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Recasting particle physics by entangling physics, history and philosophy

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Summary. — The paper presents the design process we followed to recast particle physics so as to make it conceptually relevant for secondary school students. In this design process, the concept of symmetry was assumed as core-idea because of its structural and foundational role in particle physics, its crosscutting character and its epistemological and philosophical value. The first draft of the materials was tested in a pilot-study which involved 19 students of a regular class (grade 13) of an Italian school. The data analysis showed that the students were in their "regime of competence" for grasping subtle nuances of the materials and for providing important hints for revising them. In particular, students' reactions brought into light the need of clarifying the "foundational" character that symmetry attained in twentieth-century physics. The delicate step of re-thinking the materials required the researchers to articulate the complex relationship between researches on physics teaching, history and philosophy of physics. This analytic phase resulted in a version of the materials which implies the students to be guided to grasp the meaning of symmetry as normative principle in twentieth-century physics, throughout the exploration of the different meanings assumed by symmetry over time. The whole process led also to the production of an essential, on-line version, of the materials targeted to a wider audience.

1. – Introduction

The main goal of the paper is to present the design process we followed with the goal of recasting particle physics so as to make it conceptually relevant for secondary school students.

The process foresaw a first production of teaching materials for introducing elements of particle physics at school, their testing in a pilot-study, data analysis and successive revision of the materials themselves. In this paper, we will show *how* and *when* issues of

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meaningfulness raised by the students required the researchers to articulate, in a specific way, the relationship between the disciplinary contents presented to the class (particle physics concepts) and historical and philosophical considerations. The paper is organized as follows:

– in sect. 2 arguments supporting the choice of introducing particle physics at secondary-school level are discussed together with the relevance that the concept of symmetry can play for recasting this physics domain from an educational perspective;

– in sect. 3 the pilot-study testing a first draft of the teaching materials is briefly described (rationale of the experiment, teaching materials, methods of data analysis) and a special emphasis is posed on those data which triggered the successive phase of re-thinking to the materials;

– in sect. 4 the phase of re-thinking is fully described: it will be shown what questions researchers have set in response to specific issues raised by students and what role was played by the of history and philosophy in answering these issues. The analysis led to the design and realization of a virtual exhibition within the Museo-Officina dell'Educazione (MOdE) of the University of Bologna.

2. – State of the art

The problem of introducing elements of particle physics at the secondary-school level has recently received a renewed attention in Italy in the light of the fact that the reformed secondary school curricula (MIUR, 2010) requires students of "Liceo Scientifico" to address, at grade 13, topics belonging to twentieth-century physics. The new requirements raise several issues of concern for Physics Education Research (PER), from the teacher-training to the realization of suitable materials. It is well known for example that, because of the advanced and specialized character of the topics, textbooks usually present particle physics as a fragmented patchwork of notions (pieces of historical information, experimental results, theoretical hypothesis) which sounds as a sort of "appendix" to the central body of knowledge represented by classical physics.

The plausibility of introducing selected topics belonging to the twentieth-century physics at secondary-school is not new within PER: the last thirty years have seen a relevant number of studies supporting the idea that an educational research-based introduction of relativity, quantum physics, even of the quantum theory of the fields, can confer to the study of physics an exceptional cultural relevance (Levrini, Fantini; 2013; Bertozzi; 2013).

The materials we produced on particle physics were structured on the concept of symmetry. This concept occupies a prominent place within the PER panorama and not only. Starting from the works of Weyl and Wigner, the concept of symmetry played a significant role firstly within the reflections that scientists developed about physics itself (Weyl, 1952; Wigner, 1967). Then, since Feynman Lectures on Physics (Feynman, 1964), the roles that symmetry can play in education have been progressively investigated. Recently, within the field of physics education, some scholars have been exploring the conjecture that re-designing the physics curriculum, or parts of it, by emphasizing the foundational role of symmetry can help physics to become meaningful, interesting and relevant for a large number of students. The studies regarding relativity and conservation laws are achieving interesting and promising results (Hill, Lederman 2000; Van der Veen, 2012; 2013; Van den Berg, 2006). It is within this framework that we assumed that the concept of symmetry could be the core-idea for developing teaching materials aimed at enabling students to grasp the fundamental features of particle physics.

3. – The pilot-study

A detailed description of the pilot-study and of its first results has been already published (Bertozzi *et al.*, 2014) and only a brief overview of them is provided in this section. The aim of this overview is to bring out the aspects that imposed us, as researchers, to re-think of the materials and, at the same time, to bring into light the contribution that researches in history and philosophy of science can provide for this purpose.

3˙1. *Experiment design: classroom context, materials and data sources*. – The experiment involved a regular class of 19 students, grade 13 of an Italian scientifically oriented secondary school (Liceo Scientifico "A. Serpieri") in Rimini (teacher M. Rodriguez). At the time of the experiment, the class had been studying physics as mandatory course along the five years of upper secondary school (grades 9-13).

The materials used in the experiment consisted of a document about antimatter and of a lecture, held by one of the researchers (EB) where students had been introduced to the essential aspects of particle physics. More specifically, the document included two different texts on the same topic (antimatter): the first text was taken from the website of the Exploratorium in S. Francisco([1]) and, in researchers' opinion, it represents an example of the common, paradigmatic, way of presenting antimatter to non physicists. The second text was elaborated by the researchers as an alternative way of introducing antimatter by assuming symmetry as "key-concept": in particular, the symmetry observable in a bubble-chamber in electron-positron pair production was discussed in the light of the symmetries that can be observed in other situations (*e.g.* an ice-crystal and a musical sheet).

The 2 hour lecture was divided in three segments: each segment focuses on a specific aspect concerning symmetries in contemporary particle physics. In particular:

a) Symmetry and the properties of space and time: translation, rotation (continuous);

b) Symmetry and properties of the particles: C, P and CPT symmetries (discrete); electric charge, spin (internal);

c) Symmetry as a tool for classification and prediction: historical episodes coming from cosmic ray researches.

Data on students' reactions to the teaching materials were collected through: a) a questionnaire designed to guide the students in a critical analysis of the two texts about antimatter; b) audio-recordings of the lecture and the classroom discussion which was carried out the day after the lecture; c) an individual written task.

3˙2. *Data analysis*. – With regard to the main goal of the study, *i.e.* making particle physics (usually presented as an "additional appendix") conceptually relevant for secondary school students, the analysis of students' reactions brought into light that a

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([1]) The text "Antimatter" is available at `http://www.exploratorium.edu/origins/cern/ideas/antimatter.html`.

promising way of achieving the goal had been intercepted. Students appeared to be in their regime of competences for grasping subtle nuances of the materials, picking up different roles that the concept plays in physics and for ascribing the concept an inner epistemological value. For example, since the analysis of the texts, some students were able to recognise a methodological role of symmetries for the development of science. In the words of Isabella:

"Scientists try to explain the world around us by means of laws of symmetry and, if they find some anomalies, they try to discover their origin and to solve them [...]. [the second text on antimatter] provides us with information not only on antimatter but, just, on the way of thinking of physicists themselves and on what pushes scientists to research" (Isabella).

At the same time, a significant part of the classroom discussion carried out the day after the lecture, brought into light a specific point: the idea that symmetry becomes a fundamental principle in contemporary physics clashed with the discussed examples, like the pair production process as observed in a bubble-chamber, where symmetry emerged as a phenomenological regularity. The students complained about this as follows:

"I thought that contemporary physics considers symmetry a fundamental principle. Seeing symmetry in the phenomenon [...] it seems strange. It seems that you can have different symmetries according to different phenomena. Maybe here in the case of the photon I have a certain symmetry while in another [...]" (Lorenzo).

"So, is it a fundamental principle or something that you observe and understand that it is always there?" (Luca).

This reaction deeply problematized how the so-called *foundational character* of symmetry was introduced in the materials: our interpretation was that the distrust expressed in this particular classroom context was the signal that relevant elements were missing in the overall structure of the discourse. Specifically, a more complex and rich way of contextualizing symmetry in twentieth-century physics was needed and, somehow, claimed.

4. – Re-thinking

As hinted in the introduction, the search for the missing elements of knowledge triggered a process of re-analysis on the relationship between physics contents, philosophy and history of physics: along this process, we re-thought about the first draft of the discourse that structured the materials so as to incorporate students' requirements. The process implied us to:

a) carry out a deep philosophical analysis on the so called *normative role* of symmetry as peculiar for the physics of the last century;

b) search for a way to illustrate this meaning to a non-specialist audience.

After the presentation of the results of this process, we will show how the new discourse about the symmetry guided the design and realization of a virtual exhibition for a wide audience that intends to include secondary school students.

4˙1. *Symmetry as normative principle: philosophical studies and educational perspective*. – The physicist, mathematician and philosopher Eugene Wigner, in his "Philosophical Reflections" published in 1967, picks up a precise moment in the history of physics, after which the *normative role* came into playing:

"The significance and general validity of these principles were recognized, however, only by Einstein. His papers on special relativity also mark the reversal of a trend: until then the principles of invariance were derived from the laws of motion. Einstein's work established the older principles of invariance so firmly that we have to be reminded that they are based only on experience. It is now natural for us to try to derive the laws of nature and to test their validity by means of their laws of invariance, rather than to derive the laws of invariance from what we believe to be the laws of nature" (Wigner, 1967).

Wigner's statement draws the attention on Einstein's use of symmetry principles both in Special and in General Relativity (covariance): successive literature on philosophy of physics extensively quotes the two cases as paradigmatic examples of how the requirement of invariance acts as a restriction on the form that a theory may take. Gauge theories and their relation with fundamental interactions extend this paradigm to particle physics and complete the framework of the *normative role* played by symmetry within the physics of the last century.

While Wigner is focussing on the role of *symmetry* for *the laws* of physics, the Italian physicist and philosopher Giuliano Toraldo di Francia stresses the relationship between *symmetry* and the *micro-objects* of physics: unlike the objects of classical physics that display a *contigent* nature, particles, the objects of contemporary physics, display a *nomological* nature being "knots of invariants properties prescribed by the laws" (Toraldo di Francia, 1978, 1998).

These two cues concerning the fundamental, normative, role of symmetry in defining *the shapes of the laws* and *the objects* became the basis of the elaboration of apposite schemata in order to make these cues accessible to a non specialist audience: in these schemata, we establish an analogy between the symmetry properties of simple geometrical figures and the symmetry properties of the elementary particles and of the *laws* governing their interactions. The negative character of these analogies marks the transitions from a classical view of physics to a contemporary one, bringing into light an inner, educational value. The tenability of the proposed analogies has been already discussed in apposite environments (conferences and journals) where the relationships between symmetry and physics are at issue (Bertozzi, Levrini; 2014).

4˙1.1. The shape of the laws. Figure 1 shows how the laws of physics are normed by symmetry in twentieth-century physics. The modern definition of "symmetry as operation" developed throughout nineteenth-century is represented in the first row where it is applied to a geometrical figure (a square): in this meaning, symmetry expresses the invariance of an object (for example a square) under a space transformation (for example the rotation of 90° degrees). The general structure of symmetry is extracted from the example and reported in the second row.

The way how such a general definition of symmetry works in twentieth-century physics is reported in the third row. Here, space transformations are replaced by spacetime transformations (the Lorentz transformations of Special Relativity) and the geometrical figure is replaced by a mathematical expression (law of physics). The new transformations applied to new objects allow physicists to verify if a particular physical law maintains the same shape between different inertial systems of reference (Lorentz-invariance). In our reconstruction, these considerations mark the first encounter with the normative role of symmetry in twentieth-century: Lorentz transformations act as norms to select those laws of physics which match the relativistic framework (*e.g.* electromagnetism) and to point out those laws which do not (*e.g.* Newtonian mechanics) and must be modified.

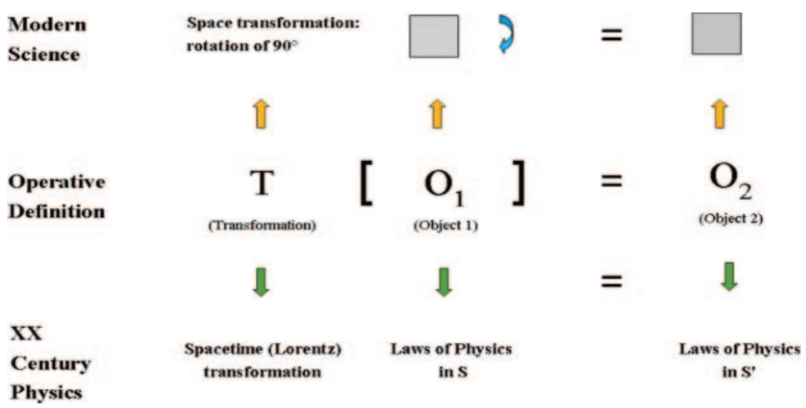

Fig. 1. – Operative definition of symmetry at work in the case of a square and a physical law.

4·1.2. The definition of the object. The second philosophical cue addressed by our reconstruction concerns the definition of the micro-objects (particles) in terms of their symmetry properties. Actually, if one focuses on the relation symmetry-object, the modern definition of symmetry has two different meaning, according to the perspective from which it is looked at. Indeed, the two statements "the square *is invariant* under rotations of 90° degrees" and "the square is *what is invariant* under 90° degrees rotations" are significantly not equivalent: in the first, we start from the object and, then, we recognise its symmetry properties; in the second, symmetry properties are used to define the object itself. It is this second perspective that is adopted in contemporary physics for defining elementary particles.

Particles are detected in physical experiments by the measurement of quantities that universally identify them: electron *is what has* a given value of mass, electric charge, spin and lepton number. Such "identity-card" is just what can be characterized in terms of symmetry properties grounded on the laws of invariance([2]): as Toraldo di Francia wrote, particle are knots of invariants prescribed by physical laws.

4·2. *The meanings of symmetry in science: historical studies and educational perspective.* – When observed from an historical perspective, the idea of symmetry as *normative principle* for physics appears to be the ultimate and most technical form acquired by the concept within the development of science. In particular, Castellani and Brading emphasize how, starting from the antiquities, the concept of symmetry progressively gained a modern meaning and how the word "symmetry" evolved semantically over the history of science (Brading, Castellani; 2003).

In the light of the analysis carried out, an historical path about symmetry was designed and, in collaboration with the Museo Officina dell'Educazione (MOdE) of the University of Bologna, it became the basis for a virtual exhibition targeted to secondary school students and general audiences. The exhibition is available on the web([3])

([2]) Within the theoretical framework of the quantum field theory, a formal construct, the action, is associated to the physical entity (particle). Noether's theorem links the symmetry properties of the action to Noether charges (*e.g.* energy, impulse, electric charge, spin); these quantities, that are invariant during the free evolution of the system, and globally conserved in its interactions, are the ones which are measured in physical experiments.

([3]) http://omeka.scedu.unibo.it/exhibits/show/simmetriafisica.

In the exhibition, three meanings acquired by symmetry throughout history are explored in 3 different virtual rooms and, in each room, specific objects of interest for science are displayed.

In particular:

a) The room of poliedra explores the meaning of "symmetry as proportion": from the Timeo of Plato to the Mysterium Cosmographicum of Kepler (1596) the principal function of symmetry was to express harmony between the different parts and the whole. The central elements of this room are *polyhedra* that, due to their inner properties of proportionality, have been privileged objects for the investigation of natural world in antiquity.

b) The room of crystals – "symmetry as operation": during the XIX century, the introduction of the group theory in mathematics led to a new, modern meaning of symmetry and turned it into a powerful classificatory tool. Crystals and their role in XIX Century physics are the central elements of the room.

c) The room of the fundamental laws and objects – "symmetry as principle": the path through the previous two rooms is supposed to put the visitor in the mood to reach the third room and to catch the essence of the examples discussed, that it to recognize: i) the plausibility of generalizing the notion of symmetry-as-operation to transformations which include time, as well as space, or refer to abstract spaces whose nature is no more geometrical; ii) the meaning of switching the common relationship between object and its properties and getting to define physical objects by means of symmetry properties.

5. – Conclusions

In the paper we presented an articulated process of instructional design where students' requirements guided us to extend and deepen our reflections on history and philosophy of science to elucidate the fundamental role played by symmetry in twentieth-century physics. The new materials represent a special entanglement of physics, philosophy and history of physics, realized for educational purposes. They are now used in contexts of teacher education and, as we saw, are the basis of a realized virtual exhibition.

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