, much more detailed research will still be needed to ascertain or strengthen the claims I will be making. However, I am convinced that the general structure laid out here and in Section 2.4 will be largely confirmed.

To gain a perspective from outside of the natural sciences, let us collect a very few every-day expressions used to speak about justice.³⁸ They speak of the aspects of the force-dynamic gestalt of justice.

36. In common sense notions, a physical driving force appears to correspond to the concept of tension known from physical, emotional, and social interactions. It is associated with the notion of differences set up by polarities that drive the dynamics of the world (as in mythic cosmology; see Section 1.4).

37. This is not to say that force or power (and whatever else is associated with these force-dynamic gestalts) is the only aspect of these concepts. Each of them may be conceptualized in many additional ways for which we use other metaphors or metaphorical systems.

38. I collected these expressions by doing a simple Internet search for certain terms and combinations of terms.

- (1) I don't think there is much justice in the world.
- (2) The source of justice.
- (3) Justice denied anywhere diminishes justice everywhere. (Martin Luther King, Jr.)
- (4) The quality of justice in capital cases.
- (5) Harsh justice puts lives in the balance.
- (6) The weak justice system led to a climate of insecurity.
- (7) I have always found that mercy bears richer fruits than strict justice. (A. Lincoln)
- (8) The healing power of justice.
- (9) Justice compels us to help this state find a way to serve all its people...
- (10) Hence justice hinders theft of another's property.
- (11) Create a terrible imbalance in our criminal justice system...
- (12) Justice is a proper, harmonious relationship between the warring parts of a person.
- (13) How to distinguish justice from injustice in our characters.
- (14) What justice and the reality of injustice demand of us.
- (15) He got the justice he deserved.
- (16) With this move we are coming closer to true justice.

The first three expressions are examples of justice as an entity, the next three show the quality or intensity of justice. 7–10 speak of the power or force of the gestalt, whereas expressions 11 and 12 introduce the notion of balance or equilibrium. 13–14 show that this particular gestalt is a polarity (between justice and injustice). The last two expressions demonstrate something very interesting. In metaphor theory, systems of dual metaphors have been identified (Lakoff and Johnson, 1999). One set of metaphors is the figure-ground reversal of the other. In 15, justice is the figure and the person receiving justice is the ground. Expression 16 is reversed: We are the figure that is moving with respect to justice which represents some kind of landscape or path in or along which we move.

It does not take much imagination to see that the structures identified for justice are also used to conceptualize the phenomena of fluids, electricity, heat, chemical substances, and motion. Here we have clear-cut cases of the conceptualization of the entity associated with a phenomenon as being a fluid substance, of the intensity as being conceptualized metaphorically as a vertical manifold, and of the application of force-dynamic structures (such as conductances or resistances). The phenomena are associated with power—they cause other things to happen—and with balance or equilibrium. Naturally, we still have to investigate the full range of common sense conceptions including their ontogeny in the child to make certain that the con-

jectured structures actually exist not only in physics but also in intuitive reasoning.

Only the case of figure-ground reversal may take some explaining. If we say “the body received some heat,” heat is the figure and the body is the ground. If we say, however, that “the temperature of the body is going up,” the body is the figure moving in the (vertical) thermal landscape created by the notion of hotness; so there is a “thermal ground.” In summary, the following conceptual structure is emerging (see Fig.9):

- One aspect of a the gestalt of a phenomenon X is that of an un-individuated entity conceptualized as a fluid substance (in the abstract, non-material sense). It makes sense to add fluid substance to the list of image schemas (Section 1.2).³⁹ Then we can say that quantities such as liquids, electric charge, entropy, amount of substance, momentum, and angular momentum are structured metaphorically with the help of the image schema of fluid substance (the schema is projected metaphorically onto the phenomenon).

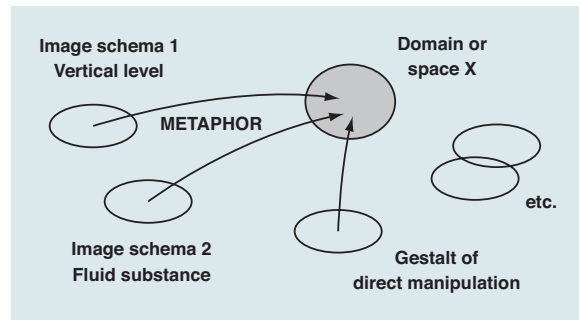


Figure 9: A phenomenon is structured metaphorically by projecting various (image) schemas upon it. Note that the projections are unidirectional as is expected of metaphors.

- The aspect of intensity or quality is obtained from the metaphorical projection of the scale image schema or the schema of verticality.⁴⁰
- There are force-dynamic aspects of the phenomena which are described by the concepts of resistance or conductance.

39. The structure of the schema of fluid substance still has to be investigated (see Schmidt, 2002, and Janda, 2004, for a discussion from outside of physics). The models of continuum physics or the physics of uniform dynamical systems suggests the following elements of this structure: (a) fluid substance is an un-individuated entity that occupies some region of space (a container); (b) fluid substance can flow or be transported (into and out of regions of space or containers); fluid substance can be generated or destroyed. In other words, fluid substance satisfies a generalized law of balance.

- Further force-dynamic elements together with the gestalt of direct manipulation are projected onto a phenomenon. In particular the latter may be the source of conceptualizations of force or power, and of energy.
- The notion of equilibrium is most likely associated with the image schema of balance (see Johnson, 1987, for a detailed discussion of balance).
- I submit that the aspects of quantity and intensity are related to each other through figure-ground reversal. To say that “the body received momentum” or “the body got faster” introduces the concept of momentum as the figure through the first expression, whereas the second expression introduces the notion of speed (the intensive quantity of motion) as the ground. This hypothesis establishes a strong link between two of the aspects of the gestalt of physical processes. Quantity and intensity are not just two independent fundamental concepts, they are related through the basic operation of figure-ground reversal.

The last point tells of a relation between elements or aspects of the cognitive structure of physical processes. There are several more relations which could be the reason for the difficulties we have with differentiating between aspects. Aspects such as quantity, intensity, and force (power) form a tight network:

- A fluid-like quantity is related to its vertical level by virtue of the metaphorical projection of the schema of verticality onto quantity (this is the metaphor MORE IS UP).⁴¹
- Force or power is directly linked to intensity (or rather to a difference of intensities). The concept of force seems to be structured metaphorically in terms of the schema of verticality as well (“high power”). If the difference of intensities—i.e., the tension—goes up, so does the force or power of the process.
- Force or power of a process are linked to the amount of the fluid-like quantity (or rather, to its flow). If the amount (or flow) goes up, so does the power.⁴² Here we map quantity upon quantity: The distinction between the fluid-like quantity and the power does not appear obvious at first sight (see Clausius on heat, Footnote 30).

40. Here is an interesting (linguistic and conceptual) aspect of the conceptualization. We use adjectives to denote the intensities (strong-weak, hot-cold, fast-slow...) which is how the scale image schema is structured (see Croft and Cruse, 2004). Then we introduce (count) nouns to denote the abstract concept of an intensive quantity (pressure, temperature, speed...) which are conceptualized by projecting the schema of verticality. To my knowledge, this phenomenon has not yet been described in cognitive linguistics.

41. This suggests why we easily exchange level for quantity and vice versa in common sense reasoning. In the physics of uniform dynamical systems, this is called the capacitive relation. The capacitance is the factor relating (stored) quantity and its associated intensity (level). Naturally, the concept of capacitance requires the differentiation of quantity and intensity.

- Balance is related to level differences or tension (differences of the intensive quantity), and therefore to power or force.

Most likely, there are some additional structures inherent in the gestalt of a phenomenon. I have not said anything about basic concepts such as time, space, process, event, etc. Furthermore, the notion of dissipation (waste of power or force) seems to be quite intuitive as well which brings up the question as to its cognitive roots. Also, I have not made a decision as to which features of the model should be included in a minimal version. A truly detailed representation of our conceptual structure of force-dynamic gestalts still awaits construction.

2.4 ANALOGY AND CONCEPTUAL INTEGRATION (BLENDING)

The foregoing discussion lets me introduce the concept of analogy between force-dynamic gestalts as a (partial) bi-directional mapping made possible by the fact that the domains or spaces of different concepts (such as fluids or heat) are structured similarly or even equally (Fig.10). In terms of conceptual integration (blending) theory (Fauconnier, 2001; Fauconnier and Turner, 2002), the spaces (domains) of our concepts share the same generic space. In our case, the generic space may be considered the totality of the schemas and structures projected onto the spaces of the various concepts.

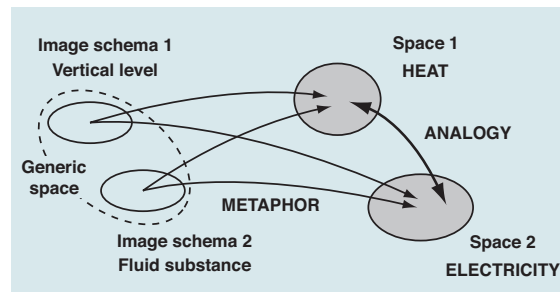


Figure 10: Two phenomena such as heat and electricity acquire similar structure due to our projection of the same schemas upon each domain or space. This allows us to map elements and structure between the spaces of the phenomena. Note that, in general, the mapping is bi-directional. We can understand thermal phenomena in terms of electric ones, and vice-versa.

42. The power of a detergent increases with both the quantity and the intensity. The quantity of detergent is easily visible whereas the intensity may be related to the intuitive notion of how aggressive the substance is from a chemical viewpoint. In physics, we would measure the latter factor in terms of the difference of the chemical potential between reactants and products.

Take the example of fluids and heat. Objectively, they do not really have anything in common. However, we humans perceive both of them as (force-dynamic) gestalts having certain aspects. These aspects emerge from the projection of schematic structure upon the domain or space of a phenomenon. To be concrete, we metaphorically project the schemas of fluid substance and of scale and verticality (among others) upon the phenomena of (material) fluids and heat. We talk about amounts of fluids and heat, fluids and heat flowing, fluids and heat rising, levels and temperatures falling, fluids driving water wheels and heat driving heat engines, etc. (We also speak of heat being produced—for example in fires or by rubbing our hands—but we do not apply the same language to material fluids.)

I assume that we use this language for water and for heat independently. In other words, this is not (yet) the result of analogical reasoning. Analogy is made possible by the fact that the same or similar conceptual structures have been created for fluids and for heat.⁴³ Expressed differently, the mental spaces that contain our concepts for the gestalts of water and heat have been structured (almost) equally since they share the same generic space of the basic schemas and structures discussed before (Fig.11).

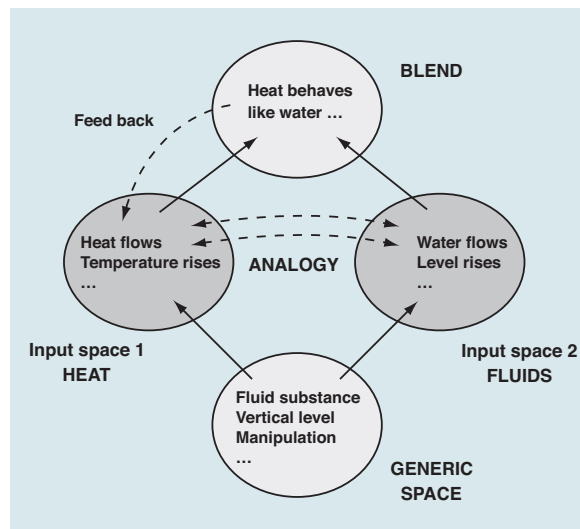


Figure 11: A simple conceptual integration (blending) network for fluids (such as water) and heat. It consists of a generic space consisting of schematic structure that is shared by the two spaces of water and heat which are the input spaces to the blended space. New conceptual structure emerges in the blend and is fed back to (one of) the input spaces.

43. Remember that heat is assumed to be produced in irreversible processes. This means that the mapping of structure from fluids to heat or from heat to fluids does not have to be complete.

Cross-space mapping between heat and fluids can now account for the phenomenon of blending (Fauconnier, 2001). We create a new mental space, called the blend, that borrows selectively from the input spaces of fluids and heat. Possibly some additional structure is imported into the blend. In this blended space we create new structure and new concepts. Amin (2001) suggested that the notion of heat as a substance (possibly a material substance) is an emergent structure resulting from the operation of blending, and not a preexisting fundamental structure of human thought that exists irrespective of circumstances. Basic structures would be the image schemas postulated in cognitive linguistics. (Remember that Amin uses the idea of a minimal cognitive model consisting of schematic structure; the notion of heat as a substance does not have to be included in this minimal model).⁴⁴

This is an example of the observation that concepts constructed by learners are not always clear, unified, and stable; rather, they are fluid, can be constructed spontaneously, and need not survive for a long time before being replaced by a different thought (remember the discussion of the fluidity of thought and concepts in Section 1.6; see in particular, Atkins, 2004). The fluidity of thought may well be an important element of creativity in the production of hypotheses. In the end, I would argue that ideas and hypotheses are born of the processes of metaphoric and analogical projections and of blending. They are the result of the metaphoric nature of our mind which goes back to at least the mythic stage of human culture.⁴⁵ If we want to truly understand and strengthen creative and scientific work, we have to make explicit use of these processes. This is the theme I will now turn to.

44. At this time I would defer an answer to the question of a minimal cognitive model for the force-dynamic gestalts identified in this essay. However, I believe that we should at least add the element of the gestalt of direct manipulation to Amin's minimal model (to account for the aspect of force or power). Whether or not schemas such as balance and force-dynamic structures should be added as well, or if they should be called upon in a conceptual integration network (i.e., in blending), I cannot say yet.

45. Given the model of the embodied human mind, the mimetic culture before the advent of spoken language can be conjectured to contribute to the source of metaphoric thought rooted in what Zlatev (2005) calls mimetic schemas.

3

**COGNITIVE TOOLS AND THE FOUR-CYCLE OF
INQUIRY BASED LEARNING**

Learning has much in common with other complex processes such as problem solving, design, the construction of a science, or thinking in general. If I analyze these activities I see certain structures emerging that can be represented as interacting cyclic processes. Two such cycles are well known from scientific research and industrial design (they play equivalent roles in the other areas mentioned). They are the construction of models or whole theories, including the deduction of their consequences, and experimental or observational activities that provide the data with which we compare the results of our models (Section 1.4). Two cycles are not enough, however. We are left with the problems of how we come up with good questions for our investigations, and where we get—or rather, how we construct—ideas for hypotheses upon which we build our models (see Fig.5). It seems that we can identify methods and activities that allow us to produce questions and ideas. I propose here to put these methods in the form of two more cycles⁴⁶ that brings the number of categories of cognitive tools in thinking, learning, designing, and doing research to four (Section 1.4).

3.1 FOUR CYCLES

Traditional accounts of the scientific method can be put in the form of a Bi-Cycle (see Fig.5 and Fig.7) where the cycles represent the activities or tools of modeling (conceptual modeling, see Hestenes, 2006, and Fig.8) and experimentation (physical modeling). In a more general sense, both cycles can be said to represent acts of formal symbolic modeling.

There are important processes going on in learning, thinking, and acting that are not caught in the Bi-Cycle. These represent forms of thought that are often belittled as non-scientific. Or,

46. This idea developed in discussions with Karl Weber (2004). Weber has since used the Four-Cycle to describe different phenomena, among them the structure of Egyptian cosmology (Weber et al., 2002-2007).

when considered from a more positive perspective, these forms are considered to be of the creative type reserved for a few special individuals who come up with important new ideas. However, they are essential to successful learning. I have identified two such general processes which I would like to call the generation of hypotheses (H) and the formulation of good questions (Q) for the subject to be investigated. This brings the number of important individual activities to four. These are the four cycles (Fig.12):

1. *Symbolic formal thinking and acting* in the construction and performance of experiments, and in observation of nature;
2. *symbolic formal thinking and acting* in the construction and simulation of conceptual models (on paper or in the computer);
3. *imaginative thought* as the power to recognize and classify problems to arrive at motivation and good questions for investigations;
4. *metaphoric and generally figurative thought* as the source of explanations (hypotheses for models).

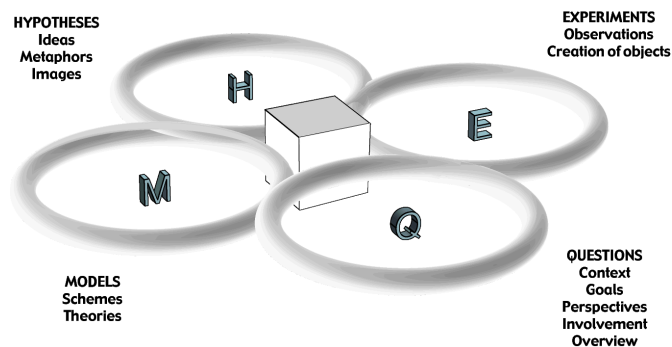


Figure 12: Symbolic representation of the Four-Cycle for inquiry based learning and action. It consists of four individual cycles that represent special cognitive tools. The results of using tools come together in the thinking and acting person (symbolized by the cube at the center) where they are compared and judgements are made (on the role of judgement in the process of human thought see Dewey, 1910 and 1916). Naturally, the person also interacts with the environment through perception and action.

3.2 OPERATIONALIZING THE CYCLES H AND Q

Using Kieran Egan's theory (Egan, 1997), I will say that the additional processes are handled best with two additional sets of cognitive tools—namely those of mythic and romantic culture

(H and Q cycles, respectively). As a result, the cycles can be operationalized and made concrete. This is important since the thought processes associated with these two cycles are typically considered to be soft skills at best, or irrational at worst. To say the least, the cycles represent thought processes we are not commonly aware of and that all too often are not developed through years of schooling. The goal of education seems to be to quickly replace the figurative irrational and not really “useful” thought of the child by what we deem rational, abstract, practical, and scientific. To make the processes of the formation of questions and the generation of hypotheses accessible, we need proper tools (see Egan, 2001, 2005). Briefly stated, romantic understanding leads to encompassing research of a field that can result in overview, understanding of context, motivation, and good questions to be answered. Mythic thought, on the other hand, is the source of primary and primitive (in the sense of fundamental) explanations that are strongly driven by image schemas and metaphors. First models can be constructed in the form of narratives. A summary of steps the four cycles may be constructed of is shown in Fig.13 and described below.

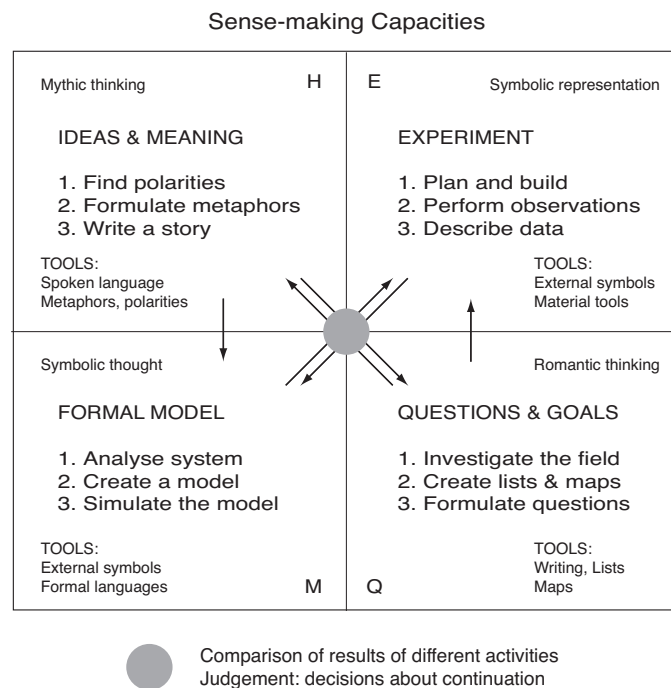


Figure 13: The Four-cycle as a synthesis of sense-making capacities that are driven by specialized cognitive tools. Note that there is no definite starting point in this scheme, nor do we run through the cycles in a pre-scribed manner. Many of the processes will proceed in parallel.

Here is a brief description of some of the cognitive tools that can be brought to bear on thinking, problem solving, designing, and so on. The structure of the cycles Q and H is influenced by Egan's work (2005), and by the form of inquiry based physics described in this essay.

Modeling

1. *Analyze*: Objects and systems are "taken apart" and processes are identified.
2. *Create a model*: Ideas representing the nature of the processes are formulated, cast in the form of relational diagrams, and translated into equations.
3. *Simulate the model*: The equations resulting from modeling are solved and the results are presented and investigated.

Experimenting

1. *Plan experiment*: Based on goals and on knowledge derived from models, experiments and/or observations are planned.
2. *Build and execute experiment*: The physical model representing the system to be investigated is built and/or equipment for measurement and observation is added. The physical model is "simulated," i.e., experiments are performed.
3. *Represent and analyze data*: Represent data with the aim of gaining an idea of the relevant phenomena and of facilitating comparisons with results of models.

Mythic thought

1. *Identify polarities*: Find polarities that drive the processes envisioned; find out what is being driven or caused.
2. *Formulate metaphors and analogies*: Translate basic ideas of what is happening into schematic pictorial representations; create and use analogies between new and well known phenomena.
3. *Produce a narrative*: Bring ideas into the form of a narrative that reflects meaning and understanding (formulate a non-formal word-model).

Romantic understanding

1. *Collect systematically*: The field of study is researched as completely as possible; findings are collected.
2. *Create lists and maps*: Put what appears important into structured lists and diagrams (maps, mind maps, hierarchical maps, flow diagrams, etc.).
3. *Generate questions*: Formulate one or more "good" questions. (What are we interested in? What do we want to know or understand?)

4

PHYSICS AS A SYSTEMS SCIENCE

Basic concepts in physics result from the embodied nature of the human mind (Section 2), and this nature suggests that we have a number of cognitive tools at our disposal beyond the formal ones commonly used in science learning (Section 3). In this section I shall propose a concrete curriculum for introductory university physics for students from natural sciences, engineering, medicine, and environmental sciences that incorporates the most important elements of cognition and pedagogy I have identified so far. I shall describe a curriculum called Physics as a Systems Science (PSS) that has been developing for some years now. It makes use of tools for modeling that support the conceptual structure of physics outlined in Section 1.3 and Section 2, integrates modeling with the lab, and brings physics close to applications where a systems approach is most natural. Naturally, other curricula can also profit from this development as has been demonstrated by high school courses related to this one.

Physics as a Systems Science has at least three important dimension: a thematic one, a dimension of inquiry based pedagogy, and one relating to its figurative conceptual nature. The last of these aspects has been described in the previous sections and need not be repeated here.⁴⁷ The first two, on the other hand, deserve some attention and allow me to develop a concrete perspective of the foregoing discussion.

4.1 THEMATIC DIMENSION OF PSS

It should be relatively simple to develop the thematic dimension of physics as a systems science. Partly, the motivation to do so comes from engineering, medicine, and environmental sciences. These fields have experienced at least a partial re-orientation toward concerns for larger and more complex systems. The basic sciences (physics, chemistry, biology) have reached a degree of maturity that allows us to apply them to these ever more complex systems. We now

47. Maybe it is worth remarking that we will not arrive at a systems science version of physics if we just add some aspects of systems and system dynamics modeling to a standard curriculum (Fuchs, 2004).

recognize the importance of generalized, unified, and interdisciplinary curricula. In engineering education, one such example is the project of the Foundation Coalition (1998-2007). One element of their restructured curriculum is a reliance on laws of balance and dynamical modeling as a unifying perspective for fields of engineering (Richards, 2001).

To develop a systems approach to physics thematically, we can choose some objects that clearly demonstrate the character of systems and then proceed to use them as examples for the physics we wish to teach. Table 3 contains the chapters of a particular PSS curriculum (Fuchs, Ecoffey, and Schütz, 2001-2007) and ideas for case studies that can serve as interesting and more or less complex examples of real life systems for which physics and physical chemistry are relevant.⁴⁸ I commonly use one of the case studies as a guide for the elements of physics one should learn to understand if one wants to deal with the case successfully. Success is measured by the quality of experimental investigations and models a learner can create. The same or other cases can also serve as the basis of semester projects.

Table 3 Subjects and case studies for Physics as a Systems Science

	Field	Case Studies
1	Storage and flow of fluids	The systemic blood flow circuit of mammals Transport of water in soil
2	Electrical systems	Super-capacitor support for batteries
	Processes and energy	Charging capacitors with photovoltaic panels
3	Heat, fluids, and radiation	Heat from the ground: Heating buildings Thermoelectric cooling The atmosphere and the production of winds
4	Reactions and transports	Osmosis in potatoes Dynamics of batteries and fuel cells
5	Oscillations and waves	Wave-guides The chaotic heart
6	Motion, fluids, and fields	Keeping time: Mechanical clocks Bungee jumping Parking spacecraft at L4

48. Note that the structure of the physics of uniform dynamical systems described in Section 1.3 and Section 2 does not require us to start the exposition with mechanics. Fluids, electricity, and heat lend themselves quite naturally for a development of physics and the systems aspects of physics.

It is quite clear that a course that builds on systems and case studies does not lend itself easily to a traditional lecture-lab format. The studio environment (Wilson, 1994) is the most natural choice of a learning environment that allows for a high level of active involvement on the part of the student during phases of learning and of working on projects (Fuchs et al., 2001).

4.2 METHODS AND TOOLS

Computer based tools for the laboratory and for dynamical modeling have changed the way we can design and construct curricula and learning environments. It is quite common to use software and interfaces for data acquisition and data analysis. However, it is still rather uncommon to find learning environments that explicitly integrate dynamical modeling with the lab.

The computer-based lab. Several companies offer relatively cost-effective data acquisition and data analysis equipment consisting of interfaces, sensors, and software. Traditional approaches and materials largely restricted dynamical phenomena to the realm of mechanics with some scattered applications in electric circuits. The computer-based materials open up the dynamical world of heat, electricity, fluids, chemistry, and biology thus allowing us to create a much more diverse learning environment—one that is more naturally systems oriented. Different sensors for temperature, for conductivity, pH, gas pressure, voltage, colorimetry, etc. all collect real-time data and bring the dimension of time into the learning of physics.⁴⁹ The software tools give us access to easy-to-use data analysis solutions including methods of numerical calculus (for rates of change or for integrated quantities).

Dynamical modeling tools. Dynamical phenomena leading to initial value problems have been with us in physics since Newton's time. In fact, we may trace the roots of system dynamics all the way back to Newton's program for a mathematical science. However, the widespread and consistent use of simple system dynamics tools for explicit modeling in the general physics class room seems still to be in its infancy.

Fortunately, there are programs available today that are not too expensive and that can be learned in little more than a couple of hours (see Stella, Berkeley Madonna, Powersim, Vensim; Matlab with Simulink will take much longer to learn). The programs typically employ a visual metaphor for representing dynamical processes that is close to the metaphors I have identified in Section 2.3 (Simulink is an exception here). There are only a handful of elements used to create graphical representations of the initial value problems that describe dynamical models in uniform systems (Fig.14). One of these is a reservoir or stock element for stored amounts of

49. Some projects mentioned in Section 1.6 have integrated these new possibilities (see, for example, ABP, 2007; McDermott, 1996).

a fluid substance, another is a flow symbol used to represent processes (conductive and convective currents, and sources for radiative transports and for production/destruction). Constitutive laws for process quantities are formulated with the help of a symbol for additional variables and parameters and a connector tool that allows us to create direct and feedback relations. Numerical methods are built in that let us solve completed initial value problems.⁵⁰

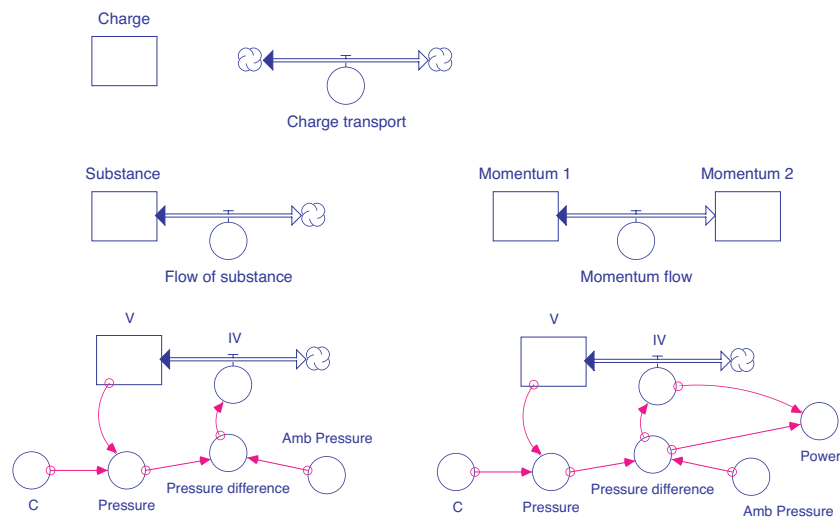


Figure 14: Basic elements of the graphical metaphor for representing processes used in system dynamics modeling tools (here: Stella). Note the rectangle for stored quantities, and the fat arrow for processes. Rectangles and flows are used to construct expressions for laws of balance (or—in some cases—for simple integrators). Circles and thin connector lines are used to set up constitutive laws. The diagram at bottom left represents the typical calculation of a process quantity (a flow) from a level difference (pressure difference). On the right (bottom), the calculation of the power of the flow has been added.

Methods and pedagogy. Again, if we really do make use of an integrated learning environment—one where experimenting and explicit modeling form the cornerstones—traditional lecture-lab formats hardly serve the purpose.⁵¹ Considering that data acquisition and dynamical modeling give us a chance to treat much more complex real-life applications than was hitherto possible, we should not deny students direct access to these examples and tools.

50. The quality and number of numerical methods varies considerably from tool to tool. Berkeley Madonna, for one, has methods for variable step integration and for stiff IVPs. In addition, it lets the user perform automatic curve fits between simulation results and measured data (for automatic parameter adjustments).

51. However, see models of active engagement in large lecture based physics courses (Mazur, 1997).

4.3 SYSTEM DYNAMICS MODELING IN PHYSICS EDUCATION

System dynamics modeling tools are used daily in our PSS course. Models are constructed for applications ranging from the very simple introductory (equilibration of water levels in communicating tanks) to the rather complex (such as the thermal dynamics of a building or the chaotic behavior of mechanical systems). For a description of the pedagogy and of models of physical dynamical systems, see Fuchs (2002a, 2006a,c) and Fuchs, Ecoffey, and Schütz (2001-2007).⁵²

To give the reader an impression of an interesting real-life application, consider the physical and system-dynamics modeling of a part of the systemic blood circulation system of mammals (Fuchs, 2006c; Fig.15, left, data at center). In the first approximation, the part of the circuit consisting of the left ventricle of the heart, the aorta, and the systemic vessels is represented by the simplest possible windkessel model (Fig.15, right). The left ventricle of the heart is a pump for setting up a pressure difference that forces the liquid into a container. The pressure of the liquid in the container (which models the elastic aorta) depends upon the quantity of liquid. From there the fluid can flow through a hose out of the tank (windkessel).

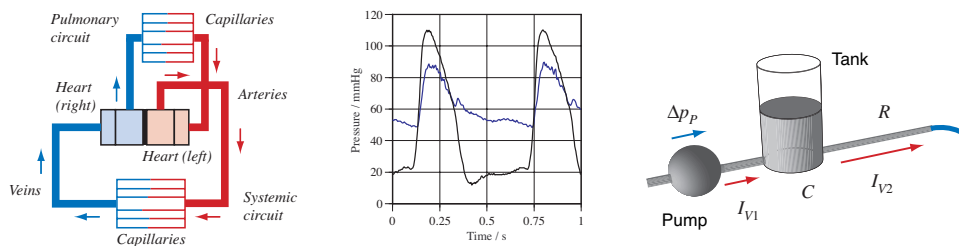


Figure 15: Left: A diagram showing the blood circulatory system of mammals (systemic circuit in the lower half). Center: Data of blood pressure in the left ventricle (large amplitude) and in the aorta near the heart for a sheep. Right: A hydraulic windkessel model of the systemic blood flow circuit. Note that apart from a pump and a valve (between the pump and the tank), we only use RC elements in the model.

The hydraulic windkessel can easily be represented in the form of an electric circuit (Fig.16, left) that lends itself to experimental investigations. In a case study, students would build such a circuit, take data (Fig.16, right), change parameters and retake data, model the circuit using a system dynamics tool, and compare simulations to the data taken. The diagram of the SD

52. To my knowledge, there is one other investigation of the use of system dynamics modeling in physics instruction (Schecker, 1998). The approach does not make use of the cognitive structure of the physics of uniform dynamical systems identified here. As a result, mechanical examples are treated almost exclusively, and laws of balance (of momentum) are not used explicitly. See also Zaraza and Fisher (1999).

model is visually similar to the physical model of the circuit in Fig.16 (the hydraulic version of the SD model is shown in Fig.17 on the left).

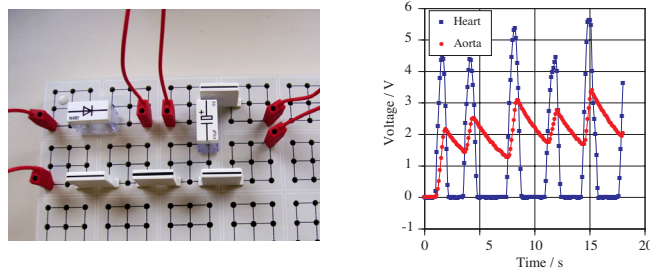


Figure 16: An electric (physical) model of the windkessel in Fig.15 (right). Note the diode and the capacitor that represent the valve and the tank, respectively. The voltage of the power supply (on the left in the photograph) is changed rhythmically by hand (data showing large amplitude), and data of the voltage across the capacitor is taken (small amplitudes in the diagram on the right).

If the model is deemed reliable for the circuit, i.e., if we manage to get a satisfactory agreement between data (Fig.16, right) and model results, we transfer the model to the hydraulic case. Simple electric circuits can usually be modeled well, so the agreement is good if the model represents basic ideas of how electric circuits function. The step of transferring the model only requires changing names and adjusting parameter values—therefore, electric and hydraulic SD models for the windkessel are graphically identical. At this point, real data can be compared to the hydraulic model (Fig.17, right).

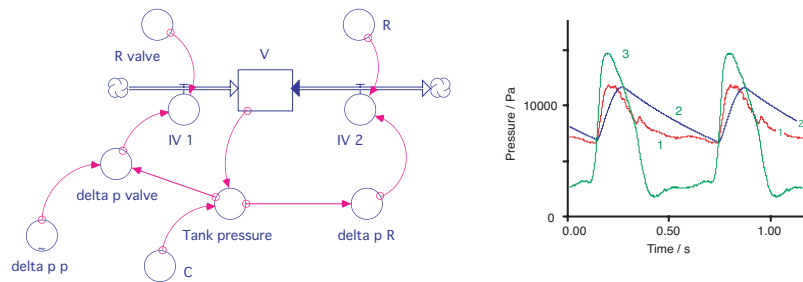


Figure 17: System dynamics model diagram for the hydraulic windkessel (left) and data (curves 1 and 3) plus simulation results (curve 2).

Now it turns out that the fit of data and of the first model is less than satisfactory (Fig.17, right). Consequently, we should think about how to modify the model. One possibility is to divide the aorta into a number of segments and then create a pseudo-finite element representation of the system (see Fig.18).

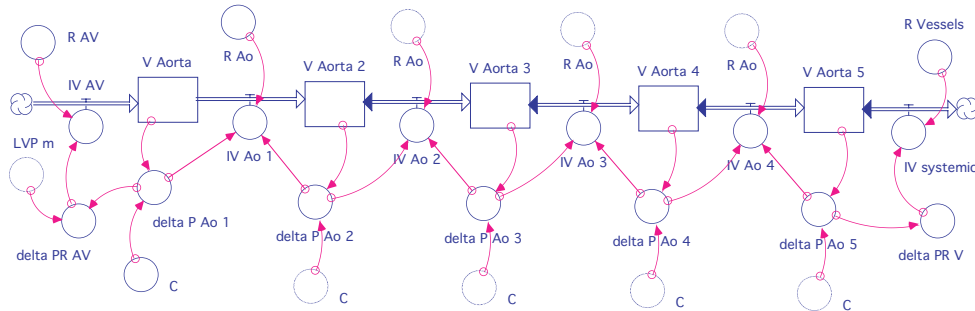


Figure 18: A pseudo-finite element model of a sheep's aorta using a representation in terms of RC elements. By adding (hydraulic) inductive elements, the model can be made even more realistic.

When the new and improved model is simulated, we see that the results for the pressure of blood in the aorta can be made to agree quite closely with actual data (Fig.19). Naturally, we could also build a physical electrical model for the systemic circuit before making the step to a multi-compartment SD model. Finally, we should add the effect of fluid inductance (inertia) to obtain still better results (such as for reversed flow of blood in the aorta; Fuchs, 2006a).

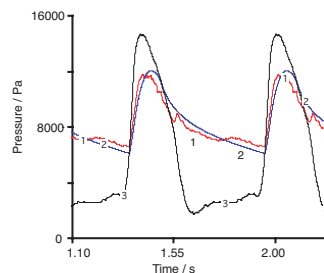


Figure 19: Data of the pressure of blood in the left ventricle (large amplitude curve) and in the aorta (curve 1) of a sheep and simulation results (curve 2) for the multi-compartment system dynamics model of Fig.18.

4.4 MODELING, INQUIRY BASED LEARNING, AND THE FOUR-CYCLE

The case of the blood circulatory system of a sheep is interesting and useful in that it lets us apply the Four-Cycle of inquiry based learning (Fig.12) quite well. I did not discuss work that typically precedes the steps described in the previous section—namely, investigation of the case, i.e., researching what is already known about the subject. In the present case we find a lot of material in books, papers, and on the Internet. If we apply the cognitive tools of researching

and ordering information (the cycle Q in Fig.12), we may be likely to generate good questions that can actually be answered by a study such as the one I just described.

In real work, thinking about how the system works will go on in the back of a person's mind as the qualitative investigation proceeds. If we make the step of hypothesis generation conscious and public, i.e., if we apply some of the cognitive tools of the H-cycle in Fig.12, we can prepare the important step of producing physical and conceptual models for experiments and computer modeling. For people learning a science, laying this step out in the open is particularly important, since it introduces them to generating ideas based on analogical reasoning (which is itself based on the basic forms of figurative thought outlined in this essay). Knowing that one is capable of constructing conceptual models from mental ones may very well build a learner's confidence in his or her abilities to do physics. Naturally, hypothesis formation is not a one-time operation that precedes experimenting and (computer) modeling; rather, it will run in parallel with these steps that are represented by the E and M-cycles of the Four-Cycle (see Fig.12 and Fig.13).

The description of the case study in Section 4.3 is probably detailed and vivid enough to let us get a feeling for experimenting and modeling and for the interaction of these activities. Let me just add a last remark on explicitly modeling: System dynamics modeling with its modern easy-to-use tools is important for inquiry based learning because it allows us to work on complex real-life cases that would otherwise be beyond students' ability of producing and working with dynamical models in mathematical form. This is so for two reasons. Firstly, and most obviously, the equations resulting from a model of a real-life dynamical system typically resist simple manipulation, both analytical and numerical. Secondly, and most important for our purpose, most students could never formulate the models in the first place were it not for the graphical interface that is a useful representation of some of the metaphors with which we understand nature.

5

**SUMMARY AND AN AGENDA FOR PHYSICS
EDUCATION RESEARCH**

Human reasoning is embodied. Figurative structures of thought are the norm, and they show up in physics as in any other field of inquiry. Continuum physics in particular uses a fairly simple gestalt to structure its contents. This force-dynamic gestalt has a few important aspects such as quantity, quality, and power. The aspects are structured with the help of metaphoric projections of image schemas and force-dynamic schemas. Since the same schemas are used for the various fields of physics, they obtain an analogical structure that can be extended by conceptual integration processes.

If we take an evolutionary perspective of human thought, we see that the figurative structures identified here reach back to mythic culture which—in the individual—develops in early childhood as a consequence of the acquisition of spoken language. This and the subsequent romantic phase provide us with cognitive tools for increasing the range and depth of inquiry based learning beyond the standard formal symbolic reasoning known from science. An integration of older and newer forms of thought can lead to a novel approach to activity based learning that is in accord with the figurative structures of physics.

Finally, modern tools in the lab and for dynamical modeling let us create practical versions of learning environments geared toward physics and its applications. It turns out that the force-dynamic gestalts of physical processes are similar to what is known from systems science which, in turn, provides us with modeling and computational tools that can be integrated with the modern laboratory for introductory courses.

A part of the research and development outlined here has been carried out, but much still remains to be done. There are exciting questions whose answer will strengthen our understanding of the learning of a science. Some of these will be discussed briefly in the remaining parts of this section. They can be taken as a suggestion for future physics education research.

The origin and development of figurative thought in young children. We know quite a bit about early development of conceptual thought in infants (Mandler, 2004, 2005), we have investigations of intuitive physics in the child (Wilkening, in press; Wilkening et al., 2006), and we have

data on science conceptions of young learners (Driver et al., 1985, 1994). Above all there is the standard view of child development created by Piaget which, however, has been criticized lately from various perspectives, not least that of Mandler (2004). What is missing is research into the development of early verbal thought based on cognitive linguistics—covering the range from maybe 2 to 8 years of age—related to concepts of the physical world. I would be most interested in knowing how the force-dynamic gestalt of processes so evident in Alex' story about the snowman and dragons comes about. What are the roots of these structures of figurative thought that seem to underlie much of (macroscopic) physics? Knowing an answer to this question may influence our attitude toward learning and teaching of physics in all stages of education ranging from primary school to university.

Differentiation of aspects of gestalts and the construction of reality. Research outlined here shows that common-sense conceptions of nature may be much more useful than has been realized up until now. Rather than having to change students minds, we should be concerned with how abstract gestalts are differentiated and made into useful formal concepts upon which later science learning can be securely built. The question is how do we support the differentiation of the aspects of the gestalt of physical processes during early school years to prepare for the learning of a formal science? I have outlined reasons for why it is difficult in common reasoning to distinguish between the different aspects of the force-dynamic gestalts, even though the aspects are clearly visible in human language and thought (see Section 2). Therefore, careful studies of how to further the process of differentiation through the early years of schooling should be very helpful for strengthening science teaching.

The years following the mythic phase of early childhood deserve just as much attention. We have to develop a science pedagogy for middle school (secondary school) that applies the cognitive tools of literacy—distinct from those of formal philosophic or theoretic thought—to physics and the other sciences. The distinction of aspects of undifferentiated gestalts which should be achieved during earlier years must be followed by a phase of “collecting information about reality,” a phase where information gathering and organization increases students detailed knowledge of the physical world (Egan, 1990)—without already leading to formally structured theories of phenomena. To what extent knowledge of the process of science should already be included during this phase must be studied carefully (American Association for the Advancement of Science, 2000).

Inquiry based pedagogy and dynamical modeling. The later years of schooling before university can be used to develop a strong sense of the process of science while at the same time deepening content knowledge of the sciences themselves by letting the learning occur in inquiry based environments. We already know much about the theoretical basis of activity oriented learning, but I am not aware of any attempts to generalize the process to include mythic and romantic understanding based on an evolutionary perspective of human learning. Pedagogy

that uses the Four-Cycle to guide inquiry based learning still has to be designed in more detail. Initial feedback from students has been encouraging and shows potential for studio learning.

Beyond the more theoretic questions, we can turn our attention to the development of learning environments for physics that serve different goals and direct our research toward ascertaining to what degree certain pedagogical approaches actually work best. My personal interest lies with curricula that stress the systems aspects of the physical sciences and make explicit use of system dynamics modeling. We should investigate to what extent such an orientation helps in creating applied and interdisciplinary courses—courses that lend themselves to an integration of the natural sciences and engineering. I am convinced that in order to strengthen a science such as physics, chemistry, or biology in the education of adolescents, the different disciplines should take advantage of the common language of systems science. If aspects of the environment—to mention just one of today's burning issues—become increasingly relevant to the training of the university graduate, these considerations should be all the more important for learning during the high school years.

Software tools that implement the gestalt of physical processes. Hestenes (1996) has already pointed out how useful modeling software could be in supporting a modeling oriented pedagogy. For many years, Werner Maurer and I have been developing pedagogy and examples of system dynamics modeling for physics instruction in engineering education (Maurer, 2005-2007; Fuchs et al., 2001-2007) and for students studying applied linguistics and technical communication (Fuchs, 2002a; Weber et al., 2002-2007). Enough experience has been collected so we can turn to designing modeling environments that support the learning of the physical sciences.

I propose to design and build software for modeling of dynamical systems that (1) is integrated with software for laboratory environments (data acquisition and analysis), and (2) uses a graphical interface that supports the model of the force-dynamic gestalts outlined here. SD tools implement some of the metaphoric structures of physics and other fields, but by no means all of them. In particular, visual tools for levels (potentials) and potential differences or driving forces, and the relation of energy (storage, transport, and release) to the fluid substance like quantities of physical processes are missing. A joint effort of researchers in modeling pedagogy, cognitive science, and of companies specializing in the development of computer based laboratory equipment for schools could drive this effort.

A dynamical theory of heat in physics instruction and a transition to quantum physics. Let me add as a final point a proposal for the conceptual overhaul of thermal physics in high school and introductory university courses. We have seen in this essay that thermal processes take center stage regarding the conceptual structure of theories of nature. Thermodynamics should be at the center of any redesign and streamlining of science learning and teaching. More than any other field, thermodynamics tells us teachers what we have to change if we want to engage human imagination as a tool for understanding a science.

Moreover, thermodynamics has an important if detrimental relation to chemical physics. In standard pedagogy, chemical processes are not recognized as such but any explanation of the drive of chemical change is made dependent upon classical thermodynamics with its awkward conceptual structure (Fuchs, 1986). To make chemical processes more generally accessible from a unified viewpoint, it is important to introduce the chemical potential from the beginning in courses (Rüffler and Job, 2007). Only when this has been done, and chemical change is understood as an independent category of natural (physical) processes, should we deal with the relation between chemistry and thermal physics. Again, this presupposes a clarification of the fundamental cognitive structure of modern continuum thermodynamics.

Finally, our predilection for little particles⁵³ in thermal physics and in chemistry could be made positive use of in an introduction to quantum physics. I propose to investigate an approach to teaching quantum physics in school and university science that builds on quantum statistics in thermal and chemical processes. This is a tall order, but I am convinced that there is hardly any other way that would not lead to another example of the current split between so-called classical and modern (quantum) physics. Students who have learned about entropy from the beginning and are able to relate this concept to common-sense cognitive structures may just be more inclined to develop a solid base for quantum processes. After all, the main characters of quantum physics are not forces and trajectories but momentum, charge, angular momentum, substances, entropy, and energy.

53. Whereas we have a fair idea of the basic cognitive structure of continuum processes (Section 2), there is no comparable understanding of the figurative basis of kinetic, statistical and quantum physics. To say that there is a metaphor HEAT IS (RANDOM) MOTION OF LITTLE PARTICLES is stating the obvious. But we do not know much about the role and cognitive (linguistic) structure of this figure of speech, nor do we know how it relates to the force-dynamic gestalts of macroscopic phenomena. This opens up another fertile ground for research at the intersection of physics education research and cognitive science.

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