Conceptual Metaphor in Physics Education: Roots of Analogy, Visual Metaphors, and a Primary Physics Course for Student Teachers

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Abstract

We show in what sense macroscopic physical science is a product of figurative (imaginative) structures of the human mind. Conceptual structure in physics is perception based and schematic and uses metaphoric, analogical, and narrative forms to extend direct perception and conception to cases of less directly accessible phenomena. For instance, a theory of the dynamics of heat can be rendered in a form analogous to that of fluids or electricity.

We show how tools using visual forms of metaphors employed in macroscopic physical science can be designed and applied, and we briefly outline one application of the principles discussed here: a novel course for kindergarten and primary school student teachers.

Keywords: Embodied cognition, metaphor, analogy, forces of nature.

1. Introduction

Human thought is figurative—we make use of embodied imaginative structures such as metaphor, analogy, and narrative when we conceptualize experience (Johnson, 1987; Lakoff and Johnson, 1980, 1999; Fauconnier and Turner, 2002; Fillmore, 2006; Amin et al., 2015; Bruner, 1990; Herman, 2013). It stands to reason that this is true also when we create, do, or learn science (Fuchs, 2006; Hestenes, 2006; Amin, 2009; Fuchs, 2015; Corni, Fuchs, and Savino, 2017).

In this paper, we show how and in what form imaginative structures appear in theories of macroscopic physical and chemical systems and processes, i.e., in continuum physics (Fuchs, 2010 [1996]; see Section 2). Briefly stated, a perceptual unit (gestalt) called *gestalt of force* is structured metaphorically and narratively (Fuchs, 2015). Forces have aspects of *quantity* (size or amount), *quality* (intensity), and *power*—these aspects are rendered intelligible to the human mind by metaphorically projecting abstract schemas that form early in life through the interaction of an organism with his or her physical, social, and psychological environments. There are schemas for the intensive aspect of a phenomenon (vertical level, vertical position in a landscape, tension as level difference), for amount (fluidlike quantity, container, in-out, path…), and for power (agency, causation, direct manipulation…).

Using blending (conceptual integration) theory (Fauconnier and Turner, 2002), we can demonstrate particular processes of conceptualization whereby different fields of experience (different forces of nature such as fluids, electricity, heat, substances, motion…) are structured with the help of the same types of metaphors leading one to see these phenomena as (structurally) similar. This structural similarity is then the source of analogy between the various fields.

For purposes of analysis of and learning about macroscopic physical dynamical systems, graphical tools have been developed that employ visual representations of the metaphors found in physics (Fuchs, 2010 [1996]; see Section 3). Such process diagrams visualize the roles of fluidlike quantities, levels and tensions, and power (the latter concept leads to and is elaborated in terms of the energy principle). Using and combining visual representations of metaphoric structures, we can create process diagrams for (chains of) natural and technical elements and devices and the processes they admit. (An example for a chain would be a solar photovoltaic system for some use in a home.)

A second form of visual tool discussed in Section 3 are so-called system dynamics computer modeling programs. They make use of a somewhat restricted set of visual metaphors but have the undeniable advantage of allowing us to easily create mathematical computer models for rather complex dynamical systems.

The authors have applied the model of conceptualization outlined here for various forms of science education. We use metaphor and narrative to design stories of forces of nature for small children (and teach student teachers how to write such stories); we use the power of analogy to create a novel physics course for student teachers; and we teach engineering students who are learning to create dynamical models of sophisticated technical and organizational systems. In Section 4, we shall outline the course created for kindergarten and primary school teachers at the University of Modena and Reggio Emilia.

We conclude the paper with a short summary (Section 5) where we discuss possible consequences of the model of embodied imaginative structures in macroscopic physical science for physics (and science) education.

2. Roots and Forms of Analogy in Macroscopic Physics

When we interact with macroscopic physical processes, we perceive a perceptual unit called *force of nature* (Fuchs, 2006, 2011) for whose conception we employ the tools of imagination. Put differently, we represent our imagination rather than natural processes directly (Hestenes, 2006; Fuchs, 2006). As we shall see, this means that analogy is not built upon an objectively “given” similarity between different types of natural processes but is, rather, resulting from constructions of the mind.

Tools of imagination upon which our rationality is built are, chiefly, metaphor (Lakoff and Johnson, 1980, 1999) and narrative (Herman, 2012; Fuchs, 2015). Our conceptual system is structured with the help of image schemas (Johnson, 1987), domains (Langacker, 1987), frames (Fillmore, 2006), and mental spaces (Fauconnier, 1994). Metaphors, in particular, create the same schematic structures for new concepts by projecting knowledge and relations from one domain to another (Koevecses, 2017).

It has been shown how concepts of macroscopic physics are constructed metaphorically (Fuchs, 2006, 2010, 2013; Corni et al., 2017). An important element of the analysis concerns what we call forces of nature; in macroscopic physical theories, these include fluids, electricity (and magnetism), heat, chemical substances, linear and rotational motion, and gravity. A particular force of nature is a perceptual unit (gestalt) that is analyzed in terms of three main aspects—those of *quality* or intensity, size or *quantity*, and *power* (Fuchs, 2006, 2011). These aspects are elaborated by image schematic structures and frames that are constructed metaphorically from image schemas and basic frames that give us our understanding of these conceptual units in the first place (Koevecses, 2017).

Using blending theory (conceptual integration theory, Fauconier and Turner, 2002), we can show how our understanding of a domain such as *heat* arises from imaginative processes

(Fig. 1). We assume that perception of phenomena involving fluids leads, first, to the construction of a space (*input space* FLUIDS), and then, through abstraction driven by image schemas formed from sensorimotor engagement of our organism with the environment, and by narrative practice, to the creation of a *generic space* containing abstract knowledge of fluid behavior. For our understanding of forces of nature, these are vertical level and level differences (tensions); fluid substance; and agentive power, among others.

We also build a space for our perceptual experience of thermal phenomena (*input space* HEAT). This space is structured metaphorically by projecting schemas present in the generic space. For example, temperature becomes a "vertical" quantity, heat flows or accumulates, heat is powerful like water, etc. On the other hand, it also feeds back upon the generic space—after all, direct experience of thermal phenomena is not at a different level compared to perception of fluid behavior. In other words, abstractions generated by perception of both fluids and heat come together in the generic space. (There is a perceptual element in heat that is not present in water—heat can be produced.)

All of this lets the input spaces for FLUIDS and HEAT appear similar to our mind's eye—they become analogous much in the sense explained by Gentner in her model of *structure mapping* (Gentner, 1983; Gentner and Markman, 1997). Finally, our mind *blends* the two input spaces and a new *blended space* emerges where heat becomes a fluid quantity that behaves much like water.

We can repeat the analysis for perception of other forces of nature and realize that all of them are structured in very much the same way. Certainly, there will be some differences as already remarked in the case of production of heat. In summary, it appears that we can apply similar conceptualizations to the various branches of macroscopic physics.

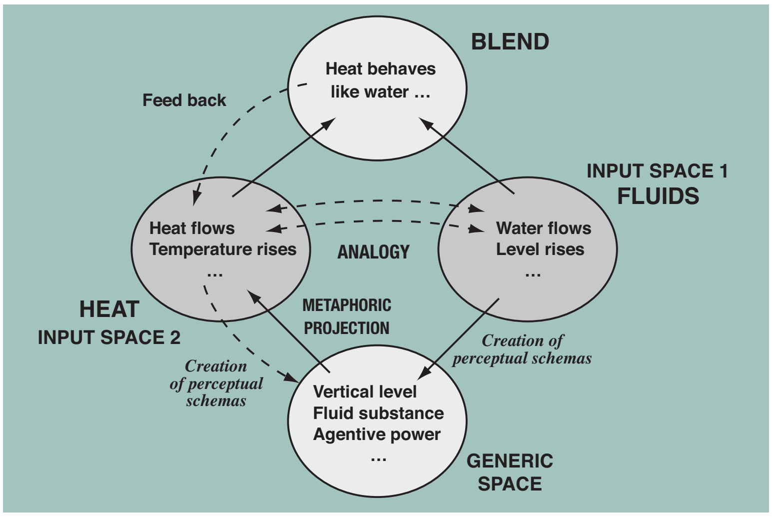


Figure 1. *Blending (conceptual integration) of mental spaces of fluids and heat leading to metaphoric structuring of the domain of heat. The same mechanism applies to other macroscopic physical phenomena (i.e. forces of nature) that makes all of them similar in our perception.*

This is borne out by the structure of continuum physics (Fuchs, 2010, 2013c). Every field (chemistry, heat, electricity, motion…) admits a *fluidlike quantity* x (amount of substance, entropy, charge, momentum…) or an associated *potential* φ_x (chemical potential, temperature, electric potential, velocity…). A fluidlike quantity can be thought of as residing in space (admitting a density ρ_x), being able to flow down the gradient of its own potential (admitting a conductive current density $j_{x,cond}$) or being transported by a fluid (admitting a convective current density $j_{x,conv}$), and possibly being transported by radiation (represented by a source rate density σ_x). Some of these quantities are conserved, others are not, a circumstance we describe by production rate densities (π_x) being zero, strictly positive, or positive and negative. In summary, these fluidlike quantities are subject to expressions of balance that exhibit features of strong analogy (Fig. 2).

$$
\begin{aligned}
&\frac{\partial \rho_n}{\partial t} + \frac{\partial}{\partial x}\left(j_{n,cond} + j_{n,conv}\right) = 0 + \pi_n \\
&\frac{\partial \rho_S}{\partial t} + \frac{\partial}{\partial x}\left(j_{S,cond} + j_{S,conv}\right) = \sigma_S + \pi_S \\
&\frac{\partial \rho_p}{\partial t} + \frac{\partial}{\partial x}\left(j_{p,cond} + j_{p,conv}\right) = \sigma_p + 0
\end{aligned}
$$

***Figure 2.** Analogy between the domains of (chemical) substance, heat, and momentum at the level of laws of balance (single-dimensional equations used in continuum theories). Note that $\pi_n \lesseqgtr 0$, whereas $\pi_S \geq 0$. All balance equations have been formulated for the single-dimensional case only.*

Furthermore, all of these forces of nature are characterized in terms of *power*—they are more or less powerful which is to say they can *make energy available* at a certain rate that can be *used* ("picked up") by follow up processes (i.e., processes that are driven by the phenomenon that makes energy available; these points will be elaborated upon when we describe the introduction of visual metaphors for physical processes in Section 3 below; see also Fuchs, 2010). The density of the rate at which energy is made available or used is calculated in exactly the same manner for the different phenomena covered by macroscopic physics, namely, as the product of current density of gradient of potential.

The following observations are important when discussing the issues of metaphor and analogy in physical science. First, the forgoing analysis clearly shows the difference between metaphor and analogy; they are simply not the same mental processes. Second, the domain of HEAT is not metaphorically structured in terms of our knowledge of fluids (theory of fluids, hydraulics, etc. Both FLUIDS and HEAT are domains of direct perceptual knowledge. Rather, metaphors for HEAT are the result of projections of structure found in the generic space which is the result of massive processes of abstraction from direct experience. In other words, relating a theory of heat directly to our knowledge of a theory of fluids is the business of analogy.

3. Visual Metaphors for Physical Processes

In the previous section, we have outlined the general conceptual structure of macroscopic physics based upon a model of imaginative tools and structures. Here, we show how the imaginative interpretation of physical processes can be represented in terms of visual metaphors, i.e., visual symbols and constructs that parallel the metaphors identified in cognitive linguistics.

The schematic elements needed reflect the properties of fluidlike quantities (storage, transport, production), their related potentials and tensions, and their combined effect upon the power of processes and energy quantities related to them (Fuchs, 2010).

The fluidlike quantities are not directly represented, but their properties are. We need a symbol for the container image schema for representing containment, lines and arrows for the path schema representing transports, and a source (or sink) symbol for the schema of production (see Fig. 3, right). Potentials are represented as levels and potential differences are represented by two related level symbols indicating (positive or negative) level differences.

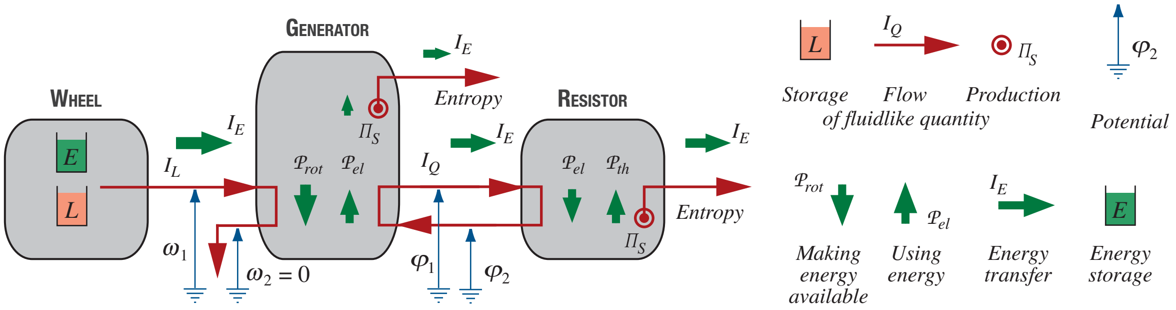


Figure 3. *Process diagram of electrically breaking a flywheel (excluding mechanical friction): The flywheel drives a generator to which a resistor is connected. Elements of visual metaphors are listed on the right.*

Finally, and quite importantly, we need to come up with visual metaphors that represent the properties and activities of energy in physical processes. Energy (1) can be made available and used (when fluidlike quantities flow from higher to lower or lower to higher potentials), (2) can flow, (3) can be stored, and (4) is conserved (which means there are no sources or sinks related to energy quantities). Note that we do not have an item for energy “conversion”—there is no need for this type of imagery if processes are represented to their full extent including fluidlike quantities and potentials and not just energy quantities.

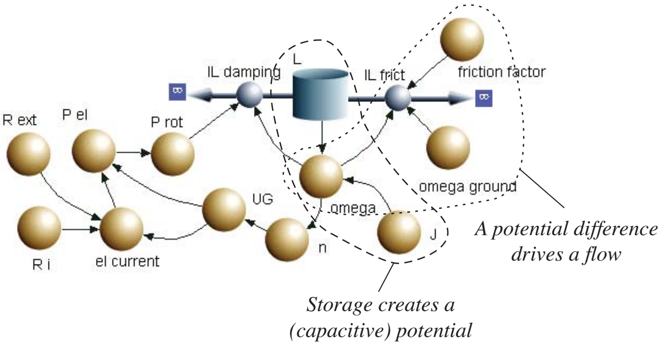
Representations of energy transfer (item 2) are well known from engineering. One usually applies arrow like symbols, often of varying thickness to indicate relative strengths of energy currents. We continue this tradition here. However, there will never be energy flow arrows by themselves—“pure energy” flowing by itself does not exist; there is always a fluidlike quantity we can visualize as “carrying” the energy along (see also Falk et al., 1983).

The concept of *availability* is known from and well appreciated in modern (engineering) thermodynamics (Corning and Kline, 1998; Fuchs, 2010). Making energy available and using it (item 1) may be the first instance of conceptualizing what, in the formal sciences, becomes the concept of energy—it represents, in an important embodied perceptual way, our sense of agency and causation. In macroscopic phenomena, energy explains the coupling of processes.

For this reason we emphasize how important a visual metaphoric symbol will be (Fuchs, 2010 [1996]): we have created this in the form of fat energy arrows inside system elements in process diagrams (see the boxes representing the generator and resistor, respectively, in Fig. 3). Such arrows point down when energy is made available by the fall of a fluidlike quantity (energy is “offloaded”) and up if energy is used for pumping (energy is “uploaded” to the fluidlike quantity that is visualized as an energy carrier).

Storage of energy (item 3) is symbolized analogously to storage of fluidlike quantities—we introduce a container image schema. Balance of energy including conservation (item 4) then follows from (2) and (3). Prepared in this manner, we can create process diagrams of single or multiple interconnected elements (see Fig. 3 on the left) by assembling the various visual elements described. In general terms, process diagrams like the one in Fig. 3 are representations of dynamical systems (as long as they contain storage elements; otherwise, they reflect steady-state processes).

There exists a class of computer programs for modeling of dynamical systems that let users create flowcharts (model diagrams) as an intermediate step between mental and mathematical modeling (see Fig. 4).



A potential difference drives a flow

Storage creates a (capacitive) potential

Figure 4. *Diagram of dynamical model of electrically breaking a flywheel (flowchart created in the program BerkeleyMadonna; www.berkeleymadonna.com): The flywheel drives a generator to which a resistor is connected. Mechanical friction is included. Note how the energy principle is used on the left of the flowchart in order to calculate the feedback between resistor and generator. Symbols: L: angular momentum, IL: angular momentum current, J: moment of inertia (i.e., the angular momentum capacitance), P: power, R: resistance, n: revolutions per time, UG: generator voltage.*

These flowcharts apply a slightly different form of visual metaphoric representation than the one developed for process diagrams. However, they also make use of container–flow symbolism to express laws of balance of fluidlike quantities or energy (see the construct consisting of a reservoir and flow symbols). They also let the modeler express potentials created by storage and potential differences that drive the flows (or, expressed more generally, drive the processes responsible for changing the amount of a fluidlike quantity stored in a reservoir). However, these latter visual constructs are probably less suggestive than their counterparts in process diagrams—we should wish for software that turns process diagrams into dynamical models in mathematical form.

4. An Innovative Primary Physics Course for Student Teachers

As mentioned before, the approach to macroscopic physical science described above has been applied to a number of different courses and learning environments at various levels of formal sophistication. It allows us to create stories of forces of nature suitable to small children (Fuchs, 2013a,b); we have created a narratively driven approach to mechanics in an Industrial Educational Laboratory at Ducati in Bologna, Italy (Corni, Fuchs, Savino, 2017); it provides the foundation for an introductory course on dynamical systems and systems science in physical and technical fields (Fuchs, 2010 [1996]); and it has given us the motivation and rationale for an innovation for student teachers—this course will be described now (Corni and Fuchs, 2017).

Over the last five years, the theoretical foundations outlined in the previous sections have been used to develop a physics course for student teachers for kindergarten and primary school levels in Reggio Emilia. There are two reasons that make this approach particularly suitable to their needs: their academic science background is usually quite weak, and they need to learn how to understand nature in a way that will prove useful for their future work as teachers of young children. They need to be able to connect everyday (embodied) experience to their learning and, consequently to their own teaching.

The course is taught in the third year of the Master Degree in Primary Education. It is made up of 56 hours of lectures, plus 16 hours of laboratory activities, and a final examination.

The topics dealt with in the lectures include philosophical (2 hours), linguistic (4 hours), methodological (6 hours), as well as disciplinary (44 hours) aspects. Specifically, philosophy introduces the theory of the embodied mind (see, in particular, Johnson, 1987); linguistics is concerned with conceptual metaphor and narrative (Lakoff and Johnson, 1980, 1999; Corni, 2013); methodology concentrates upon cognitive tools (Egan, 1997); and disciplinary aspects encompass the physics of dynamical systems (Fuchs, 2010). System dynamics computer modeling and process diagrams (Section 3) are used to formalize the narrative treatment of the contents (Corni, Fuchs, Savino, 2017). In the final lectures, stories of forces of nature are introduced so that students learn to create, analyze, and use them with their future students (Corni, 2013). A laboratory part is taught after the lectures are over. It provides experiential and embodied activities related to the themes of the lectures allowing the students to be actively involved in small projects.

To exemplify how the (philosophical and disciplinary) theoretical framework outlined above can be actually employed, we will describe a course section about the analogical treatment of water, electricity, and entropy.

Fluids, electricity, heat, gravity, linear and rotational motion are treated as *forces of nature* (see Section 2). Each force has its own *extensive quantity* (volume, electric charge, entropy, gravitational mass, momentum, or angular momentum, respectively), which accumulates in materials and bodies (schema: container). A quantity travels (schema: following a path) driven by a negative difference of *intensity or potential* (pressure, electric potential, temperature, gravitational potential, velocity, angular speed, respectively; schema: polarity and verticality), or is carried by matter (convective transfer; note the container schema), or is conveyed by fields (radiation; schema: radiation, such as light, is a container).

The scientific concept of *capacitance* relates to the way the potential goes up when the extensive quantity accumulates inside a container. *Resistance* (one of the force dynamic schemas; see Talmy, 2000a,b) relates to the way in which the potential difference leads a certain flow. Table 1 summarizes the forces of nature treated in this course and the corresponding basic quantities, demonstrating the structure of analogy among them.

Forces of nature	**Extensive quantity**	**Intensive quantity**
Water in lakes, in a container; air in a balloon, in a room, …	Volume	Pressure
Bodies in motion; water in motion, rivers; wind; …	Momentum	Velocity
Rotating bodies and wheels, spinning tops; …	Angular momentum	Angular velocity
Objects above ground (stones, pencils, clouds, …)	Gravitational mass	Gravitational potential
Hot objects, hot stones, hot water, hot air, …	Entropy	Temperature
Electrified objects, lightning, electric circuits, …	Electric charge	Electric potential

Table 1. Forces of nature and the corresponding extensive and intensive quantities

Fig. 5 (left) shows the experimental setups used to introduce water, electricity, and entropy (top to down). We discuss the case of water here. The description of the system and a concrete process shown in the sketch (Figure 1, right top and middle) is developed narratively, using natural language. Care is given to use of some recurrent metaphors in language like: a force of nature has an aspect of a fluid substance; the intensity of a force of nature is a vertical scale; bodies are containers; difference of intensity is a drive for a process.

Here is a particular narrative form. We add water to tank 1 continuously to keep the level there constant. The water can flow into tank 2 through a pipe and, from here, into the retention basin that marks the hydraulic environment (having a level of zero). Tank 2 is the container holding the amount of water we are interested in—initially, it is nearly empty. Its level rises because there is an inflow of water, forced by the difference of levels (pressures) between the two tanks; this drive is strong in the beginning and decreases progressively. There is an outflow as well, forced by the difference of levels (pressure) between tank 2 and the environment. When the two currents become equal, the level in tank 2 becomes steady—it will be lower than the level in tank 1 due to the water loss to the basin.

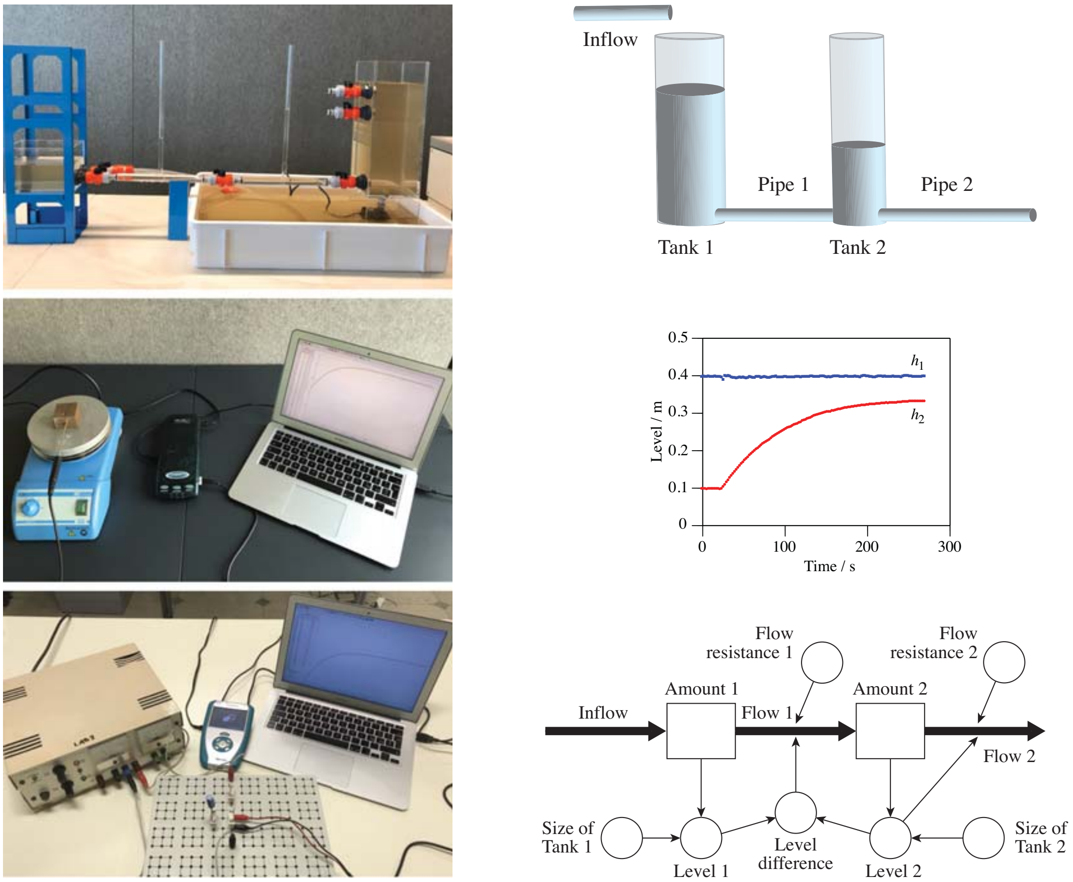


Figure 5. *Experimental setups (left: hydraulic, thermal, electrical), experimental hydraulic system (top right) and data (center right), and system dynamic model (bottom right).*

In the system dynamics model (Fig. 5, right bottom), combinations of reservoirs and flows express laws of balance for the volumes of water. The model demonstrates how the flows are determined (caused) by differences of levels (pressures). Tank sizes (cross sections) are tank capacitances and are needed to determine water levels in the tanks. Resistances control the magnitudes of flows for given pressure differences. In the present case, a simulation of the model shows a close to perfect fit between simulation results and measured values.

Perfectly analogous thermal and electrical systems can be built and operated where the relevant quantities measured show the same temporal behavior as those shown in Fig. 5 (center, right).

5. Summary

We have described the nature of imaginative structures (chiefly, metaphoric) in macroscopic physical systems and processes and demonstrated the roots of analogy between different phenomena such as fluids, electricity, heat, substances, and motion. Moreover, we have shown how particular graphical tools can be used to create visual metaphoric equivalents of the metaphors that are commonly evident in (natural) language but also in equations representing the formal versions of physical science (here: continuum physics).

We have applied the foundations afforded by this type of embodied approach to natural science to various courses and learning environments. Currently, we are researching the extension of metaphoric approaches to full-fledged narrative learning environments (Fuchs, 2015; Corni, Fuchs, Savino, 2017).

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