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First education in the fundamentals of figurative thinking in physics

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Summary. — This paper presents the theoretical and practical developments of research in physics education carried out at Free University of Bozen-Bolzano, which focuses mainly on primary physical science education. Our research is characterized by a move toward integrating the discipline and its didactics with the humanities to properly consider the human component of education. Both qualitative and quantitative outcomes, especially relating to prospective teachers' education, will be presented. Moreover, the main national and international projects that have been completed or are still active at Free University of Bozen-Bolzano will be briefly outlined.

1. – Introduction to physics education research developed at UNIBZ

The early years of school present a great opportunity for guiding and structuring a child's future personality and cultural formation, and this obviously relates to science education as well. It is therefore of paramount importance to think about how to introduce children to science. At the Faculty of Education of the Free University of Bozen-Bolzano (UNIBZ), we are well aware of this importance, and that is why our research in physics education is mainly focused on Primary Physical Science Education (PPSE) [1,2]. Here, the term *primary* is used in a dual sense. It means *early* in the sense of education addressed to children when they build their primary understanding of the world. It also refers to the understanding of concepts of physical science that may rightly be called primary, *i.e.*, the concepts that form the *roots of scientific thought*. These two senses determine the character of our research that comprises and integrates i) the way our mind constructs and develops concepts, ii) the development of cognitive tools as pupils grow, iii) the human forms of communication, and iv) the science content. The theories that inspire our research are the cognitive sciences in general and cognitive linguistics in particular [3-5], the recapitulation of cultural forms of understanding [6-8], the model of the embodied mind [5,9,10], narrative experientiality [11], and the physics of macroscopic phenomena, particularly in the form of continuum physics and the physics of uniform dynamical systems [12-14]. This line of research follows the one started in 2010 at the University of Modena and Reggio Emilia growing around the biannual international conference "*Innovazione nella didattica delle scienze nella scuola primaria e dell'infanzia: al crocevia fra discipline scientifiche e umanistiche*" [15-18], the action research project "*Piccoli scienziati*" [19], and the involvement of student teachers in internship, and teachers and pupils of several kindergarten and primary schools in the provinces of Modena and Reggio Emilia. In the last years, this work has continued to develop and become more and more focused. In other words, in the attempt of coming back to the roots of the discipline for educating children and their teachers, we felt the need for an integration between the natural sciences and humanities, to properly consider the human component of education.

In addition to primary school children, we have also directed our exploration of narrative-based science education toward middle and high school pupils. In this case, our research concerns primary aspects of the physical sciences (including aspects of the "scientific method") and the identification of strategies for approaching science in an interdisciplinary context, particularly involving the humanities.

This paper will outline the state-of-the-art of physics education research at UNIBZ, both in terms of its theoretical and practical development (sect. **2**) and its results (sects. **3** and **4**). Section **2** will summarize developments in the design of an integrated physics curriculum for kindergarten and primary school (pre- and in-service) teachers. Regarding follow-ups, sect. **3** presents reactions of student teachers to the courses, collected from a recent end-of-course survey, held in the Master Degree in Primary Education at the Bressanone campus of UNIBZ. In sect. **4**, we shall briefly describe the main national and international projects on physics education, both completed and still active at UNIBZ.

2. – An integrated physics curriculum for kindergarten and primary school teachers

The integrated curriculum derives from the PPSE project "Primary Physical Science Education – Courses and materials for teacher education based upon an imaginative, metaphoric and narrative approach to the experience of Forces of Nature", funded by UNIBZ in 2019–2022. Briefly stated, the curriculum is created upon the foundations of an imaginative and narrative approach to physical science in general and to Forces of Nature in particular (sect. **2**·1), as well as on how it is taught and learned (sect. **2**·2). Extensive treatment of the theoretical foundations of the project can be found in [1] and the results of its implementation and evaluation in [2].

2·1. *Primary Physical Science.* – While we accept the formal discipline of physics as the "final" goal of our project, the science is re-thought and re-structured in the light of forms of experiencing nature and the growth of understanding in children. In view of teacher and child education, existing approaches to physics cannot be just simplified to become intelligible: knowledge must be reconstructed starting from what we know about how humans encounter and make sense of physical nature.

The Forces of Nature. – Central to such an innovative approach is the notion of a perceptual unit (*gestalt*) we call Force of Nature (FoN) [13, 20-23]. It is important to point out that we do not use the term *force* in the sense of mechanics proper, but in its primitive sense of a phenomenon that is endowed with power or recognized as any form of powerful agency. We claim that perception and conceptual elaboration of different FoNs such as water, wind, fire, ice, light, soil, food, electricity and motion, and their interactions, guide much of human engagement with and understanding of nature and, consequently, of physical science. We call these Primary FoNs [22]. Despite their individual specificities, they have a common structure that allows us to trace them back to a few phenomena that are present in macroscopic continuum physics, *i.e.*, fluids, electricity and magnetism, heat, substance(s), gravity, and linear and rotational motion. We call the members of this group of FoNs found in physics Basic FoNs([1]) [22].

Extensive and intensive quantities. – A FoN is characterized by three main elements or aspects: quantity or extension, quality or intensity, and power. In the case of electricity, these are charge, electric potential, and electric power; in linear motion, they are momentum, velocity, and mechanical power; in the case of wind, they are spatial extension, wind intensity, and wind power. Understanding these aspects derives from embodied experience by metaphorical projection of *image schemas* [24] upon the phenomena in question [25, 26]. For the Basic FoNs, the quantitative aspect derives from the projection of the (fluidlike) SUBSTANCE or the AMOUNT schemas, whereas the intensive aspect comes from the projection of the VERTICALITY or LEVEL schemas; moreover, a tension is created as a difference of intensities at two points in a region of space. This shared conceptual structure makes FoNs similar to each other: our mind can then make use of *analogical structure mapping* [27-29] to reason about a FoN in terms of another.

Power and energy. – The power of a FoN is directly related to its extensive and intensive aspects. For example, water flows from a higher to a lower level: the amount that flows per unit time (conductive current) and the height of its fall (difference of potential) determines the power of a waterfall. The power is the rate at which energy is made available in the gravitational process. In analogy to the archetypal phenomenon of a waterfall, the power of any FoN is understood figuratively, employing the DIRECT MANIPULATION or POWER schemas, by combining (multiplying) a current and its fall through a potential difference. By studying the interactions of FoNs, a generalized energy principle can be developed where the energy made available by a first FoN —whose potential drops— is "used" by one or more FoNs to raise its (their) potential(s). As a visual metaphor for energy [30, 31], one may use a "substance" such as dust which was introduced in The Perpetuum Mobile animation [32, 33]; it has been used in several projects (*e.g.*, FCHgo and e^4 projects, see below). The animation depicts the FoNs as spirits passing on dust in a circular chain of technical devices creating the perpetuum mobile, a complex machine that should power itself. In each device two spirits meet, the first "drops" through a potential difference (relaxes) and releases energy, the second tenses (its potential rises) and absorbs (part of) the energy of the first. The video conveys several metaphoric concepts and constructs the many faceted concepts of energy [22, 34]. Naturally, it is found that the perpetual motion machine cannot work since dust "falls by the wayside" and is used to power the creation of a new FoN, *i.e.*, heat, that carries away the energy used for its production. The circular chain of devices and processes is

([1]) It should be noted that, in common physics courses, mechanics is treated first, as the archetype of all processes; in our perspective, though, motion can be treated on equal footing with other basic FoNs. We believe that, because of the difficulties it presents to students, it should even be treated in a second time.

broken and opened: it creates an open flow system.

Table I presents the structure of intensive and extensive quantities of the basic FoNs. The concepts of power and energy are identical for all FoNs. There are no "different forms" of energy, there is no energy conversion, or the like.

Law of balance. – Turning now to a quantitative treatment, a FLUIDLIKE QUANTITY residing in a system (CONTAINER) obeys a *law of balance*: its temporal rate of change is given by the sum of all the possible FLOWS (conductive, convective, and radiative currents), as well as production and destruction rates applying to the case of non-conserved FoNs. For example, the entropy in a system can change by flowing out into the environment due to a temperature difference (conductive flow), or by being transported by a flow of matter (convective flow), or by electromagnetic radiation (radiative flow), as well as by production in irreversible processes.

Constitutive relations. – Besides the law of balance and the structure and meaning of potentials and tensions, which are valid in general, the behavior of a FoN is described by means of *constitutive relations*, making use of a large number of schematic spatial and dynamic knowledge [1, 25]. For example, collecting and storing an AMOUNT of air in a rigid CONTAINER raises the pneumatic LEVEL, pressure. A conductive current of air depends upon a pressure gradient, which is understood in terms of the metaphor of a pneumatic landscape with its HIGHS and LOWS and steep or gentle SLOPES, and how the

TABLE I. – *The aspects of intensity and quantity of the basic FoNs. Fluids could be subsumed under substances (and pressure interpreted as an aspect of chemical potential). Energy is common to all FoNs and allows their changes in an interaction to be calculated (adapted from* [22]*).*

Basic Force of Nature	Potential & tension	Fluidlike quantity	
Fluids	Pressure & pressure difference	Volume of fluid	
Electricity & magnetism	Electric potential & electric tension	Electric charge	P O W
Heat	Temperature & temperature difference	Amount of heat (entropy)	E R
Substances	Chemical potential & chemical tension	Amount of substance	&
Linear motion	Speed & speed difference	Quantity of motion (momentum)	E N E R
Rotation	Angular speed & difference of angular speed	Spin (angular momentum)	G Y
Gravitation	Gravitational potential & difference of gravitational potential	Mass (gravitational)	

nature of the PATH (the pipes and the holes) taken by air enables (schema of LETTING) or opposes (schemas of OPPOSITION, or RESISTANCE) its flow.

Language. – FoNs, being embodied perceptual units structured by a number of metaphoric projections, are dealt with using narratives in natural language. Narratives can be thought of as using webs of metaphors that describe a more or less complex phenomenon [35]. The rationality contained in narratives and the logic of natural figurative language allow the aspects of intensity and quantity of FoNs to be singled out, differentiated, and put in relation. Besides, the causal schemas of narrative accounts of interactions of FoNs suggest and structure the aspects of power and energy [36]. Once the tools of literacy are well mastered by pupils, teachers can proceed to refine the language by working on balance and constitutive relations, making it more specific, precise. This allows moving in the direction of developing formal modes of communication (see *process diagrams* and *dynamical systems* below), possibly using mathematical language. Mathematical language and formulas are not at the beginning, but at the end of the development of the curriculum; this holds for (student) teachers as well.

Process diagrams. – A step toward the formalization of language consists in the graphical metaphoric rendering of the idea of interaction of FoNs and so created process diagrams. We apply the VERTICALITY schema for expressing fall and rise of potentials, the FLOW schema for expressing currents, the idea of sources and sinks for symbolizing production and destruction, and the CONTAINER schema for indicating their storage (of fluidlike quantities and energy). Consequently, we apply the SUBSTANCE and FLOW schemas [1, 31] to energy; power is interpreted as the rate at which energy is made available and used. On this basis, process diagrams of interacting FoNs can be drawn. Figure 1 shows the definitions of graphical symbols and an example of a process diagram for an electric pump [22] present in The Perpetuum Mobile movie [32]. In fig. 1 left, gray rectangles represent the physical objects that form the ground for actions, blue vertical arrows represent levels/potentials, red is used for various aspects of fluidlike quantities, green is for energy-related concepts. Note the storage elements at the bottom. In the process diagram in fig. 1 right, electricity arrives from the left to the electric pump at high potential, carrying energy (represented by the green horizontal arrow). From there, after undergoing a fall of potential and making energy available, it leaves at low potential. The energy made available by electricity is used in the pump for raising the pressure of the water coming from the right and for producing heat caused by friction and other irreversible processes. Note that here and in other process diagrams, the term "heat" denotes entropy.

Fig. 1. – Definitions of graphical symbols in process diagrams and an example of process diagram for an electric pump (adapted from [22]).

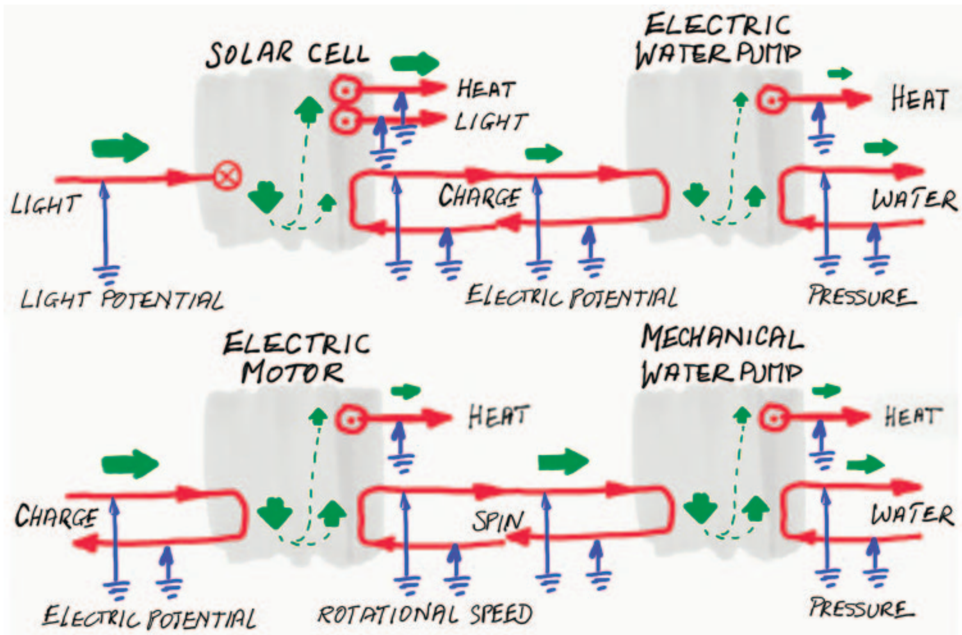

Fig. 2. – Top: Process diagram for a PV-water-pump chain. Note that this diagram is a combination of two simpler ones. Bottom: Process diagram of water pump in fig. 1 explored in more detail, displaying the electric motor, where electricity drives rotation, and the water turbine, where rotation drives a hydraulic process. Adapted from [22].

Process diagrams can be chained: elementary process diagrams can be connected to represent chains of interactions of FoNs (fig. 2 top). Moreover, a single process diagram can be "split" into two or more parts to reveal its sub-interactions (fig. 2 bottom).

Dynamical systems. – Narrative language with its figures and rational structures can be used to describe the temporal behavior of dynamical systems in terms of the behavior of FoNs. A further step in the direction of the formalization of language is performed by representing the law of balance and the constitutive relations using System Dynamics modeling. In the Stock & Flow paradigm [37] the extensive aspect of a FoN is represented by a *Stock* (the rectangles in fig. 3 bottom right) whose value changes dynamically due to in- and out-*Flows* of quantity (the thick arrows in fig. 3 bottom right). This basic structure of stock and flows represents the Law of Balance of the extensive quantity. The strengths of the flows (currents) are determined using a web of *Variables* according to the potentials (and tensions) and constitutive relations specific of the system (the circles and the thin arrows in fig. 3 bottom right).

The structure of Stocks, Flows, Variables, and links is the model: phenomena having the same model, but with different labels of the elements, are conceptually analogical. Figure 3 shows the System Dynamics model of three analogous phenomena, *i.e.*, filling and simultaneous discharging (through a horizontal pipe at the bottom) of a water tank, heating and simultaneous cooling of water in an open pot on a stove, and charging of an electric capacitor with a battery and discharging through a parallel resistor.

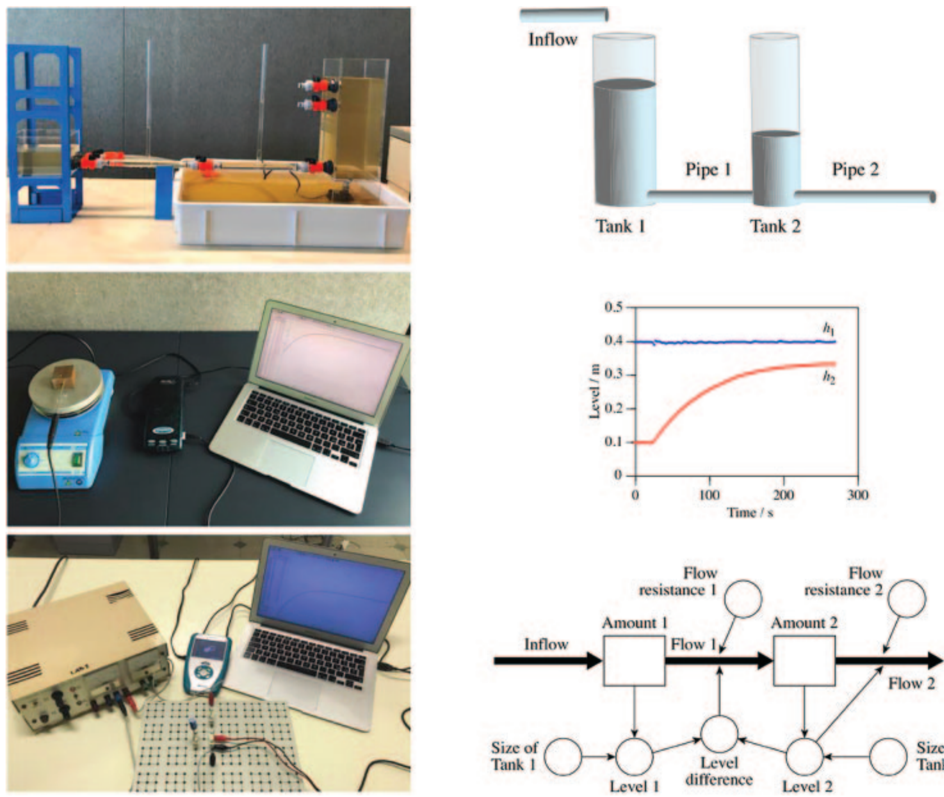

Fig. 3. – Experimental setups (left from top to bottom: hydraulic, thermal, electrical), experimental hydraulic system (top right) and data (center right), and System Dynamics model (bottom right) (from [31]).

Important features of dynamical systems are created by the storage of quantities, leading to delays and transients in the evolution of phenomena, and by the possibility for caused phenomena to influence their own causes (feedback). This is the case in natural systems, like the natural (water, carbon, electricity, wind, etc.) cycles, not to speak of biological systems that may include activities by humans, where the large number of predictable and/or ephemeral phenomena lead to complex behavior [38].

2·2. *Integration with the humanities.* – A neat separation between physical sciences and humanities cannot be drawn. Teachers cannot be just trained in the content of physical science, even if informed by an innovative perspective. As active subjects of education, they must be aware of the contexts of science. For this reason, the syllabus at UNIBZ integrates the discipline (lectures and laboratory activities) with elements of cognitive linguistics and narratology so that student teachers learn to understand the role of the use of everyday language in the context of natural phenomena and science, rather than just conceptual structures in macroscopic physical science. Moreover, and very importantly, we integrate primary science with the theory of recapitulation of cultural phases of understanding and of cognitive tools [6-8]. According to Egan, cognitive tools are tools that are "recapitulated" by children stemming from the cultural environment they are growing up in. These tools develop in phases, which Egan calls *understandings*, that are related to children' levels of language acquisition and mastery and to cultural phases of human development from which the names are taken: somatic, mythic, romantic, and philosophic. For the age range of children we target in this paper, we are primarily interested in *mythic understanding*, connected to the acquisition and mastery of oral language (3–8 years old children) and to mythic cultures. We will mention here, for the sake of brevity, two of the main tools of this set, with reference to the humanities where they are commonly studied: *i.e.* metaphor and narrative. Metaphor is not to be considered a mere rhetorical ornament added to literal language, nor a strictly linguistic entity; and narrative is no longer to be considered just a literary genre nor simply a sequentially organized representation of events.

Metaphor. – According to Lakoff and Johnson [3, 5], conceptual metaphors are figurative structures given by the projection of embodied understanding of a domain (the source domain) onto another domain of experience (the target domain). Metaphors are primarily conceptual, and secondarily linguistic, gestural, and visual [10]. Metaphors create meaning by transferring knowledge from a domain of embodied understanding. This is valid also for natural science in general and physics in particular. For example, the expression "*heat flows through the wall of a building*" is a metaphoric expression of the conceptual metaphor HEAT IS A FLUIDLIKE SUBSTANCE, where FLUIDLIKE SUBSTANCE is the embodied source for understanding an aspect of the target domain of heat. The sources of metaphors used in macroscopic continuum physics are the most elementary and embodied ones, *i.e.*, image schemas [24]. Table II lists the main image schemas from cognitive linguistic studies [24, 39]. Examples of metaphorical expressions are present in the previous subsections *Low of balance* and *Constitutive relations*, where small caps identify the image schemas used in the metaphorical expressions for balance of entropy and for flow of air.

Metaphors are easily learned and mastered by student teachers due to their frequent humanistic inclination and background [40-42].

Narrative and stories. – Metaphoric linguistic expressions are relatively small-scale imaginative structures. Webs of metaphoric expressions coming from different interconnected conceptual metaphors are used for describing and understanding larger-scale phenomena and appear in and structure narratives or stories [21, 26]. Stories, in turn, make clear the meaning and import of metaphors and metaphoric webs [35].

TABLE II. – *Examples of image schemas (from* [43]*).*

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
Existence	removal, bounded space, object, (fluidlike) substance

Stories tell the tales of several agents interacting in a more or less complex world, recounting and explaining events obeying certain rules. In particular, stories provide us with an overall sense of time, place, and agency [44, 45]. Since FoNs are conceived of as agentive perceptual units, they can be treated in stories as characters that interact in natural or technical systems and process unfolding through time [21, 35](2). See, for example, the stories of FoNs in [22] or "An Apple Story"(3) in the Toolkit of the FCHgo European project (see also sect. **4**). The natural language the stories of FoNs are written in, with its grammar and imaginative rationality, allows us to describe and understand the features and activities of FoNs, their mutual interactions and their interaction with the physical world. Moreover, according to the theory of narrative experientiality [11], stories lead to a form of experience, making embodied and imaginative understanding of FoNs and related phenomena possible. Parallel physical and narrative forms of experience, interacting with other forms of experience (see below *Imaginative forms of expression*), contribute to a deep and significant understanding of nature and technology.

Imaginative forms of expression. – Communicating about FoNs can take many different forms that may occur separately or in parallel and interacting. The impact of physical experience, integrated with narrative experience, will be greatly enhanced by additional communicative methods.

In recent years, we have created and experimented with designs for Embodied Simulations (ES) and FoNs Theaters (FoN-T) performances for teachers and their young learners to combine direct physical experience of FoNs in natural and technical settings with narrative experience.

Embodied Simulations. – Embodied Simulation [34] are modes of communication employing our body for representing storage and flow (and production/destruction) of fluidlike quantities (extensive quantities) related to tension (*i.e.*, differences of potentials). Figure 4 shows a sketch of the scene for the three analogous examples cited in subsection *Dynamical Systems* above related to hydraulic, thermal, and electrical processes.

In a version of ES, a few student teachers or children are initially inside the "storage element" represented by an area on the floor. The simulation game consists in periodically entering and leaving the area by predetermined numbers of people, in between periods of time needed to count and record the number of people currently in the area. According to the predetermined numbers of people entering and leaving, the area will fill, empty, or be unchanged over time. If, in particular, the number of people leaving is determined in terms of the number of the people present inside the area, the system can reach a dynamical equilibrium with the environment. The density of people inside the area determines the intensity of the fluidlike quantity in the storage element, and this, in turn, determines an outflow.

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(2) Note that rendering FoNs as characters in stories does not necessarily mean we have to personify them in a strongly anthropomorphizing sense. As an element of narrative experience, the tools of natural language (schematism, metaphor, analogy) let FoNs emerge directly as characters—we do not need to make them into and give them specific names of monsters, gnomes, giants, or gods. Just using a FoN as the subject of a sentence, with the verb expressing its behaviour, is a way of making that FoN a character in a story.

(3) `https://drive.google.com/file/d/1ei2JZu3jnvknFHyG2hbF3oXiFQz2OwjK/view?usp=sharing`.

Fig. 4. – Floorplan and actors performing how to keep track of amounts of fluidlike substances in an Embodied Simulation. A designated area serves as a storage element, the amount of fluidlike quantity is represented by the number of people. The participants move into and out of the storage area, representing flows of different strengths. Their density in the area indicates the intensity of the fluidlike quantity in the storage element (from [34]).

Forces of Nature Theaters. – A FoN-T performance is a dynamical embodied simulation of a process diagram (see subsection *Process diagrams* above). Process diagrams are visual representation, often of steady states, of processes; referring again to the water pump of subsection *Process diagrams* above, they do not simultaneously represent the initial transient phase of acceleration of the mechanical parts inside a water pump, the normal functioning of the pump, and the final stage that brings the pump to a standstill. In contrast, a FoN-T allows all phases to be experienced and explored by the participants.

The set for a FoN-T provides areas on the floor representing the devices where the agents meet (the grey boxes in a process diagram) and connecting lines as paths for the movement of agents (the red lines in a process diagram). The performance consists of people taking the roles of agents moving in an orderly way along the paths, carrying and exchanging confetti as a symbol for energy. Figure 5 shows the sketch of the scene of a FoN-T performance related to the functioning of an electric water pump. Note the similarities to the process diagram of fig. 1.

The people available for a performance are divided into three groups: electricity people, water people, and heat people. The three groups form moving queues for electricity and water, respectively. Ideally, this will allow the actors to get a feeling for the strength of the current of a fluidlike quantity, by adjusting the density and/or the speed at which they move along their assigned paths. The density and the speed at which actors move is a metaphor for the strength of the current and, as a consequence, of the rate at which energy is carried from device to device as well.

The moving electricity and water queues meet in the designated space for the electric water pump, in a counter-flow arrangement, as suggested by the floor plan and in the process diagram of fig. 1. The electricity people reach the pump area from the top of the figure at high potential, carrying a lot of confetti, and meet the arriving water people, from the bottom of the figure at low pressure, carrying little confetti. When two actors meet, the electricity person gives most of the confetti (energy) to the water person. After the interaction, the electricity people leave the area at low potential, while the water people leave at high pressure. The levels of electric potential and pressure are displayed by the actors by their bodily attitude: people carrying a lot of confetti may walk upright, erect, with face showing high tension or happiness; on the contrary, people

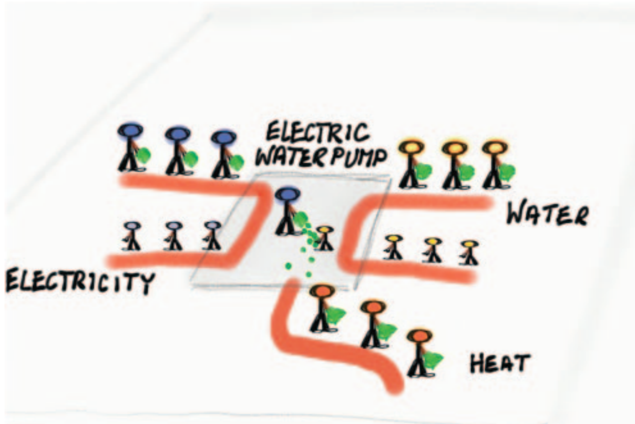

Fig. 5. – Floorplan and actors of a FoN-T performance representing the functioning of an electric water pump (from [34]).

with few confections may walk bowed or drop their shoulders, showing a sad, drooping face.

In the act of exchanging confetti, the actors will very likely drop some confetti. This is the representation of non-ideal irreversible interaction: the more confetti is dropped, the less ideal the interaction will be – the fraction of effectively exchanged confetti represents the efficiency of the device. This fraction should unavoidably decrease with increasing speed of the interacting queues. As confetti falls on the floor, the third group of people, the heat people, come into play and collect the confetti and take it out of the device. Note that FoNs like electricity and water are conserved (they are neither created nor destroyed), so actors simply move, exchange confetti, and change their bodily attitude. In contrast, in the example above, heat is created: heat people will then have to assume an appropriate behavior, *e.g.*, start by sitting or lying down in the area and then stand up with confetti in hand (they are literally born in the act).

Process diagrams and FoN-T allow the role of energy [12,13,46,47] and of FoNs [22,34] in systems and processes to be clearly discussed and understood. Energy never appears by itself, there is no "pure energy", but it is always coupled to fluidlike (extensive) physical quantities and their potentials; there are no forms of energy, FoNs are not energy, and do not transform into one another, etc.

Results of experimentation of ES and FoN-T have been reported in the FCHgo project (see below) and in [2, 30, 48].

Narrative approach to physics in higher school grades. – The possibility of linking scientific topics, such as physics, to subjects that are typically humanistic —for instance through the identification of parallels, analogies and metaphors, and inclusion in stories— is based precisely on the ubiquity of conceptual metaphors created upon image-schemas. In fact, it is possible to identify the same image-schemas both in literary or artistic archetypes and in scientific models. For example, if in a physical system the temperature can rise or fall, in a novel it is the psychological tension that can rise or fall. Equally, the use of certain words in different cultural contexts reveals something that is much more than a coincidence: if one speaks of *resistance* in relation to a context of war or the dissemination of an idea (*e.g.*, *an idea loses valuable energy in clashing with* *those who oppose it*), one speaks of it as well in relation to an electrical circuit (*e.g.*, *an electric current loses energy in passing through a conductor*). This is so because, although we are dealing with phenomena concerning profoundly different phenomena, we metaphorically project the same powerful basic image-schemas, such as AGENT/PATIENT, PATH, OBSTACLE, LEVEL.

In secondary school, a sample of integrated approaches to physics and art [49] and physics and literature [50], have been constructed and tested in various classes, and interesting qualitative feedback has been obtained. In a quantitative analysis, we looked at the possibility of explaining quantum mechanics using interdisciplinary connections with the humanities [51]. This investigation showed how the narrative approach is able to raise students' awareness of the cultural value of the physical sciences rather than just their technological importance.

3. – Reaction of student teachers to the course

Qualitative and quantitative results of student teachers' feedback (including results from exams) have been presented at conferences (GIREP, ESERA, WCPE). Learning science as covered in the course has been assessed [30, 48, 52, 53]. Students' abilities for creating and analyzing stories of forces of nature and for applying metaphor analysis [40, 41] have been evaluated [53, 54], and we have collected feedback concerning students' inclination towards and perceived personal skills in physics [53]. Several student teachers have prepared their master thesis on one of the topics outlined above.

Recently, student teachers' reactions to the courses attended in the Master-Degree in Primary Education at UNIBZ have been collected and analyzed by means of an end-of-course survey; 27 student teachers', mainly women, participated voluntarily in an anonymous online survey. All participants had attended the courses in the 3rd and in the 4th year (30 hours lecture and 20 hours labs, each), and passed the exams. In the survey we used some scales of the Nature-Human-Society-questionnaire [55] and a series of course specific items, all with a 5-level response format, where 1 means "strongly disagree" and 5 means "strongly agree".

Experience of and interest in physics. – The results show that the participants' previous school experiences with physics tended to be negative (M = 2.4, SD = 0.9) and in this way, their physics experiences were even more negatively pronounced than in a sample from another study [56].

After the physics course at university, participant's general interest in physics (M = 3, SD = 1) and their perceived capability to teach physics (M = 3.0, SD = 0.7) are in the midfield. Compared with the results from another study [57], the general interest in physics and the perceived capability in teaching physics of students participating in the course can be classified as higher than those of female freshmen.

Self-awareness. – In the survey, participants also indicate that their attitude towards physics has improved compared to before the course (M = 4.0, SD = 0.8). Specifically, students indicate that they gained helpful methodological knowledge for teaching physics (M = 4.3, SD = 0.7). They reasonably appreciate having learned a new approach to physics in the course (M = 4.3, SD = 0.5). The concept of Forces of Nature was well understood by the students (M = 4.4, SD = 0.6) and most of them claim to have had occasion to think about the FoNs in their everyday lives (M = 4, SD = 1). The survey participants are also convinced that concepts can be expressed narratively (M = 4.4, SD = 0.6) and that metaphors are helpful for a better understanding of physics (M = 4.2, SD = 0.8).

Teaching/learning methods. – Additional results of this survey show specific opinions held by students regarding the different, newly introduced methods for communicating about FoNs, namely FoN-T, storytelling, process diagrams.

Students find the FoN-T very helpful for understanding the role of energy when FoNs interact (M = 4.7, SD = 0.6). They feel themselves capable of implementing FoN-T in school (M = 4.6, SD = 0.6), but consider FoN-T more appropriate to primary school (M = 4.6, SD = 0.7) than to kindergarten (M = 4, SD = 1).

Stories of FoNs helped students as well to understand the role of FoNs in natural and technical processes (M = 4.4, SD = 0.6). However, they feel themselves less able to create their own stories about FoNs (M = 3.6, SD = 0.8). They state that such stories would be slightly more appropriate for primary school classes (M = 4.5, SD=0.6) than for kindergarten (M = 4, SD = 1).

According to the students, the process diagrams were helpful for improving their own understanding of the role of energy when FoNs interact (M = 4.4, SD = 0.8). They saw themselves reasonably capable of creating such process diagrams (M = 3.7, SD = 0.8) and realized that process diagrams are less suitable for use in kindergarten (M = 2, SD = 1) and primary school (M = 4, SD = 1).

Students completely agree that direct experiences with FoNs are essential for understanding natural phenomena (M = 4.8, SD = 0.5). They find it tendentially possible to enable children to experience nature in this way (M = 3.9, SD = 0.9) and are also convinced that this should already be done in kindergarten (M = 4, SD = 1) and in primary school (M = 4.4, SD = 0.9).

Similar statements can be made about the method of science experiments. Students find experiments relating to FoNs important to understand natural phenomena (M = 4.7, SD = 0.5), but do not find it quite as easy to carry out experiments with children (M = 3.7, SD = 0.7), even though they find scientific experimentation important in both kindergarten (M = 4, SD = 1) and primary school (M = 4.3, SD = 0.8).

Opinions about the course. – Finally, students were given the opportunity to express their opinions about the course content through open-ended questions, asking for both positive and negative impressions.

Positive feedback is as follows:

- "Of the course, I particularly appreciated the fact that it allowed us to discover a new way of approaching physics, allowing me to observe the topics covered in everyday life as well. In addition, I liked the many cues we were given that allow us to adapt a discipline that can seem very complex even to children in kindergarten and primary school."
- "The course allowed me to learn about a methodology I did not even know existed, giving me not only a new point of view but also a new tool I could use with children. I find it an effective method to convey difficult content in a simple way."
- "I particularly appreciated the identification of what the forces of nature are and their characteristics because they made me understand the workings of natural phenomena and the concept of energy, which I would not have been able to distinguish or describe before."

- "I appreciated the talk on FoNs and particularly the method by which they are taught to children through storytelling and theater of the Forces of Nature."
- "I appreciated this new way of interpreting and explaining physics, totally different from the experience I had from high school."

On the other hand, critical student voices noted the following:

- "Creating FoNs stories was complex, especially including metaphors. I would add more concrete examples of FoNs stories to have as a cue, so that it is not necessary to construct one's own story."
- "I was not particularly convinced by the use of analogies and metaphors with children, as very often classrooms are multicultural and not all children have the same command of language, so they can become barriers."
- "I believe that teaching physics by analogies is a very useful strategy for children to learn about physical phenomena, but it may happen that, the excess of these, makes the topic too abstract and distant."
- "What has convinced me the least is perhaps at times it is too abstract. Some concepts are also too complex and elevated to be used in classroom. I wished me more concrete didactical examples for young children."
- "I find the approach extremely interesting and innovative, yet more critical to be adopted in school. Many topics are not taught in primary school, such as hydrogen, and due to the complexity of some topics I absolutely do not feel I can teach them, neither in kindergarten nor in primary school. The course should contain more simple experiments suitable for children."

Student feedback is felt to be very valuable in improving and emphasizing course contents. Especially the point of criticism regarding the applicability in kindergarten also led us to studies carried out directly in practice in order to gather practical experience and to explore the accessibility of Forces of Nature for young children [58-60]

4. – Projects at UNIBZ

In this section, we briefly outline the main national and international projects, completed or still active, conducted at the Faculty of Education of UNIBZ that contribute to the research described above.

PPSE (2019-2022). Primary Physical Science Education – Courses and materials for teacher education based upon an imaginative, metaphoric and narrative approach to the experience of Forces of Nature. – The goal of PPSE is investigating approaches that integrate otherwise separate fields of human cultural achievement, ranging from the natural sciences to the humanities [1, 2, 22, 38]. Concretely, it allowed us to set up an Analogy Laboratory with experiments that exhibit FoNs, with examples taken from physics, chemistry and biology, that are commonly experienced as being strongly analogous. The laboratory allows for activities that help learners develop and strengthen their skills in metaphoric and analogical reasoning, as well as in creating stories of the FoNs they have been exploring.

An important outcome of PPSE is the design and the publication, partly still ongoing, of the two-volume innovative textbook for *Primary Physical Science Education: 1. An Imaginative Approach to Encounters with Nature* [22], and 2. *Experiencing Forces of Nature in Natural and Technical Systems* [61].

FCHgo (2019-2021). Fuel Cell HydroGen educatiOnal model for schools (fchgo.eu). – FCHgo is a Horizon 2020 European project dedicated to fostering knowledge about fuel cell and hydrogen technology by delivering an educational model for schools. It is an application of the imaginative and narrative approach developed above. It invites pupils and their teachers alike to discover the energy of hydrogen with innovative teaching materials and along inspiring activities in classrooms and beyond [62, 63]. The outcomes are:

- Toolkit to facilitate understanding of how energy works through stories, play and image.
- Classroom activities and pilot lessons at European primary and secondary schools
- International award on the theme "The World of the Future: Best FCH Application, contributing to a better and cleaner future with hydrogen"
- FCHgo at home: activities suitable to be carried out at home during the COVID pandemic.

VidNUT (2021-2023). Vignettes in Science, Technology and Textile Education – eLearning Modules to Enhance Professional Vision. – VidNUT is aimed at the production and validation of video vignettes in form of condensed case studies in classroom with actual teachers and pupils working on a topic. The video vignettes, with pauses of reflection, questions, and suggestions, are designed for student teacher preparation and are available on a platform on-line.

AT-NE-ST (2020-2023). Discovering complexity: Advanced Technology for Narrative Education and System Thinking. – This interdisciplinary project, founded by UNIBZ and joining researchers of the Faculty of Education and of the Faculty of Science and Technology, aims at introducing primary and secondary school students to complexity and system thinking by means of didactic materials offered to teachers with a specific training.

The didactic materials are collected in the form of two suitcases:

- Introductory Suitcase – Teaching materials and paths for primary schools for an initial approach to complexity through analogical thinking at different levels [64];
- Advanced Suitcase – Teaching materials and paths for secondary school for the study of the relationships between different physical quantities in a building model.

e^4 (2022-25). Higher Educational tools for an Embodied & creative Education on Energy (energy4teachers.eu). – This Erasmus+ project, coordinated by UNIBZ, aims at the elaboration of innovative advanced training modules for primary and secondary school teachers on energy using the tools of imagination.

The materials to be produced in this project are:

Project Result 1: Guidelines addressed to universities for partnerships with public and private decision-makers in order to foster joint training programs;

Project Result 2: Educational modules on energy in various fields for higher education using imaginative tools;

Project Result 3: Interactive web platform to support the module and their employment.

5. – Summary

We have outlined the state-of-the-art of the main topics of physics education research at UNIBZ.

We have carefully outlined the theoretical foundations alongside methods and outcomes.

Research involving empirical investigations in cooperation with schools and teachers, as well as international collaborations with scholars and research groups, is ongoing.

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