Figurative Structures of Thought in Science

An Evolutionary Cognitive Perspective on Science Learning

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Abstract

Current research in cognitive science and cognitive linguistics demonstrates that human understanding is based on the projection of simple structures of imagination onto objects of experience. This is reflected in figurative language with its most important elements: metaphor, metonymy, and stories.

Structures of figurative thought are based on image schemas that develop early in the life of a child and form the basis of later every-day and formal thought. Image schemas are projected metaphorically upon a wide range of phenomena.

In this talk I will identify a structure of human imagination and thought that I call Force Dynamic Gestalt. These gestalts have three aspects at their roots: quantity (amount), quality (intensity), and force or power. FDGs can be seen in any number of general abstract phenomena such as justice, pain, fear, love, the market, etc. Interestingly, FDGs can be shown to go back at least as far as mythic (oral) cultures.

I will demonstrate that the same Gestalt exists in classical physics and chemistry, proving that simple and historically ancient figures of thought form the basis of formal reasoning in the sciences. It appears that all people have access to the formal basis of science. Thus an important task of pedagogy is to tap the source of these conceptualizations and to support students in learning how to differentiate aspects of FDGs as a means of formal reasoning.

1 INTRODUCTION

A story told by a five year old boy to his grandmother shall guide us through this talk where I want to investigate how we humans confront and understand nature. The story demonstrates the power of imagination even—or particularly—in the young, and can be used to ask some important question regarding the origin, evolution, and use of this imagination.

> *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 (Fuchs, 2006a). Briefly stated, Alex makes use of schemas of (fluid) substance (quantity, size…), intensity (quality), and power or force to make sense of a multi-faceted experience such as heat (I call these schemas aspects of a Force Dynamic Gestalt). These schemas are projected metaphorically upon the phenomenon in question to yield conceptual structures rich enough for complete narratives.

In this talk I want to demonstrate how the boy's imagination leads quite naturally to this powerful structure that can be formalized to yield modern continuum physics (including its relation to chemistry and biology). I shall use the story to ask four questions which I will try to answer here:

(1) What is the origin of the structures of imagination revealed in Alex' story? How does this relate to the evolution of the human mind and the development of the mind of a (young) individual?

(2) What is the structure of this imagination? How can research into figurative language help us identify this structure?

(3) How can these structures of thought be used to develop a modern science curriculum? To what extent can it be called the foundation of conceptualization in science?

(4) Does the structure revealed here go far enough in providing the basis of 20th century physics and chemistry, or do we now use other, more modern (figurative) structures in current science?

The following four sections will deal with these questions in turn. I will discuss theories of the evolution of the human mind and of the development of cognitive tools in a modern young human. The structure of Alex's imaginative description of natural processes will be discussed in the light of modern cognitive linguistics and will be shown to coincide with a major branch of physics—namely, continuum physics. The main theoretical result of the research reported here is the identification of Force Dynamics Gestalts in our imaginative description of processes in nature and in society. Then I turn to the question of how a science curriculum might be formed that leads all the way from the early years of a child to the beginnings of formalization in the later years of high school. Finally, I will briefly discuss the question of conceptualizations in 20th century quantum physics—such as chance and random motion of particles—which seem to go beyond the structures needed to understand macroscopic physics.

2 ORIGINS OF IMAGINATION

In this section, I will briefly mention theories of the phylogenetic and ontogenetic development of the human mind and imagination, and conclude with a look at an example of an evolutionary philosophy of human thought.

2.1 EVOLUTION OF THE HUMAN MIND

Merlin Donald (1991) creates a view of the development of the human mind through stages that are strongly influenced by language development and use (see Table 1). It agrees well with other accounts of human evolution, with models of the development of language, and is most in line with the theory of individual growth (Egan, 1997) discussed in the following subsection. 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) possessed this ability. Simply stated, mimesis allows hominids to begin to tell stories (Fig.1, see the path from E:episodic to M:mimetic).[1]

Table 1 **Stages of the evolution of the human mind**

Donald[a]	Egan[b]	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, "modern" realism	Written language, Formal languages	Paper, Film, Computer, RAM, HD, DVD, Experiment	1 ka 100 a

a. Merlin Donald (1991): Origins of the Modern Mind. Three Stages in the Development of Culture and Cognition. Harvard University Press, Cambridge.
b. Kieran Egan (1997): The Educated Mind. How Cognitive Tools Shape Our Understanding. The University of Chicago Press, Chicago.

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.1, L:linguistic). This early stage of the development of what we normally call natural language will be very important for my story here.

If we add visual symbolic means to our representations (Donald, 1991, p. 296-305; see Fig.1), we arrive at written languages with the tools of literacy and theoretic culture (Ong, 1982; McLuhan, 1962, 1964). In this phase, we create and uses external symbolic storage systems ranging from paper to computer storage to film.

1. 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).

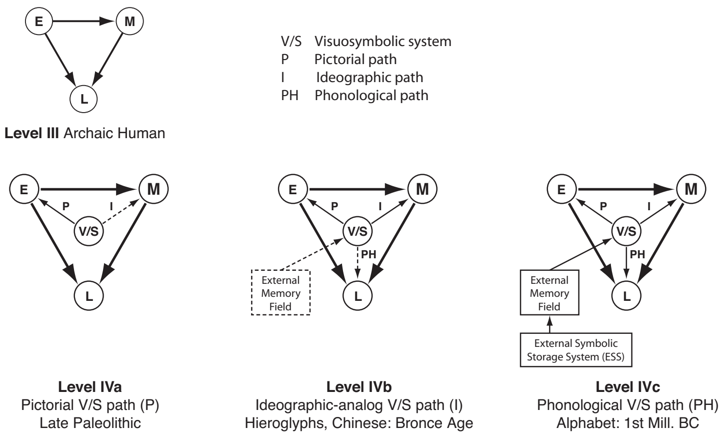

Figure 1: The development of mimesis, spoken language, and literacy as forms of representation (modeling) of an older form of understanding with the help of new tools. According to Donald (1991, p. 305).

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.

2.2 COGNITIVE TOOLS: DEVELOPMENT OF A YOUNG HUMAN

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. He is very 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[2] 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 oppositions 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 3).

Romantic understanding (Egan, 1990, Table 2) emerges with early literacy and develops together with a special and hightened sense of reality which is still absent from mythic culture. Children between the ages of 8 and 15 become interested in "the world out there" and begin to collect detailed knowledge of things that can be found—particularly extreme and wondrous things. Elements of literacy such as list making, maps, diagrams, and flowcharts help in keeping track of the of the bewildering diversity of reality (see also Ong, 1882; McLuhan, 1962, 1964; on the role of media—from print to film to the internet).

Table 2 Cognitive tools (K. Egan, 2005)

Mythic Thinking	Romantic Thinking	Philosophic Thinking
Story	The sense of reality	The sense of abstract reality
Metaphor	Extremes of experience and limits of reality	The sense of agency (causality)
Binary opposites (polarities)	Association with heroes	Grasp of general ideas and their anomalies
Rhyme, rhythm, and patterns	The sense of wonder	Search for authority and truth
Jokes and humor	Collections and hobbies	Meta-narrative understanding
Mental imagery	Knowledge and human meaning	
Gossip	Narrative understanding	
Play	Capacities for revolt and idealism	
Mystery	Changing the topic and the viewpoint	
	The literate eye (forms, lists, flowcharts, diagrams, maps…)	

2. 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.

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 (Table 2, Egan, 2005), and he provides examples for how to develop these tools. 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 1, and Donald, 1991).

Egan has not added all that much beyond general statements to the last phase of the development of cognitive tools—*philosophic* thought—at least not for science. I would turn to philosophers such as John Dewey (Section 2.3) and to modern models of scientific methods (Fig.2, Fuchs, 2002, and 2007, Section 3) to expand on how to develop what I call *formal* thought.

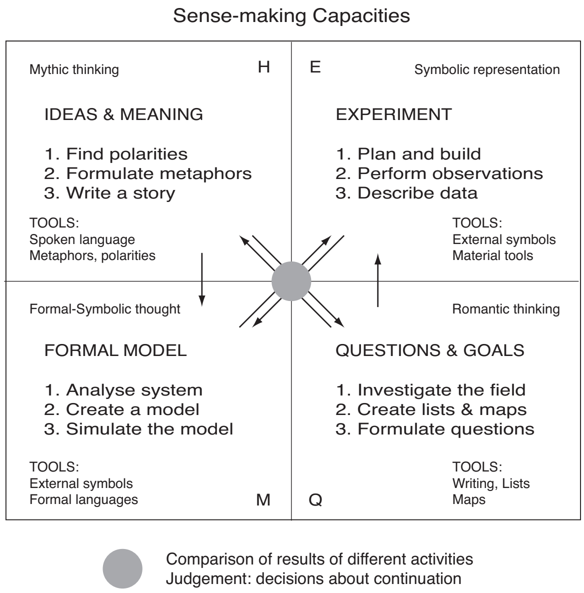

Figure 2: The Four-Cycle (Fuchs, 2007) as an integrated model of scientific practice and thought. It adds Egan's (1988, 1990, 2005) elaboration of mythic and romantic sense-making capacities to a double-cycle representation of scientific methods and technical design.

2.3 PHILOSOPHY OF THE HUMAN MIND

Philosophy of mind pervades the work of many if not most philosophers. Here, I am interested in one particular philosopher whose basis of analysis is an evolutionary view of human nature. Even though he did not have access to the detailed investigations of later researchers such as

Donald (1991) and Egan (1997), John Dewey provides a philosophy of mind that is most useful as an underpinning of these modern developments. In his *Experience and Nature* (1925), as in the earlier *How We Think* (1910) and *Democracy and Education* (1916), he describes a view of the human mind that is most closely aligned with recent advances in cognitive science in general and cognitive linguistics in particular (see Section 3). His notions of *experience* and *inquiry* are very important for our current view of how meaning arises in humans through their interaction with their physical and social environments (Fig.3).

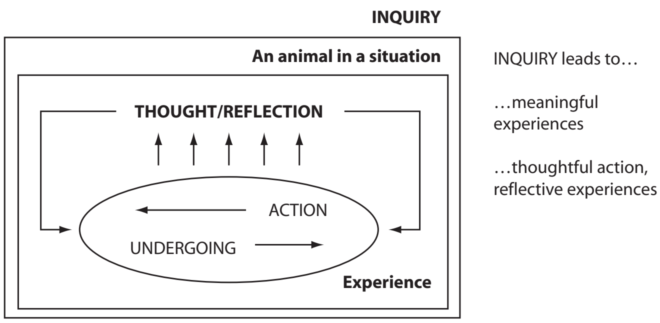

Figure 3: "The nature of experience can be understood only by noting that it includes an active and a passive element peculiarly combined. […] When an activity is continued into the undergoing of consequences, when the change made by action is reflected back into a change made in us, the mere flux is loaded with significance. We learn something." (Dewey, 1916, Chapter 11, p. 139)

3 STRUCTURE OF FIGURATIVE THOUGHT IN SCIENCE

Cognitive linguistics (CL) has added much to our current view of the human mind. In recent years, CL has been expanded greatly and a vast literature on linguistic phenomena and theories has been created. Here, I can only scratch the surface of this exciting new field of research and explain how it contributes to my understanding of the roots of the conceptualization found in macroscopic theories of nature (especially in continuum physics and the physics and chemistry of uniform dynamical systems). I will briefly explain elements of CL and then turn to my theory of Force Dynamic Gestalts (Section 3.3) and how it applies to physics (Section 3.4).

3.1 CONCEPTUAL METAPHOR

The main results of CL support the view that language and the human mind operate figuratively rather than literally, i.e., they make use of structures of embodied imagination (Johnson, 1987).

Expressed still differently, we believe that human understanding does not take the form of truth conditional propositions.

Consider the examples of metaphoric linguistic expressions given in Table 3 (column on the right). These concrete sentences are examples of expressions which testify to the existence of a structure of thought—a metaphor. So, for example, the sentence "We've covered a lot of ground" is a linguistic member of the metaphor ARGUMENT IS A JOURNEY which can be put into the class of structural conceptual metaphors. Note that a conceptual metaphor is typically part of conventional language and as such it is unconscious—we are not aware that the expressions are part of a deeper understanding.

Table 3 Examples of conceptual metaphors

CLASS	METAPHOR	Linguistic metaphoric expression
ORIENTATIONAL	MORE IS UP	The number of books printed each year keeps going up
	SIMILARITY IS CLOSENESS	These colors aren't quite the same, but they're close
	STATES ARE LOCATIONS	I'm close to being ill, and a little more will send me over the edge
ONTOLOGICAL	PURPOSES ARE DESIRED OBJECTS	I saw an opportunity for success and grabbed it
	CATEGORIES ARE CONTAINERS	Are tomatoes in the fruit or vegetable category?
	MONEY IS A SUBSTANCE	Put money into your account!
STRUCTURAL	LIFE IS A JOURNEY	Two roads diverged in a wood, and I — I took the one less travelled by, and that has made all the difference (R. Frost)
	ARGUMENT IS A JOURNEY	We've covered a lot of ground
	ARGUMENT IS WAR	I defended my argument
	IDEAS ARE FOOD	I cannot digest all these facts

Researchers in cognitive linguistics have identified many conceptual metaphors which can be classified in different ways. Some of the common categories are *orientational*, *ontological*, and *structural* metaphors listed in Table 3, and *basic* metaphors not listed here. Some of the structural metaphors may be examples of conceptualizations of rich experiential gestalts such as the Force Dynamic Gestalts which I will identify in Section 3.3. For some of the extensive literature on the subject see Lakoff and Johnson (1980, 1999), Lakoff and Nunez (2000), Grady (1997, 2005), and Kövecses (2002).

Metaphor, as understood in CL, is one of the most important and prominent elements of figurative thought and language that demonstrates the main tenets of CL referred to in the previous paragraphs. A conceptual metaphor is a structure of understanding where knowledge of a *source domain* (often a less complex or abstract domain) is *projected* onto a *target domain* (often a more complex or abstract domain), see Fig.4.

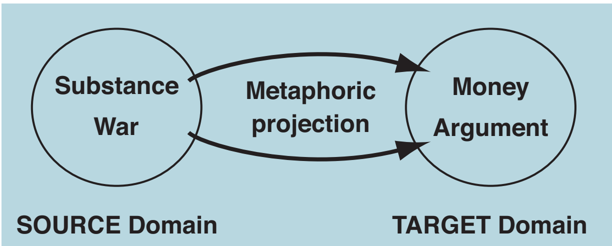

Figure 4: A metaphor projects understanding or knowledge of a source domain onto a target domain (example: substance to money).

The view of metaphor in CL contrasts sharply with traditional theories of metaphor (Table 4). Traditionally, metaphor has been considered a purely linguistic (surface) phenomenon rather than evidence of structures of human thought.

Table 4 **A comparison of traditional and CL views on metaphor (Kövecses, 2002)**

Traditional View	Conceptual Metaphor Theory
Metaphor is a property of words, a linguistic phenomenon	Metaphorisapropertyofconcepts
Metaphor is used for artistic or rhetorical purpose	The function of metaphor is to better understand certain concepts
Metaphor is based on a similarity between two entities that are compared	Metaphor is often NOT based on similarity; it creates similarity
Metaphor is a conscious and deliberate use of words; you need a special talent for metaphor	Metaphor is largely unconscious; it is used effortlessly in everyday life by ordinary people
Metaphor is a figure of speech that we can do without; we us it for special effects; it is not a part of human thought and reasoning	Metaphor is an inevitable process of human thought and reasoning

3.2 IMAGE SCHEMAS

Some of the source domains for metaphors are complex, others seem to be much more basic (see Table 3). Among the latter are up/down (verticality), closeness, location, object/substance, and container. These are examples of what Johnson (1987) calls *image schemas* (see Table 5 for some examples). Image schemas are perceptual gestalts that develop in a human through recurrent experiences. They have enough internal structure to serve as bases of reasoning. Such schemas are applied by metaphoric projection (the image schema is the source domain).

Table 5 Examples of image schemas

Polarity	light-dark, warm-cold, female-male, good-bad, just-unjust, slow-fast
Space	up-down, front-back, left-right, near-far, center-periphery, contact, path
Process	process, state, cycle
Container	containment, in-out, surface, full-empty, content
Force / Causation	balance, counterforce, compulsion, restraint, enablement, blockage, diversion, attraction, manipulation
Unity / Multiplicity	merging, collecting, splitting, iteration, part-whole, mass-count, link
Identity	matching, superimposition
Existence	removal, bounded space, object, (fluid) substance

Image schemas are subject to intensive research and debate (see Hampe, 2005). The development of such schemas in an individual casts some additional light on the question of the ontogenesis of the human mind (Section 2.2). For example, Mandler (2004, 2005) uses the notion of image schemas in her account of the cognitive development of a child and shows how babies that are just a few months old develop concepts. It is conjectured that the processes identified in pre-lingual development are also the ones that lead to the development of language in an individual.

This research makes it plausible that the figurative structures of (spoken) language are the cognitive tools of mythic understanding (Section 2.2). Some of the image schemas have been identified as basic mythic structures (polarities, substance, dynamics…; recall the brief discussion of Egyptian and Babylonian cosmologies in Footnote 2). Now we can understand the relationship between modern cognitive linguistics and Egan's theory of cognitive development.

3.3 RICH EXPERIENTIAL GESTALTS

Lakoff and Johnson (1980) give an account of a rich (multi-faceted) experiential gestalt, namely that of direct manipulation (Chapter 14). This gestalt may be considered the source of our understanding of causation. It is too rich or complex to be a simple image schema—it actually contains several schemas. It is partially emergent and partially metaphoric.

Motivated by my research into and development of the physics of uniform dynamical systems (Fuchs, 1996), I have recently identified a structure of experience which I call a *Force Dynamic Gestalt* (Fuchs, 2007). It appears that we use FDGs—along with other structures—to conceptualize complex phenomena such as justice, pain, love, heat, etc. Simply stated, FDGs are gestalts having three main aspects, those of quantity, quality, and power. Consider, for example, how we speak about justice. We clearly treat the phenomenon as a quantity ("Give me justice"), quality or intensity ("The quality of justice in capital cases"), and power ("The healing power of justice").[3] Interestingly, the aspects listed here make use of the directly emergent schemas of substance and scale, and of the concept of causation which itself forms a cluster of components.[4]

3.4 THE STRUCTURE OF CARNOT'S THERMODYNAMICS AND THE PHYSICS OF UNIFORM DYNAMICAL SYSTEMS

I claim that our conceptualization of basic physical phenomena such as fluids, heat, electricity, or motion makes use of FDGs. Alex's story (Section 1) is a beautiful example of this. Cold as a snowman has quantity (size), intensity (coldness or degree of cold), and power (it can make the boy sick). A second example is furnished by the classic description of experiments performed by members of the Accademia del Cimento (Fuchs, 2006b). According to Wiser and Carey (1983), the experimenters conceptualized heat and cold as having three aspects: *substance* (particles), *quality* (hotness), and *force*.

The most important historical example for me is the thermodynamics of Sadi Carnot (1824). It not only shows the use of an FDG, it also demonstrates how the aspects can be distinguished or differentiated, and how the concept behind the experiential gestalt can be formalized in a

3. There are many more components or aspects of the gestalt of justice. Just consider schemas such as balance and equilibrium, enabling and resistance which, according to Table 5, can be considered elements of the class force/causation.

4. Mark Johnson (2007) analyzes music from the viewpoint of figurative structures. He comes up with a result that is very similar to my Force Dynamic Gestalts. He identifies three main metaphoric projections that underlie our embodied understanding of music: (1) music as a moving object, (2) music as a landscape in which we move, (3) music as a force. The first corresponds to the aspect of substance, the second to intensity (we move up and down, back and forth, in the musical landscape), and the third to power or force.

simple manner. For Carnot, a particular analogy which is created as a consequence of the structure of thought outlined here (see Section 3.5), was instrumental in visualizing heat, its intensity, and its power. Here is how he put it:

> *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.*

Here, the differentiation of the aspects of the FDG is complete and its formalization is at our fingertips. Heat is a fluidlike quantity for which we can express a law of balance, and temperature is the thermal potential. The power of heat is simply equal to the product of the current of heat flowing from a hot place to a cold place and the difference of temperatures between hot and cold (Fig.5).

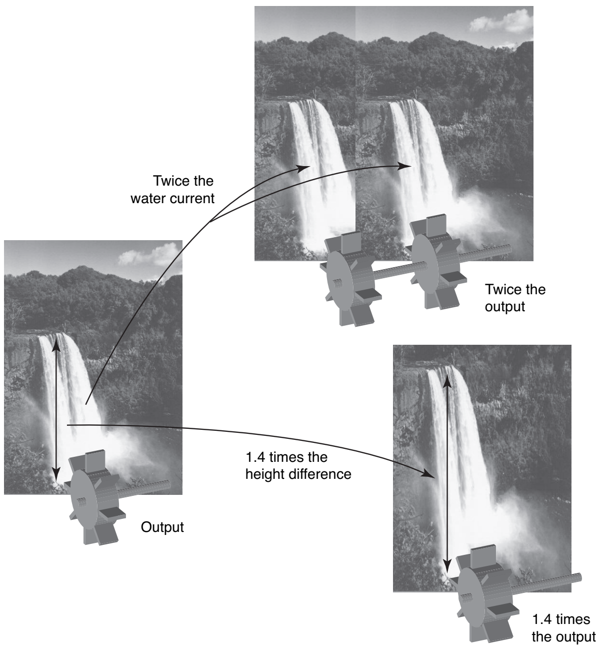

Figure 5: Power of a waterfall. The power is proportional to the flow of water and to the height through which the water falls. This image can be transferred to all physical processes.

A theory of the dynamics of heat (as a part of the physics of uniform dynamical systems) can be constructed upon this conceptualization (Fuchs, 1996). Physics courses that build on this image have been created for middle school, high school, and university (Herrmann, 1989-1999; Borer et al., 2005).

3.5 IMAGE SCHEMAS, METAPHOR, AND ANALOGY

Carnot makes use of analogical reasoning. Analogy between force-dynamic gestalts can be introduced 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.6). 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.

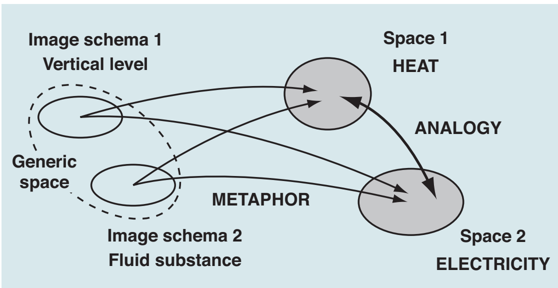

Figure 6: Two phenomena such as heat and electricity acquire similar structure due to our projection of the same schemas upon each domain or space. This allows us to map elements and structure between the spaces of the phenomena. Note that, in general, the mapping is bi-directional. We can understand thermal phenomena in terms of electric ones, and vice-versa.

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.[5]

5. Naturally, there are differences—analogies are not complete. 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.

Analogy is a major force in learning and it is a strong foundation of the physics of uniform dynamical systems which itself is a subset of modern continuum physics. Analogy can be made used of in a much wider sense than is typically assumed.[6]

4 CONSEQUENCES OF IMAGINATION IN SCIENCE

Clearly, modern macroscopic physics makes use of concepts that are of mythic origin and are present in every human's natural language (and as such, according to cognitive linguistics, they are present in our thought and understanding). These are powerful structures of imagination[7] that obviously helped form physics. The question is, do they also help in *learning* of a science?

If we take what we have heard in this talk seriously, a fairly straightforward picture emerges for how we can help children and adolescents develop a sense of science. I believe we should clearly follow Egan's lead and make every effort to develop an individual's imagination through mythic and romantic phases before we start with a formal science in the classroom.

Alex' story of snowmen and dragons (Section 1) tells us where to start. We should let young children, from kindergarten on, develop their capacity of storytelling and encourage them to make increasing and conscious use of the elements of FDGs. As a child gets older, maybe already before the onset of the romantic phase, we can slowly help him or her to become aware of the difference between quantity and quality, or intensity and power.[8] Without this, a deeper understanding of natural and other phenomena will not become possible.

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 strengthened and followed by a phase of "collecting information about reality," a phase where information gathering and organization in-

6. As with metaphor, analogy is often assumed to be a "wrong" mode of thinking—what we assume in analogy is not "really so." This misjudges human thinking in general and metaphor and analogy in particular.

7. Interestingly, imagination itself is structured as an FDG. There is more or less imagination, imagination can be strong or weak (of high or low quality), and it obviously can be powerful.

8. In Fuchs (2007), 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. Quantity and intensity are related through the metaphor MORE IS UP, and quantity, intensity and power are related as we can clearly see in Carnot's reasoning (Fig.5). 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.

creases students' detailed knowledge of the physical world (Egan, 1990)—without leading to formally structured theories of phenomena. To what extent knowledge of the process of science (American Association for the Advancement of Science, 2000) should already be included during this phase, must be studied carefully. At this point, my feeling is that we should wait with this until the formal phase of education.[9] This is not to say that we should not use the process of inquiry (see Dewey, Section 2.3) in earlier education. I simply doubt that it can already lead to a conscious understanding of the process of science.

5 BEYOND FORMALIZING MYTHIC THOUGHT

Force Dynamic Gestalts (FDGs) are clearly the roots of macroscopic physics. To the extent that the concepts of (classical) macroscopic physics also serve as the foundation of our understanding of quantum and statistical physics, we may claim that they are of truly general importance.

However, as anybody who has gone through some physics education or who follows today's discussion of science knows, the conceptualization in public discourse and in much of the science community, seems to be different. Our current view of nature seems to require us to see the world as a vast mechanism in which the motion of little particles causes all phenomena. This is particularly evident in thermal physics where heat is commonly understood as the result of the random motion of countless little particles.[10,11]

It is easy to show that this world-view does not really work in the extreme form presented above. If we want to make use of the kinetic theory of gases to introduce a relation between the energy of random motion of particles and temperature, we need to already know what temperature is.[12] There is simply no way around grounding our knowledge of nature in our embodied

9. In this talk, I am not really saying much about formal science and how to teach it. My claim that an informal science can be created and taught that fits seamlessly with the formal side requires that the typical teaching of science late in high school be reformed as well. My confidence in the validity of my claim rests with practical experience in this reformed formal science teaching in high school and university. I am referring to the physics of uniform dynamical systems (Fuchs, 1996, 2010) and its didactic elaboration (Herrmann, 1989-1999; Borer et al., 2005; Job and Herrmann, 2006; Fuchs, 2006c; Hestenes, 2006; D'Anna, Fuchs, and Lubini, 2008; Fuchs, Ecoffey, Schütz, 2001-2009).

10. It is common to "explain" temperature as (a measure of) the energy of random motion of particles in a substance, or heat as resulting from irregular motion of particles: "Dazu kommt noch, dass in neuerer Zeit immer noch mehr Thatsachen bekannt werden, dass die Wärme nicht ein Stoff sei, sondern in einer Bewegung der kleinsten Theile der Körper bestehe." R. Clausius (1850, pp. 369-370).

11. There is an old form of a particle "concept" in thermal physics which, however, is not the concept of today's thermodynamics. The experimenters of the Accademia del Cimento spoke of "fire particles." Here, heat itself has a grainy structure. These "grains" are not the material particles whose motion is equated with heat.

imaginative understanding of which the aspects of the FDGs are the main constituents.

There remains, however, the question of whether or not modern quantum physics and statistical mechanics add fundamentally new concepts that go beyond a mere formalization of the mythic basis of scientific thought. I cannot yet answer this question since I have not investigated the conceptual basis of 20th century science from the perspective of modern cognitive science. However, it seems to me that there may be two concepts that are commonly associated with modern philosophic or theoretic thought, namely, particles and chance or randomness.

At least in the form in which it was created by the Greek atomists, the doctrine of particles has much to do with the modern concept of individuality or self. The discovery of the self is typically associated with post-mythic literate culture and is an element of the desire for ultimate (absolute) or transcendental reality. The atom as the final indivisible building block of matter fits this desire.[13]

As to randomness, I do not know much about its origins and its cognitive status. It remains to be seen what the fundamental conceptualizations of 20th century physics actually are. There is no doubt, however, that these conceptualizations are as figurative and embodied as those of the older macroscopic physics.

In summary, much remains to be done if we really want to understand how we understand nature, and if we want to transform this knowledge into a consistent, encompassing, efficient, and humane pedagogy of modern science.

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12. A kinetic theory of gases uses mechanical concepts to derive relations between momentum, speed, or pressure and volume, and energy of that gas. We need the equation of state of the gas to relate pressure and volume to temperature. Since an equation of state presupposes the concept of temperature—it does not define temperature—we obviously need to know beforehand what we mean by temperature.

13. Another aspect of this modern form of explaining the world is the replacement of polarities by dualities or dichotomies of which heaven and earth, body and mind, matter and spirit, emotion and reason, are just the most prominent. The gods of mythic cultures were banned from nature into a realm beyond our world.

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