Chapter 8

History and Philosophy of Science in Physics Education
Recasting Particle Physics by Entangling Physics, History and Philosophy.

Eugenio Bertozzi, Olivia Levrini
Department of Physics and Astronomy,
Alma Mater Studiorum, University of Bologna. Italy

Abstract
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 XX 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.

Keywords
Symmetry, particle physics, physics education research, history and philosophy of physics.

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 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 Section 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 Section 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 Section 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.

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 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.

1 The text “Antimatter” is available at http://www.exploratorium.edu/ origins/cern/ideas/antimatter.html
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 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 recognize 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.

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 *contingent* nature, particles, the objects of contemporary physics, displays 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, Levirini; 2014).

*The shape of the laws*

![Diagram](image)

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

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.

*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:
as Toraldo di Francia wrote, particle are knots of invariants prescribed by physical laws.

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.

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.

References

Bertozzi. E. (2013). What is what we call quantum field? Answering from a teaching perspective by taking
the foundations into account, European Journal of Physics, 34, 603-611

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


Ministero dell'Istruzione, dell'Università e della Ricerca (2010), Indicazioni nazionali per i nuovi Licei.


**Affiliation and address information**

Eugenio Bertozzi
Department of Physics and Astronomy
Alma Mater Studiorum – University of Bologna
Viale Berti Pichat 6/2
40127 Bologna, Italy

e-mail: eugenio.bertozzi2@unibo.it
The Discovery of X-Rays Diffraction: from Crystals to DNA. A Case Study to Promote Understanding of the Nature of Science and of its Interdisciplinary Character

Francesco Guerra¹, Matteo Leone², Nadia Robotti³
¹ Department of Physics, Sapienza University of Rome; INFN Section of Rome
² Department of Philosophy and Educational Sciences - Campus of Savigliano, University of Turin
³ Department of Physics, University of Genova; INFN Section of Genova

Abstract
The advantages of introducing history of science topics into the teaching of science has been advocated by a large number of scholars within the science education community. One of the main reasons given for using history of science in teaching is its power to promote understanding of the nature of science (NOS). In this respect, the historical case of X-rays diffraction, from the discovery of Max von Laue (1912) to the first X-rays diffraction photographs of DNA (1953), is a case in point for showing that a correct experimental strategy and a favourable theoretical context are not enough to make a scientific discovery.

Keywords
History of Science; Nature of Science; X-rays; X-rays diffraction; Wilhelm Conrad Röntgen; Max von Laue; DNA;

1. Introduction
The advantages of introducing history of science topics into the teaching of science has been advocated by a large number of scholars within the science education community (de Hosson & Schneeberger 2011, Leone 2014, Matthews 1994). As it was recently observed by Matthews (2012), one of the main reasons are the “cultural, educational, personal and scientific benefits of infusing the history and philosophy of science, into science programmes and curriculum; or in current terms, of teaching about the nature of science (NOS) while teaching science”. While there has been a long tradition advocating this approach, a number of open questions about NOS still exists. These questions deal with the optimal conditions for effective NOS teaching, the relationship between learning science and learning about science, and the issue of effectively measuring a NOS learning. Last but not least, there is an unsettled matter of definition arising from a lack of agreement in the science education community about what actually are the fundamentals of NOS (for a list of NOS elements according to some of the most influential authors in the field see Schwartz and Lederman 2008).

Notwithstanding these serious difficulties, and a conspicuous lack of experimental efforts to study the actual effectiveness of including history of science into science classes, curricula, and teacher education, a number of historical case studies have been studied with the goal of emphasizing its educational significance. These studies, rather than providing a shared list of necessary and sufficient conditions for a practice to be scientific, identify “family resemblance of features that warrant different enterprises being called scientific” (Matthews 2012). In this respect, the discovery of X-rays diffraction by crystals, and some important outcomes like the emergence of X-rays spectroscopy and the discovery of DNA, are a case in point for showing that a correct experimental strategy and a favourable theoretical context are not enough to make a scientific discovery.

Max von Laue’s discovery of X-rays diffraction and the subsequent developments by William Henry Bragg and William Lawrence Bragg had been extensively discussed in Robotti (2012), to which we refer for a more detailed coverage of this topic.

2. The discovery of X-rays and of their nature
A major physics discovery occurred on November 8, 1895. For this discovery Wilhelm Conrad Röntgen, then professor of Physics at Wurzburg (Germany), was awarded the very first Nobel Prize in Physics (1901).
Röntgen had been studying the phenomenon of discharge of electricity through rarefied gases. By late 1860s it was known that if an evacuated glass tube is equipped with two electrodes and a voltage is applied, the glass opposite of the negative electrode (cathode) glows due to “cathode rays” (electrons) emitted from the cathode.

While working with a highly evacuated tube screened off by black paper, Röntgen discovered that a fluorescent screen brought near the tube, “lights up brilliantly and fluoresces, also if the screen is two meters away from the tube” (Röntgen 1895). This observation was entirely unexpected and soon became a classic case of accidental discovery.

Röntgen’s discovery was explained as the effect of a “new unknown form of invisible rays”. These new rays were shown to have a number of properties: they are emitted at the point of impact of cathode rays with wall of tube; travel in straight line; are highly penetrating; are able to impress a photographic plate; are neither reflected nor refracted. “For the sake of brevity” they were called “X-rays”. The new rays discovered by Röntgen were so spectacular that excited intense interest throughout the entire scientific world, and the first photographs obtained by them showed the by now reached ability to photograph the invisible.

From the year of their discovery to the first decade of twentieth century, X-rays were interpreted as electromagnetic waves of very short wavelength. However, in spite of this belief, no experimental demonstration of an analogy between light and X-rays existed. Furthermore, no reliable measurement of their wavelength was available. By 1912 both points were finally settled through the works, respectively, of Charles Grover Barkla and Arnold Sommerfeld. These accomplishments paved the way for the discovery of X-rays diffraction in crystals.

Röntgen had already attempted in 1895-97 to demonstrate the electromagnetic nature of X-rays by looking at an X-rays diffraction phenomenon by using both crystals and narrow slits. His attempts, however, got negative results (further efforts, to no avail as well, were made in 1899 by H. Haga and C.H. Wind, and in 1909 by B. Walter and R. Pohl, through wedge-shaped slits only a few microns wide). It was only in the 1906-1908 years that Barkla was able to provide strong evidence that X-rays consist of electromagnetic waves by studying the passage of X-rays through radiators. On the one hand, the scattered X-rays were indeed shown to be linearly polarized. On the other hand, heavy radiators were found to emit also a radiation “characteristic of the radiator material” (the so-called “fluorescence radiation”), in analogy with Stokes law on light fluorescence (i.e. the radiation was emitted only when primary X-rays were harder than secondary ones) (Barkla 1906,1908).

As for the measurement of X-rays wavelength, it was taken in early 1912 by Sommerfeld, who had charged P.P. Koch to measure Walter and Pohl’s plates obtained with a new photometer just devised by Koch. The light curves, analyzed by Sommerfeld by means of his new theory on diffraction through wedge-shaped slits, showed a diffraction effect. Sommerfeld found indeed a considerable spectral range of the X-rays, whose center laid at a wavelength close to 4 10⁻⁹ cm (Sommerfeld 1912).

3. The discovery of X-rays diffraction

In the fall of 1909 Max von Laue, former assistant to Max Planck in Berlin, went as Privatdozent to Munich at Sommerfeld’s Institute of Theoretical Physics. As he later wrote, “it turned out to be a matter of great good fortune that Sommerfeld passed to me the article ‘Wellenoptik’ (Wave optics) at that time to work upon for the Encyclopaedia of Mathematical Sciences” (Laue 1915). In the effort of writing the entry he developed indeed a new theory of diffraction, valid not only for a linear grating (optical grating), but also for a cross-grating (lattice grids).

Laue’s attention in Munich was drawn constantly to the question of the nature of X-rays, “owing to the influence of Röntgen’s work at this University” (Röntgen had moved from Wurzburg to Munich Institute of Experimental Physics in 1900) and as a consequence of “Sommerfeld’s active interest in X-rays” (Laue 1915). A further important circumstance was the presence in Munich of a third Institute, besides those headed by Röntgen and Sommerfeld: the Institute of Mineralogy and Crystallography. The idea of space-lattice arrangement of atoms was indeed widely known in Munich, mainly due to the role of P. Groth, director of this latest Institute.

In February 1912, P.P. Ewald, who was pursuing a doctorate on the optical properties of the lattice structure of crystals, under the guidance of Sommerfeld, asked Laue to help him to overcome some mathematical difficulties on the behavior of long electromagnetic waves in these structures (Ewald 1962). Having heard this, Laue “was suddenly struck by the obvious question” (Laue 1915), in view of his interests toward the X-rays:
what behavior one might expect by short waves, like waves of X-rays wavelengths ($10^{-9}$ cm), in a space lattice (constant of the order of $10^{-8}$ cm)?

Laue soon grasped that a crystal should behave for X-rays as a three-dimensional diffraction grating and that therefore space-lattice spectra would have to ensue.

At Laue's suggestion, W. Friedrich (Sommerfeld's assistant) and P. Knipping (a student graduating with Röntgen) volunteered to submit this possibility to experimental test.

By means of preliminary experiments with a copper sulphate crystal and a provisional apparatus, similar in principle to that used later, Friedrich and Knipping detected "a series of spots" together with a trace of the primary ray coming directly from the anticathode. The spots vanished if the same experiment was repeated with a "powdered" crystal, and similar results were obtained with other crystals. These results provided a strong support to Laue's idea of X-rays diffraction by crystals.

Friedrich and Knipping later made use of an improved apparatus, where a widespread and fairly powerful tube was used (a Müller X-rays tube), and where the orientation of the crystal was sharply defined by an accurate goniometer (Figure 1).

By this apparatus they obtained the first successful image of the X-rays diffraction in crystals, showing rings of fuzzy spots of elliptical shape, with the minor axis pointing to the overexposed centre of the black area produced by the primary ray (Figure 2) (Friedrich, Knipping and Laue 1912). To make the phenomenon more clear and easier to understand, they made the successful choice of using a cubic system crystal (the corresponding spatial lattice is the simplest possible), a zinc blende crystal, rather than the triclinic copper sulphate, previously used. Also, the sample was a plain parallel plate (10 x 10 x 0.5 mm) cut parallel to a face so that the X-rays struck the crystal perpendicularly to cube face.


Figure 2. First successful photograph obtained by Friedrich and Knipping (source: Friedrich, Knipping, and Laue 1912)
Friedrich and Knipping found that the position of the spots was completely symmetrical in relation to the point of impact of the primary radiation. It was possible to see two pairs of planes of symmetry arranged perpendicular to each other. The fact that a completely fourfold symmetry is present on the plate was certainly the most beautiful demonstration of the space-lattice of the crystal, and of the fact that no other property than the space lattice is involved.

Other orientations of the zinc blende sample were used, e.g., if the zinc blende was irradiated along the threefold axis or the twofold axis, one could see the corresponding threefold or twofold symmetry. Also, additional samples were used, like rock salt and diamond plate.

To explain the images obtained, Laue developed the (yet nonexistent) diffraction theory for a space-lattice upon the basis of his article for the German Encyclopedia. He resumed his equation for a linear lattice and wrote it three times corresponding to the three periodicities of a space lattice. The observed rings of rays could thus be related to the cones of rays demanded separately by each of the three conditions of constructive interference. The spatial lattice considered was the most general one, that is the triclinic type (the edges of the elementary parallelepiped may thus have any lengths and be inclined at any angles to one other).

The comparison of the theory with the experimental data was done by Laue in the simplest case, namely that of zinc blende. He arrived at the conclusion that the diagrams were perfectly explainable on the assumption that the X-rays spectrum, rather than being continuous, contained only a number of discrete wavelengths and that these ones are responsible for the spots.

The discovery of X-rays diffraction in crystals benefited not only the lattice theory of crystals, but also the wave conception of X-rays. In fact, it was the triumph of this theory.

4. A new interpretation

William Henry Bragg, Cavendish Professor of Physics at the University of Leeds, tried to explain the effect observed by Friedrich, Knipping and Laue by his corpuscular hypothesis of X-rays. This approach, however, was soon abandoned and he, jointly with his son, the physicist William Lawrence Bragg from the University of Cambridge, adopted a wave conception of X-rays and came to the conclusion that Laue’s was indeed a diffraction effect.

W.L. Bragg, however, suggested that Laue’s explanation of the diffraction pattern was incorrect and unnecessarily complex. In order to explain the place of the spots, Laue was indeed forced to assume that only a few definite wavelengths are present in the incident beam. W.L. Bragg assumed instead that the X-rays beam is composed of a continuous range of wavelengths and that the diffraction patterns are due to an effect of reflection of the beam upon the crystal planes.

After having observed that the points of a space lattice may be arranged in a series of planes, parallel and equidistant from each other (the simplest ones being the cleavage planes of the crystal), W.L. Bragg regarded “each interference maximum as due to the reflection of the X-rays in the systems of this plane” (Bragg 1913).

For a given wavelengths, the condition for the maxima was given by the law (eventually known as Bragg law)

$$n\lambda = 2d \sin \theta$$

where \( n \) is an integer, \( \theta \) is the glancing angle, and \( d \) is the spacing of the planes.

Considered thus, W.L. Bragg wrote, “the crystal actually ‘manufactures’ light of definite wavelengths, much as … a diffraction grating does” (Bragg 1913).

W.L. Bragg applied this new way of interpreting the diffraction pattern (that does not contradict Laue’s theory) to the zinc blende photographs analyzed by Laue. He assumed, following a suggestion by the chemist William Pope (Cambridge), that the zinc blende was a face centered cubic structure instead of, as assumed by Laue, a simple cubic structure (this assumption had indeed led Laue to estimate the cell size of the cubic lattice as smaller than \( \sqrt[3]{4} \) and forced him to assume that only some wavelengths were present in the X-rays beam).

By this assumption, Bragg found that all the spots can be readily explained, also if other crystals were considered (figure 3).
On December 1912, W.L. Bragg carried out an experiment on a slip of mica and observed the specular reflection of the surface of the crystal. This experiment opened up a period of close collaboration between father and son which is perhaps unique in the history of the science, both for its lasting intensity and the importance of the resulting discoveries. In January 1913 W.H. Bragg succeeded in detecting the reflected rays with a ionization chamber, and two months later developed the first X-rays spectrometer, the instruments which for decades to come was the main tool for crystal structure analysis (it is an apparatus similar to an optical spectrometer in arrangement, an ionization chamber taking the place of a telescope) (Bragg and Bragg 1913).

By this new instrument, the Braggs measured the spectral distribution of the X-rays of their tube by using anticathodes of platinum, osmium, etc, and identified the K and L characteristic radiations discovered by Barkla in 1911. These radiations, could be recognized also in the reflection from the faces of crystal. Since April 1913 the focus of Bragg’s work changed from the study of X-rays to the study of the structure of a crystal. By using the monochromatic K and L lines and measuring the angles at which these lines appeared after being reflected by the crystal, they could use the Bragg law on the reverse, that is to determine $d$ and thus the structure of the crystal. By this method, several structures were confirmed and others discovered. For example, in July 1913 the Braggs studied the structure of diamond and discovered the tetrahedral arrangement of carbon atoms. At the end of the same year the crystal structure analysis became a standard procedure.

The importance, and also the history, of the discovery of X-rays diffraction is illustrated by the three Nobel prizes in Physics awarded between 1914 and 1917 for contributions within this field: to Laue in 1914 “for his discovery of the diffraction of X-rays by crystals”, to the Braggs in 1915 “for their services in the analysis of crystal structure by means of X-rays”, and to Barkla in 1917 “for his discovery of the characteristic Röntgen radiation of the elements”.

Only a Nobel is oddly missing, notwithstanding a large number of nominations: Sommerfeld’s one (Crawford 2002).

5. From X-rays spectroscopy to the DNA

In the period 1915-1920, following the fundamental Bragg’s accomplishments, the X-rays spectroscopy laid the foundations for its successive development. Among the main results of this period are: accurate measurements of the X-rays wavelengths; analysis of large numbers of simple crystals by the new technique; discovery of a method to reliably measure the intensity of the reflected X-rays; measurement of Debye effect (that is the influence of temperature on the magnitude of X-rays reflection); development of Darwin’s formulas for the intensity of X-rays reflection in crystals; understanding that each crystal diffraction corresponds to a Fourier component of the density of crystal; availability of a new set of crystal substances by the powder method, that in turn opens the way to the analysis of microcrystalline materials (Ewald 1962).

In the 1920s the X-rays spectroscopy becomes a quantitative science and is applied to increasingly complex structures, e.g. organic crystals. By studying naphthalene and anthracene W.L. Bragg showed in 1922 that the shapes of these molecules expected by organic chemistry fit well with actual measurements. In 1929

---

**Figure 3.** Schematic representation of the reflection by a crystal of rock salt (NaCl) of an heterochromatic X-rays incident beam (Richtmyer, F.K. (1934). *Introduction to modern physics*, 2nd edition, McGraw-Hill, New York)
Kathleen Lonsdale discovered the structure of benzene and established that the derivatives of benzene are flat thereby putting an end to the mystery of aromatic hydrocarbons bonds. In 1925 the 2D Fourier analysis for crystal analysis is developed. In 1935 W.L. Patterson published a significant paper, introducing an important theoretical tool, the Patterson function, into the X-rays crystal structure analysis (Ewald 1962). In late 1930s the first studies on biological macromolecules are pursued, and to 1930 are dated the first photographs of diffraction patterns from DNA fibres, obtained by Florence Bell, at the William Astbury Laboratory in Leeds. A new important photograph of DNA was taken in 1951, still at Astbury Laboratory, by Elwyn Beighton (Hall 2014).

However, the understanding of DNA structure required a theoretical discovery made in the same year by Linus Pauling and Robert Corey: the α-helix structure of proteins. In 1953 Pauling himself attempted to understand the DNA structure by this novel idea. His triple-helical model turned out, however, to be wrong (Pauling and Corey 1953). The correct, double helix, model was suggested shortly later, still in 1953, by James Watson and Francis Crick with the help of the biophysicist Maurice Wilkins (Watson and Crick 1953; Wilkins, Stokes and Wilson 1953). This model was confirmed, and perhaps inspired, by an X-rays diffraction photograph of DNA obtained one year earlier (1952) by Raymond Gosling under Rosalind Franklin supervision at King’s College of London (Franklin and Gosling 1953).

For this discovery Crick, Watson and Wilkins were awarded the Nobel Prize in Medicine 1962. Franklin untimely died in 1958 and was therefore inelegible for nomination to the Nobel Prize. Her name, however, has lived on in history thanks to “Photo 51”: a lasting symbol of the X-rays spectroscopy triumph (figure 4).

Figure 4. Gosling and Franklin’s X-rays diffraction photograph of DNA (Photo 51) (source: https://askabiologist.asu.edu/Rosalind_Franklin-DNA).

6. Historical (and educational) conclusions
The above account shows that the discovery of X-rays diffraction was the final outcome of a lengthy process requiring a number of conditions: the success of the wave theory of X-rays mainly through Barkla’s discovery of the fluorescence rays; the reliable estimate of X-rays wavelength; the emergence of an interest toward the crystal optics and the crystal lattice structure; and, finally, the development of an experimental expertise on X-rays and the commercial availability of fairly powerful X-rays tubes. All these conditions were met by 1912, particularly at the Sommerfeld’s Department in Munich, where the scientific climate was favorable to Laue’s discovery.

However, even if the search of X-rays diffraction was in the air in Munich, Laue was the one who had the idea that Nature gave us the right tool, that is a tool of resolving power high enough to diffract the X-rays, the crystal. Röntgen and others had looked for the diffraction by crystals, but to no avail. Laue succeeded where others had failed because he understood that the crystal may behave as a diffraction grating for X-rays. He knew what to look for and how to find it.

To make Laue’s discovery a powerful experimental method, however, a new instrument was necessary, W.H. Bragg’s X-rays spectrometer, and another fundamental idea was required, that is W.L. Bragg’s idea that the diffraction might be seen as the internal reflection by the crystal planes.
These are all historiographical conclusions. However, these conclusions have also an educational significance. This case study shows indeed the presence of a number of the characteristics features of science (Matthews 2012).

The emergence in Munich of the discovery of X-rays diffraction emphasizes the social and cultural embeddedness of scientific knowledge. The way in which a crystal changes, in Laue’s hands, into something new and unprecedented, that is a tool to observe the diffraction of X-rays, highlights other crucial features of science: the creative and imaginative nature of scientific knowledge, and the experimentation, or the Galilean importance of interfering with nature.

Lawrence Bragg’s ways of looking at Laue’s data shows the importance of idealization, or the fact that nature laws may not be always obvious in the immediate experience.

A final conclusion is in order. The discovery of X-rays diffraction, in turn, gave rise to the birth of a new field of science, the X-rays spectroscopy, that eventually led to one of the most significant discoveries of the 20th Century, the double helix model of the chromosome, thereby showing the role of models, and of their ubiquity in the history and current practice of science.

References
Barkla, C.G. (1908). Note on X-rays and scattered X-rays, Phil. Mag. 15, 288-296.
**Affiliation and address information**

Francesco Guerra  
Department of Physics  
Sapienza University of Rome and INFN section of Rome  
Piazzale A. Moro, 001. Rome, Italy  
e-mail: Francesco.guerra@roma.infn.it

Matteo Leone  
Department of Philosophy and Educational Sciences  
University of Turin  
Via Gaudenzio Ferrari 9, I-10124 Turin, Italy  
Campus of Savigliano, Via Garibaldi 6, I-12038 Savigliano (CN), Italy  
e-mail: matteo.leone@unito.it

Nadia Robotti  
Department of Physics  
University of Genova and INFN section of Genova  
Via Dodecaneso 33, I-16126 Genova, Italy  
e-mail: robotti@fisica.unige.it
A Teaching Proposal on Electrostatics Based on the History of Science through the Reading of Historical Texts and Argumentative Discussions

Marina Castells, Aikaterini Konstantinidou, Josep M. Cerveró
Universitat de Barcelona

Abstract
Researches on electrostatics’ conceptions found that students have ideas and conceptions that disagree with the scientific models and that might explain students’ learning difficulties. To favour the change of student’s ideas and conceptions, a teaching sequence that relies on a historical study of electrostatics is proposed. It begins with an exploration of electrostatics phenomena that students would do with everyday materials. About these phenomena they must draw their own explanations that will be shared and discussed in the class. The teacher will collect and summarize the ideas and explanations which are nearer the history of science. A brief history of electrostatics is introduced then, and some texts from scientists are used in an activity role-play-debate type in which the "supporters of a single fluid" and "supporters of two fluids" have to present arguments for their model and/or against the other model to explain the phenomena observed in the exploration phase. At following, students will read texts related to science applications, the main aim of this activity is to relate electrostatics phenomena with current electricity. The first text explains how Franklin understood the nature of the lightning and the lightning rod and the second is a chapter of a roman about one historical episode situated in the Barcelona of XVIII. Students will use the historical models of one and of two fluids to explain these two phenomena, and will compare them with the scientific explanation of the “accepted” science of nowadays introduced by the teacher. With this type of teaching proposal, conceptual aspect of electrostatics will be learnt, but also they will learn about the nature and history of science and culture, as well as about argumentation.

Keywords
Electrostatics; Secondary Education; Pre-service Primary Education; Argumentation; History of Science; Science Communication

1. Introduction
History of Science and Science Education
The History of Science (HS) has been fundamental for the development of Science Education to which it contributes in several aspects like:
• the theoretical bases of Science Education by its relationship with the New Philosophy of Science and the Sociology of Science (Bachelard, 1938; Duschl, 1990; Izquierdo & Arduiz, 2003);
• the comprehension about the Nature of Science (NOS) (as it is built, legitimated, and communicated, actions that require argumentation and rhetoric in a central place) (Holton, 1978; Gross, 1996; Pera & Shea, 1991);
• epistemologies of nowadays consider that the Science advances by solving problems and decision taking, activities carried on by humans (Laudan, 1978; Giere, 1992);
• the inspiration for new science teaching approaches of the curricula and for the design of specific Teaching Sequences (TS) with HS as a possible context, or a source for teaching approaches and learning activities in science classes (Matthews, 1994a,b; Holton, 1978; Heering et al., 2013);
• to bring a valuable information to help teachers in the comprehension of the science ideas & conceptions of students, and so, of the difficulties of some specific conceptual changes of students; as well information about common sense reasoning and arguments students may given (Bachelard, 1938; Benseghir & Closset, 1996; Viennot, 1996; Seraglou et al., 1998; Castells & Konstantinidou, 2008);
• specific approaches, ideas, and resources for the Teacher Training courses (Arons 1988; Furió & Guisasola, 1998; Dawkins and Glatthon, 1998).
There is agreement among the experts about the NOS (McComas, 1998; Millar & Osborne, 1998) being part of the science scholar curricula, and this idea reinforces our hypothesis that a TS based on aspects of HS, and students’ debates about historical or popularization texts related to specific topics of science may be a good proposal to teach science and about science, and also about history and culture.

**Researches about students’ conceptions in science**

Researches about students’ conceptions in science, that have been carried on for more than 30 years (Driver et al., 1994; Pfund & Duit, 1998; Duit, 2009) confirms the difference between the science ideas and conceptions of students and the scientific knowledge agreed in the community of scientists. Quite often students’ ideas are incompatible with physics views (Saltiel & Malgrange, 1980; Duit et al., 2007). This also holds true for students ‘more general patterns of thinking and reasoning’ (Arons, 1988; 1997; Viennot, 1996; Viennot, 2014). Many researchers and experts on Science Education think that those differences may cause many of the difficulties students have in their learning about some topics. The need of conceptual change is accepted by experts but also there is agreement about how difficult this change may be in some cases, as it had happened in the development of science (Bachelard, 1938; McCloskey 1983).

Some experts agree that it is very difficult that students will discover the scientific knowledge to interpret the world on their own, and so, the school has to bring this scientific way to see the world to them (Guidoni, 1985; Leach and Scott, 2002; Ogborn, 1996) and the teaching has to be sensitive to the need to guide these changes and to engage students in the process of learning science. One way to help students in this process is to bring the scientific knowledge through the reading of fragments of historical texts about science or from popularization books about which debates may be carried on in the science classes (Lochhead & Dufresne, 1989); but also by other ways, as through historical reconstructions; study of historical cases; historical narratives; or performing historical experiments, or activities based on historical controversies. The reading and work on biographies can be also very useful and engaging for the students and, so on. In fact, the use of HS is not new in SE although perhaps not enough research have been done about the students’ learning based on HS.

**Students’ misconceptions related to electrostatics**

Researches on students' conceptions on electrostatics found that students have ideas and concepts very different from the ones of the scientific models to interpret these phenomena (Benseghir & Closet, 1996; Furió et al., 2004). Among other, students consider electrostatics phenomena without any relation with the phenomena linked to current electricity and so, for them is very difficult to understand electric current based on the model of charges. (Arons, 1997; Soreoglou, 1998; Criado & Garcia-Carmona, 2009). Some researchers and teachers (Arons, 1997; Harrington, 1999; Knight, 2004) found students familiar with the terminology used in electricity and magnetism but that the familiarity with the terms doesn’t mean that they have a physics understanding associated to these terms. Researches on students’ misconceptions consider that those in electricity and magnetism are at least as widespread and significant, perhaps more, than in mechanics.

We collect here some alternative ideas on Electrostatics, mainly from Knight (2000), and that many researchers coincide to attribute to students and which ones we summarize at following:

- Students don’t distinguish clearly the electric attractions from the magnetic ones. Some of them neither from the gravitatory ones. Some students say that the north magnetic pole repulses the positive electric charges. That means they may have a big confusion between attractions and repulsions that have to them a very different nature.

- Many students think that the isolated materials cannot be charged. Part of this difficulty is that students do not differentiate between charge and motion of charge (current). Because the current will not flow through an insulator (no motion of charge) students erroneously conclude that the insulator cannot be charged and they don’t distinguish between an object (insulator/conductor) and its state of charge (charged or neutral).

- Some students think about the charge as an object more than a property of the matter. Or some may think a charge is a substance that can be painted on a matter.

- Relating everyday phenomena some students think that the lightning rod are useful to collect the lightnings and because of this, they don’t arrive to the houses.
Some students think that “neutral” is a third type of charge.

Students, in general, don’t recognize the charge conservation.

They think there is a fundamental reason which do that the electrons has to be negative.

Some students think that an object positively charged has received an excess of protons and that the protons can move as the electrons do into many materials.

Students don’t have a good comprehension of the structure and of atomically properties of the solid materials. They don’t know what does neutral, not neutral or charged means at an atomic level means.

Our research about students’ conceptions on electrostatics

Some pre-service primary education teachers in the University of Barcelona have answered some questions about electricity phenomena, some of these about electrostatics. These students didn’t have any specific scientific or technologic background. The results of the analysis of their answers mainly agree with the findings of other researches edited in journals. We will not comment here about theses answers’ students because the extension of this paper and that coincidence with other findings.

2. The teaching sequence

The Framework

Our perspective is near to the Didaktik tradition in Germany, to the 'Didactique Transposition' in French and Didactic Approach in some southern European countries, as Italy. I think the meaning we give in Catalonia to the word Didàctica is not very far from these German and French traditions. The meaning of Didaktik concerns the analytical process of transposition (of transformation) of human knowledge like domain-specific knowledge into knowledge for schooling. In this process, the content structure of a certain domain (e.g., Physics) has to be transformed into a content structure for instruction. The two structures are substantially different. We have below a summary adapted from Duit et al, 2007 of the process of construction of the content structure and key ideas for instruction.

![Figure 1. Didactical Reconstruction (Adapted from Duit et al. 2007)](image)

In this TS we will use some historical texts or popularization texts because they can be instructive and illuminating of the actual historical ups and downs and controversies in the development of Electricity.

Many textbooks, after forming the concept of “charge” and examining electrostatics phenomena in the context of frictional electricity, make a discontinuous jump to current electricity by simple asserting that electric circuits containing batteries involve “charge in motion” and begin to talk of electric current. To most students, however, it is far from obvious that the current and the “charge” that has been “caused” by friction are of the same nature. And this is a big problem in the Electricity comprehension (Arons, 1997). This is not a trivial matter, and had been a serious debate about it in the scientific community late on the 1830s.
(Castells, 2000). Faraday gave many attention on this problem. In the Electrical Researches [Faraday (1965)], there is a paper, dated on 1833 and titled “Identity of Electricities Derived from Different Sources,” in which Faraday describes several experiments related to “different electricities”. These “electricities” were referred by him as voltaic, common (frictional), magneto (from electromagnetic induction), thermo (from thermocouple), and animal electricity from some fishes. Through their experiments Faraday demonstrated that each of these types produces identical effects, and arrive to the following conclusion that electricity, whatever may be its source, is identical in its nature (Faraday, 1830s).

The aims of the Teaching Sequence
Our proposal focuses on the teaching-learning the topic of electrostatics for a secondary school, which is mainly inspired by or is fitting with the history of this part of the Electricity, but also taking account of the results of researches made on students’ science conceptions related to this topics other experts have done (Soroglou et al., 2004). Our aim is not giving to students a detailed history of the Electrostatics, but some aspects of the historical development of this topic with the support of some texts (historical or of popularization ones) about which the students may argue. The main idea that we want students to understand is that there are opposite theories or conceptualizations and interpretations of the same facts in a period of time. In our proposal we try also to relate the history of electrostatics with the students’ interpretations of some qualitative experiments carried on by them in the classes or at home.

In this way, our approach fits with a teaching sequence that incorporates some of the nowadays agreements in science education, among other which consider in science classes we should try to answer questions as: What the scientists know? Which ideas, concepts, and models we select to learn in our science classes? Why? Which are the most relevant facts which interpretation has lead to the specific ideas or models? Or, how the scientists arrived to a specific explanatory model? Why we accept or belief these (.....)? How does an idea, concept, …, is related to other ones? The TS agrees with the nowadays Science Education recommendation of context-ualization of the scientific knowledge for the instruction (Gilbert et al., 2010). We participate of the Socioconstructivism (Vygotsky, 1978) perspective, and we are also interested to help the development of the Critical Thinking of our students in the meaning of Arons (1997) and considering also aspects of values. (See Figure 2)

The sketch of the Teaching Sequence about Electrostatics
From the results of our research about students’ conceptions on electrostatics, from our study of the historical development of electricity (Castells, 1996), from the reading of proposals that Science Education and HC experts have done (among other, Arons, 1978; Furió et al., 2004; Seroglou et al., 1998) and the agreements nowadays exists between experts in science teaching we will sketch a proposal of a Electrostatics’ TS and contextualized on the HS of this part of the electricity and also on a periode of history in a specific place and cultural context.

I. Exploration of electrostatic phenomena in peer-groups.
II. **Brief history of electrostatics** is introduced, and some *readings from o related to the HC are proposed* to students.

III. **Debates and arguments in the class using ancient models (of one or two fluids) to interpret the electrostatics phenomena.**

IV. **New phenomena and instruments** are introduced to be explored and interpreted with the same models.

V. **Reading texts about applications of electrostatics and related to HS** (the discovery of the Lightning rod by Franklin) and HS related to our country, in particular to Barcelona and an ancient Academy from 1764.

VI. **Introduction of the accepted explanatory model of electrostatics by the teacher and by students.**

VII. **Students in peer-group compare one of the historical models with the nowadays model** and argue in favour or against each one.

VIII. **A more modern application using the Van der Graaf generator to produce electrostatics effects is experimented.**

At following we will detail more about the main relevant elements of the TS proposed.

I. Exploration of Electrostatics’ phenomena

a) **Exploration of electrostatic phenomena of attraction and repulsion** with everyday materials in peer-group is performed:

   ° **Attraction and repulsion of bodies of small weight** (water, pendulum, small pieces of paper, of …) by electrified objects by friction (pen, globes, bar of glass …) with several different materials (silk, cotton, hear, wool…)

   ° **ASKING**
     - What happen?
     - Why do you think that happen?
     - How do you can explain this?
     - With which other phenomena do you relate them?

   If students don’t have been aware of the repulsion with the same objects once they are put in contact with the small bodies, the teacher has to ask to students to put attention on this phenomenon of repulsion.

b) **Exploration about conductors and isolators**

   ° **Exploration with conductors** (metal bars, …) and **with isolator materials** (plastic bar, …) to see if there are differences.

   ° **ASKING**
     - What happen?
     - Why do you think that happen?
     - How do you can explain this?
     - With which other phenomena do you relate them?

c) **Explicitation and argumentation about the interpretative models**

   Every group presents their interpretations of the phenomena and a whole group class about the different interpretations is then performed.

   The teacher guide the whole class debate and she/he will try to find some interpretations similar to the historical interpretative models of XVIII Century, in fact, the *theory of one fluid* (Franklin; Aepinus and others) or the one of *two fluids* (Symmer; Coulomb and others).

II. **Brief history of electrostatics and some readings from o related to the HS**

   The teachers elaborate the summary of the history of electrostatics using relevant bibliography (books and papers they can found in the University of Barcelona or in other libraries, as in the library of ‘Real Acadèmia de Ciències i Arts’ in Barcelona). Some references are included in this paper.

   Students have to read two texts about two ancient interpretative models:
Text 1: One fragment of EXPERIMENTS AND OBSERVATION ON ELECTRICITY MADE AT PHILADELPHIA in AMERICA, BY M. BENJAMIN FRANKLIN, L. L. D. and F.R.S, LONDON; D. Henry & F. Newbery, 1749, in which Franklin defends the theory of one fluid to interpret the electrostatic phenomena, and

Text 2: A fragment of the Chapter 2 of the book from Einstein A. & Infeld, L. (1939) The Evolution of the Physics, in which the theory of the two fluids is summarized by Einstein and Infeld.¹

To elaborate the TEXT 1 we have used a French translation from 1749. In concrete, our copy is from a book which belonged to Francesc Salvà Campillo, a Catalan scientist in the XVIII Century (about which we will comment below) that we have translated to Catalan language for our students in Barcelona. As the title says in this volume, there are also some letters and papers on other philosophical issues. We choice the LETTERS ON ELECTRICITY from M. Benjamin Franklin of Philadelphia (America) to Peter Collinson, from the Royale Society of London.

The Letter I is from 1749, and it is the one we have used in our Teaching Unit.

Figure 3. The cover of the book of Franklin, 1749

OPINIONS AND CONJECTURES


1. The electrical matter consists of particles extremely subtile, since it can permeate common matter, even the densest metals, with such ease and freedom as not to receive any perceptible resistance.

2. If any one should doubt whether the electrical matter passes through the substance of bodies, or only over and along their surfaces, a shock from an electrified large glass jar, taken through his own body, will probably convince him.

3. Electrical matter differs from common matter in this, that the parts of the latter mutually attract, those of the former mutually repel each other. Hence the appearing divergence in a stream of electrified effluvia.

4. But, though the particles of electrical matter do repel each other, they are strongly attracted by all other matter²: this has to be understood from which are susceptible of this.

5. From these three things, the extreme subtility of the electrical matter, the mutual repulsion of its parts and the strong attraction between them and other matter, arises this effect, that, when a quantity of electrical matter is applied to a mass of common matter, of any bigness or length, within our observation (which hat not already got its quantity), it is immediately and equally diffused through the whole.

6. Thus, common matter is a kind of sponge to the electrical fluid. And as a sponge would receive no water, if the parts of water were not smaller than the pores of the sponge; and even then but slowly, if there were not a mutual attraction between those parts and the parts of the sponge; and would still imbibe it faster, if the mutual attraction among the parts of the water did not impede, some force being required to separate them; and fastest, if, instead of attraction, there were a mutual repulsion among those parts, which would act in conjunction with the attraction of the sponge; so is the case between the electrical and common matter.

¹ We don’t copy here this text 2 because there is not enough space in this paper and because the book is very easy to drawn down from Internet.

² See the ingenious Essays on Electricity, in the Transactions Phil, by Mr. Elliot.
7. But in common matter there is (generally) as much of the electrical, as it will contain within its substance. If more is added, it lies without upon the surface, and forms what we call an electrical atmosphere; and then the body is said to be electrified.

18. These explanations of the power and operation of points, when they first occurred to me, and while they first floated in my mind, appeared perfectly satisfactory; but now I have written them, and considered them more closely, I must own I have some doubts about them; yet, as I have at present nothing better to offer in their stead, I do not cross them out; for, even a bad solution read, and its faults discovered, has often given rise to a good one, in the mind of an ingenious reader.

19. Nor is it of much importance to us to know the manner in which nature executes her laws; it is enough if we know the laws themselves. It is of real use to know that China left in the air unsupported will fall and break; but how it comes to fall, and why it breaks, are matters of speculation. It is a pleasure indeed to know them, but we can preserve our China without it.

III. Debates and arguments in the class.
Students are divided in two groups: “supporters of a single electric fluid” and “supporters of two electric fluids” and a roll play activity is performed. Both groups have to give arguments to defend their model and to refute the other group’s model. It is important not only to take a position but also to give arguments that other students may refute.

IV. New experiments and instruments in Electrostatics
a) Using the electrofor and the electroscope.
Basically the process is the same as have been done with the other explorations and interpretations. The activity focuses on the storage up of electricity with the electrofor and on the detection of the electricity with the electroscope. The instruments will be also useful to differentiate between the concepts of electrization by contact and electrization by influence.

b) Exploration and interpretation with the Leiden jar
It is convenient to build a Leyden jar in the class or at home and it may be used as another instrument that can store up “electric fluid” or electrical charge in the modern language and that had been a very important instrument in the historical development of electrostatics. Students could read some fragments of any ancient book about the Leyden jar or, particularly, in the book of Franklin in which there is a summary of the history of Electricity in which the Leyden jar is deeply commented. The instrument may be presented at the first level as an instrument that can store up “electric fluid”, if the concept of condenser is not introduced yet to students. The experiments performed will be described and interpreted by students using both models of one or of two fluids following the same methodology of the other explorations and interpretations but now interchanging their models.

c) Exploration of conduction of electricity to big distances.
Exploration and interpretation of phenomena of electricity conduction through conductors is carried on. The electrofor may be used as storage of electricity, and better if the Leyden jar is used because its great historical relevance.

V. Reading texts about applications of Electrostatics and exploring ideas about phenomena
a) Exploration of the students’ conceptions about the Lightning and the Lightning rod,
This part of the TS could have been done in several ways. One could be coming from the reading of a book of popularization about Franklin and some of his experiments and ideas. At the end of the activity the teacher ask some questions to the students which they answer in peers. The book is *Vida de Benjamin Franklin*³. The proposed fragments to discuss in class are the fragment which is a description of the experiments that Franklin had performed to understand the electric nature of the lightning and how to construct an instrument to protect the buildings from the lightning.

We suggest students may extend their readings at home about the *life and experiments of Franklin* with other parts of this book. The book is part of a collection named LIFE OF GREAT MEN edited in Barcelona many years ago. The book doesn’t present only Franklin as a scientist, but also the man with his values and social actions he did, and his life as politician too, acting very strong in favour of the independence of his country from U.K. We think this book should be a recommendable reading for our students nowadays.

b) Exploring another application of Electrostatic in a specific cultural context and period of time. The electric telegraph (XVIII century)

*Individual reading, peer–group discussion and whole group discussion and synthesis.*

The students will read a text about a new application of Electrostatics: the case of *the electric telegraph* by Salvà Campillo, from a novel from Riera (2005)⁴ based on historical facts in Barcelona at the XVIII Century. This roman can be an interesting resource to teach about science, nature of science, as well as about history and culture of a key episode in the development of science in a specific social and political context, the Catalan one, not many years after the Succession War (1714).

The chapter 4 is related to Electrostatics, in which it is presented the historical case of Salvà Campillo performing an exhibition in front of the King of Spain (Charles IV) and his family with the telegraph he had invented. In this telegraph several Leyden Jars with the electric fluid stored were connected to conductors and then the messages could be sending through theses conductors from one place to another.

The European context in which many Science Academies and other Scientific Societies were created could a larger context of the TS. In fact, the plot of the novel is related to some academics of the ’Real Academia de Ciencias y Artes’ (1764). Two main characters are: Francesc Salvà Campillo (1751-1828) (which worked on topics of Physics and Medicine) (1751-1828) and Antoni Martí Franquès (1750-1832) (which worked on topics of Chemistry and Botanics).

There are several didactical strategies teachers can use to work in the classes with this text.

---

³ Jorge Santelmo (1934) *Vida de Benjamin Franklin*, Barcelona: Seix y Barral Eds. Due to lack of space this text is not included here.

⁴ Santiago Riera Tuèbols (2005) *La ciutat del canvi* (The town of the change) which is a novel based on historical facts in Barcelona at the XVIII Century (chapter 5, pp 53-67).
VI. Introduction of the scientific accepted explanatory model by the teacher and by students looking for information in books or Internet, of Electrostatics of nowadays.

VII. Students in peer-group compare one of the historical models with the nowadays model. They could look for the advantageous and the inconvenient of the models through argumentation. Perhaps they may do new observations and interpretations. Every peer-group writes a summary of these. These summaries will be shared in the whole class guided by the teacher trough debates or agreements among all the groups.

VIII. A more modern application
Conduction of electricity through conductors (exploration, interpretation, experimentation) and sparks production with the Van der Graff.

These observations can help students to understand the lightning and to change their conception about the nature of electrostatics and of electricity of current, which is the same. With the Van der Graff it is possible to produce sparks very far from the generator, and so students can relate the electricity by friction and the electricity of current.

To conclude we can say that with this type of teaching proposal, students will learn conceptual aspects of electrostatics as well about experiments’ interpretation, but also they will learn about the nature and history of science and culture, as well as about argumentation.

Acknowledgements
The present research and proposal was supported by ARCE 2013-UB (Agrupació de Recerca en Ciències de l’Educació, Universitat de Barcelona) to GRIEC-UB (Grup de recerca en Ciències Education); and by MEC Project Nº EDU-2012-38022-C02-02 (Coo. C. Márquez UAB, LIEC-UAB, Llenguatge i Ensenyament de les Ciències)

References


Heilbron, J. (1979) Electricity in the 17th and 18th Centuries: A study in Early Modern Physics, University of California Press, Berkeley


Holton, G. (1979) Introducción a los Conceptos y a las ideas de las Ciencias físicas, Barcelona: Reverté

Iglésies, J. (1965) La Contribució Catalana al Telègraf Elèctric (Francesc Salvà i Campillo 1751 – 1718) Barcelona: Rafael Dalmau Eds

Iglésies, J. (1964) La Real Academia de Ciencias Naturales y Artes en el siglo XVIII, Memorias de la Real Academia de Ciencias y Artes de Barcelona, 3ra época, núm. 707, vol 36, núm. 1

Izquierdo, M. (1996) Relación entre la historia y la filosofia de la ciencia y la enseñanza de las ciencias. Alambique, 8, 1-21


Whittaker, E. (1951) *A History of the Theories of Aeter and Electricity*, T. Nelson and sons

**Affiliation and address information**

Marina Castells Llananera
GRIEC-UB (Universitat de Barcelona, Group Research and Innovation on Science Education)
Campus Mundet
Passeig de la Vall d’Hebron, 171
(08035) Barcelona, Catalonia, Spain

LICEC – UAB (Universitat Autònoma de Barcelona, Language and Context in Science Education)
E-mail: marina.castells@ub.edu
Nature of Science in Science Education: a Proposal Based on ‘Themes’

André Ferrer Pinto Martins; Jim Ryder
Universidade Federal do Rio Grande do Norte, Brazil; University of Leeds, UK

Abstract
This theoretical analysis addresses some issues related to knowledge about science in science education, in general, and in physics education, in particular. We point out the existence of a “consensus view” about Nature of Science (NOS) in science education research literature. Then we argue that: 1) despite its relevance to science teaching, the “consensus view” hides some important divergences that should not be overlooked. In particular, we challenge the idea of the existence of a consensus, showing that there are different routes, terminologies, starting points and conclusions when we analyse literature elaborating this “consensus”; 2) there are some problematic statements in the “consensus view”; and 3) taken (1) and (2) into account, we suggest a more open, pluralistic and heterogeneous approach to deal with the knowledge about science in school science curriculum.

Keywords
Knowledge about science; nature of science; epistemology; science curriculum

1. Introduction
It is not new that the community of science educators acknowledges the importance of learning about science within science education. This theme has a long history in the area and remains a challenge to be faced. In addition to the contents present at various teaching levels, a deeper understanding of how science works, how scientific knowledge is produced, validated and communicated, as well as the very nature of this knowledge, in regard to its epistemological particularities, has been seen as something to be sought and of value for science education.

But… what to teach? One way to tackle this question is in a negative manner, identifying “what should not be taught”. Over the past decades, many works in the area revealed the existence of a large number of misguided and naïve conceptions about science, held both by students and teachers, such as: the empirical-inductive view of science; a rigid (algorithmic, exact, infallible) view of scientific methodology; cumulative and linear views of the History of Science; decontextualized and socially neutral views of the activities of scientists; individualistic and elitist views of science, among others (see, e.g. Driver et al. 1996; Fernandez et al. 2002; Lederman 1992, 2007).

Identifying mistaken and naïve conceptions of scientific work represented significant progress in science education research, and an understanding of what “should not be taught”. But one can tackle the issue of “what to teach?” in a positive manner, i.e., seeking to build an understanding of what would be a set of themes, aspects, issues, suitable with the prospect of a teaching about sciences. This path is potentially more complex and it has a long history. Particularly over the past few years it has led to the establishment of what is conventionally called the “consensus view” of the Nature of Science (NOS) – this terminology, incidentally, came to prevail in the specialized literature on this. The so-called “consensus view” (CV) has received diverse types of criticism (e.g. Alters 1997; Rudolph 2000; Clough 2007; Allchin 2011; Irzik and Nola 2011; Van Dijk 2011; Matthews 2012; Dushl and Grandy 2013) while, on the other hand, has been developed and gaining support (e.g. Lederman 1992, 2007; McComas et al. 1998; Osborne et al. 2003; McComas 2008; Abd-El-Khalick 2012a, 2012b). Given this debate it is important to ask: is this the best way to build curricula and think about what to teach?

Following from the above, this article aims to defend three central ideas: (1) Despite its relevance to science teaching, the “consensus view” hides some important divergences that should not be overlooked; (2) There are some problematic statements in the “consensus view”; (3) Taken (1) and (2) into account, we suggest a more open, pluralistic and heterogeneous approach to deal with the knowledge about science in school science curriculum.

2. The “consensus view”: an approach and some criticisms
We begin with point (1). Firstly, it is important to state that, for us, it is clear that a consensus on a philosophical level is unattainable. Science is a much too complex social venture to enable a single characterization. Aware of the lack of consensus on a philosophical level, the consensus view (CV) seeks to present a set of factors about which there would be a broad consensus regarding what is expected to be present in school science curriculum. A pragmatic consensus on certain aspects would be valid for the inclusion of NOS contents in schools. In this sense, the criticism addressed to the CV regarding a lack of consensus among philosophers with respect to a characterization of science (e.g. in Alters 1997) loses some of its strength.

But it is precisely this second level of consensus, valid for school science education, which we will address here. When we look at the specialized literature in this respect we find studies that show the existence of multiple *paths/routes* to build an understanding related to the question “what to teach?” about NOS and also the existence of different *terminologies, starting points and conclusions.*

Principal texts supporting the establishment of the CV, such as McComas and Olson (1998), McComas et al. (1998) and McComas (2008), e.g., are based on official science education standards documents, whose analysis leads to the creation of NOS tenets. This path may be considered more normative (or nomothetic) and scholarly, and can be illustrated by the very categories used in the classification of the ideas presented in these documents (Philosophy of science, History of science, Psychology of science and Sociology of science), which represent areas of academic knowledge somehow related to the NOS theme.

Others, Driver et al. (1996) and Ryder (2001, 2002) for example, take a different path. In the first case, a description of “what to teach?” is reached starting from an empirical study with students between nine and sixteen years old. The last two works start from an analysis of thirty one case studies related to situations involving the interaction of people with science outside the context of formal education. This results in some suggestions for specific areas of NOS that are needed within school curricula aiming to promote the goals of scientific literacy. This latter path may be considered more empirical and, in a sense, more ideographic (to use the very distinction made by Driver et al. 1996, p. 58).

As a result, there are differences in the conclusions. Although there is significant similarity between aspects of NOS identified in these studies, there are also significant differences. The list of NOS tenets contains short, direct and domain-general statements about science, balancing, in a sense, contents of the four areas (Philosophy of science, History of science, Psychology of science and Sociology of science). In Driver et al. (1996, p. 144-147) we find another classification (“epistemological basis for scientific knowledge claims” and “science as a social enterprise”), whose subcategories are described in more lengthy and exhaustive way. In Ryder (2001, p. 8), the categories with the closest connection to the NOS thematic are: collecting and evaluating data; interpreting data; modelling in science; uncertainty in science, and science communication in the public domain. While issues related to sociology of science appear less represented in the studies of Ryder (2001, 2002), it seems evident that the CV does not consider more deeply the *processes of science,* which arise in such analyses of these latter works cited.

This is an important point. Thus, although McComas et al. (1998, p. 6) state: “There is no one way to do science (therefore, there is no universal step-by-step scientific method)”, information on methods does not go beyond this point. Similarly, although we can read in McComas (2008, p. 251) that: “(A) Science produces, demands and relies on empirical evidence” and “(B) Knowledge production in science shares many common factors and shared habits of mind, norms, logical thinking and methods such as careful observation and data recording, truthfulness in reporting, etc.”, a more detailed description of what such methods would be, or what is involved in collection and interpretation of data, is missing. Driver et al. (1996, p. 144) suggest the category “evaluation of evidence” that, among other aspects, emphasizes the importance of: “(…) understanding concepts of accuracy, reliability, validity and replicability (…); ways of organizing the collection of data so that logical inferences can be made about the influence of specific variables or features of a system (…)”. In Ryder (2001, p. 8) consideration of the processes of science is far more explicit in some of the study synthesis categories: Collecting and evaluating data (Assessing the quality of data and Study design); Interpreting data (Assessing the validity of interpretations in science; correlation and causation; considering alternative explanations; time horizons; Interpretation involves knowledge sources in addition to data; Multiple interpretations in science).
It does not seem appropriate to minimize such differences in routes, points of departure and conclusions, stating for example that the discussion of the processes of science\(^1\) is present implicitly in the CV. The differences are deeper than that and related directly to a consideration of what should be the object of teaching in classrooms and should, in one way or another, be present in curricula. At this point it is worth referring to the work of Osborne et al. (2003), which attempts to reconcile the CV with the results of an empirical study with experts from different fields (science educators, scientists, historians, philosophers and sociologists of science; experts engaged in work to improve the public understanding of science, and science expert teachers). Although there is some correlation between certain NOS tenets and themes emerging from the study with the Delphi methodology (Osborne et al. 2003, p. 713), it is precisely with reference to the processes and methods of science that correspondence seems unsupported: the ideas of “analysis and interpretation of data” (and the description of what this means) are broader than the CV claim that “science relies on empirical evidence”. The same goes for the theme “scientific method and critical testing”.

Another aspect of this discussion refers to the terminology present within many works. While the phrase “nature of science” has become commonplace in the specialized literature of science education and can be considered a “catch phrase” (Hipkins et al. 2005), other related studies prefer the term “knowledge about science”, “how science works”, “epistemology of science” or even “ideas-about-science”. This can even be seen in the choice made by the authors in relation to the keywords in each work (recently, an Editorial in Science & Education (Krogh and Nielsen 2013) revealed the existence of a debate about this question of terminology).

The differences pointed out above (in routes, starting points, terminologies and conclusions) suggest some limitation to a consensual perspective, even if restricted to the curricular inclusion of NOS contents. This limitation becomes more evident when we turn to some criticisms of the CV. Clough (2006, 2007), for example, points to the fact that the NOS tenets can be easily distorted by researchers, teachers and students, becoming something to be transmitted – more than investigated – in science classrooms. Thus, he proposes that nature of science aspects should be addressed as questions rather than tenets (e.g. “In what sense is scientific knowledge tentative? In what sense is it durable?” instead of the tenet “Scientific knowledge while durable, has a tentative character”). Allchin (2011, 2012) also criticizes the type of declarative knowledge presented in the lists of NOS tenets. For this author, these lists are “inherently incomplete and insufficient for functional scientific literacy” (Allchin 2011, p. 524). They omit many relevant items, for example the significant role of credibility, the social interaction of scientists, the peer review process, cognitive biases, fraud, among others (Allchin 2004, 2011). Irzik and Nola (2011) state that the CV has a number of shortcomings and weaknesses, the main one being to disregard the variations in the detail of nature of sciences across different areas of science. A similar issue had been raised by Rudolph (2000), for whom the particular practices of the various sciences should guide an understanding of the nature of science, rather than a universal conception of what science is. Similarly Matthews (2012) criticizes what he calls the “Lederman Programme”, arguing that NOS elements have to be more historically and philosophically refined. He proposes a change in terminology and in research focus: from Nature of Science (NOS) to Features of Science (FOS). Matthews claims that this shift to a more contextual and heterogeneous perspective would avoid some educational and philosophical pitfalls associated with the research in NOS.

### 3. Some problematic statements

Even accepting the limitations and simplifications inherent to the CV as well as the idea that the NOS tenets are general statements that require further detail, we consider that some aspects of the CV are unclear and/or problematic. Take, for example, the idea that “science has developed through ‘normal science’ and ‘revolution’ as described by Kuhn (1962)”, as appears in McComas (2008, p. 251). The particular view of science provided by Thomas Kuhn, notwithstanding it may have a large number of supporters in the area of science education, is far from unanimous, and this particular epistemology brings together several other controversial notions (e.g.: incommensurability, paradigm). It is entirely legitimate that someone has another view of the historical development of science and does not support to the conception of “revolution”. Thus, a commitment to a particular epistemology may be problematic\(^2\).

---

1. It is important to clarify that when we talk about “processes of science” we are not dealing with didactic strategies or conflating NOS issues and scientific inquiry, as Abd-El-Khalick (2012a) warns. We are referring to an explicit reflection on the methods and processes of science.

2. Although the reference to Kuhn does not appear in all versions and there are certainly other philosophical perspectives underlying the CV, this criticism is addressed to works where that particular ‘tenet’ is present.
Another important statement says: “Scientific knowledge is tentative, durable and self-correcting (This means that science cannot prove anything but scientific conclusions are still valuable and long lasting because of the way in which they are developed but mistakes will be discovered and corrected as part of the process)” (McComas 2008, p. 251, second stress added). On the one hand, it is fragile to state that “mistakes” will be discovered and corrected. On the other hand, it is quite plausible that the statement leads to think that a scientist is usually able to discover and correct their mistakes. Here again, a problem arises if we use Kuhn’s epistemology. After all, the practice of normal science shows that “errors” are often not fixed (or even perceived) by practitioners. The famous phrase of Max Planck, that a new scientific truth does not thrive because opponents see the reason, but because they eventually die and a new generation grows familiar with the new ideas, is emblematic here. It can be said that the statement made by the CV requires a long period of time. Still, the very idea of “errors” seem to be at odds with Kuhn’s notion of incommensurability and the idea that scientists who choose different paradigms live in “different worlds”, and suggest – implicitly – some linear and cumulative view of the construction of scientific knowledge.

Somewhat more problematic is the statement: “Science has a subjective element. In other words, ideas and observations in science are ‘theory-laden’”. We agree with the idea that science is “theory-laden”. However, it seems to us very different to say that science has a subjective element. These two statements do not say the same thing. One aspect much highlighted within the sociology of science and even by discussions on NOS in the science education area is the way in which science constitutes a socially shared knowledge, constructed collectively in a process of dialogue and, therefore, intersubjective. Scientific knowledge is endorsed by the scientific community, in a complex process which includes the peer review process. When we equate “theory-laden” with “subjective element”, we get the impression that the CV should be dismissed or overlooked. What has been said in this section is important views.

This view flirts dangerously with a commonsense view that equates “theory” with mere “opinion”, “personal view” (sometimes meaning an “abstract” – but still personal – view). It is not uncommon to hear something like: “I have a theory it is going to rain tomorrow”. Or: “advice is just theory; living is always very different”. This common usage of the term can have problematic consequences. For example, in the well-known debate between creationism and evolutionary theory, when the latter is seen as a mere “theory” (=opinion). We do not mean here that the CV is not aware of all this or it uses the term “theory” in common sense. The defence of a distinction between laws and theories (one of the NOS tenets) would point in the opposite direction. But the original statement that “science has a subjective element” may give rise to misunderstandings.

Our concern here is of similar nature to that exposed by Clough (2007) in the following passage:

Nature of science tenets may be easily misinterpreted and abused. Students often see things in black or white. For instance, when addressing the historical tentative character of science years ago while teaching high school science, my students would jump from the one extreme of seeing science as absolutely true knowledge to the other extreme as unreliable knowledge. Extensive effort was required to move them to a more middle ground position. Colleagues have told me of students who have asked why they have to learn science content if it’s always changing (Clough 2007).

The conclusion is not that the CV should be dismissed or overlooked. What has been said in this section is intended to emphasise that caution should be taken with certain statements (and with the whole set) when we think about curriculum or teacher training programs to deal, in the classroom, with NOS. The deconstruction of misconceptions about science must be accompanied by a careful construction of more current and appropriate views.

Given this complexity of issues and debates, how can the knowledge about NOS derived from research in science education guide the development of curricula? We consider this issue in the following section.

4. NOS in the curriculum: a proposal based on ‘themes’

The issues (1) and (2) treated in the previous sections lead us to conclude that a more adequate consideration of NOS in science curricula should start from a more open, pluralistic and heterogeneous perspective. The
idea of family resemblance (Irzik and Nola 2011) may be an interesting starting point for thinking about NOS contents. In any case, no list will be exhaustive and it will always have problems. Even if there was a consensus around such a list, enormous difficulties related to assessment and teacher training would remain. It seems clear to us, at this point, that lists as presented by the CV are useful to have as a reference to consult. An important next step is to construct proposals specially designed to address all levels of education and the various scientific disciplines (here the idea of family resemblance gains strength, since the characteristics of the various sciences, in relation to NOS, are different). As stated by Taber (2008), one should seek an “intellectually honest simplification” when thinking about contents to be taught. There are several valid approaches. For us, before we get to something like “NOS tenets”, it seems reasonable to think of something like “NOS themes”. Studies in the literature suggest possible paths. Following closely the book of Driver et al. (1996), we identify two main axes: the sociological and historical axis and the epistemological axis. The first axis would group themes relating to the role of the individual and the scientific community; intersubjectivity; moral, ethical and political issues; historical and social influences; science as part of culture; communication of knowledge. The second axis, a broader one, would group together themes relating to the origin of knowledge (experience vs. reason; role of observation, experience, logic and theoretical thinking; influence of the theory on experiment), methods, practices, procedures and processes of science (collection, analysis and evaluation of data; inference, correlation and causality; modelling in science; role of imagination and creativity; nature of explanation), and nature/content of the knowledge produced (role of laws and theories; notion of model; similarities and differences between science and other forms of knowledge).

Without intending to create lists or represent that idea exhaustively, we indicate in Table 1 the two axes, with examples of themes that could be explored.

Table 1 Axes for discussion about NOS content and examples of NOS themes

<table>
<thead>
<tr>
<th>Sociological and historical route/axis</th>
<th>Epistemological route/axis</th>
<th>Content / nature of knowledge produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem of the origin of (scientific) knowledge</td>
<td>Methods, procedures and processes of science</td>
<td></td>
</tr>
<tr>
<td>• Role of the individuals/subjects and the scientific community</td>
<td>• Subject(s) and object(s) of scientific knowledge</td>
<td>• Collection, interpretation, analysis and evaluation of data</td>
</tr>
<tr>
<td>• Intersubjectivity</td>
<td>• Empirical vs. theoretical</td>
<td>• Modelling</td>
</tr>
<tr>
<td>• Historical and social influences</td>
<td>• Role of observation, experiments, logic, rational arguments and theoretical thinking</td>
<td>• Observation and inference</td>
</tr>
<tr>
<td>• Moral, ethical and political issues</td>
<td>• Theoretical influences on observations and experiments</td>
<td>• Hypothesis, predictions and tests</td>
</tr>
<tr>
<td>• Science as part of a major culture</td>
<td>• {Differences between scientific areas/disciplines}</td>
<td>• Correlation and causality</td>
</tr>
<tr>
<td>• Aims of science / aims of scientists</td>
<td></td>
<td>• Nature of explanation in science</td>
</tr>
<tr>
<td>• Communication of scientific knowledge within scientific community and in a public domain</td>
<td></td>
<td>• Evaluation of theories</td>
</tr>
<tr>
<td>• Historical and contemporary controversies in science</td>
<td></td>
<td>• Role of analogies, imagination and creativity</td>
</tr>
<tr>
<td>• Science and other types of knowledge</td>
<td></td>
<td>• Common sense view about scientific method (step-by-step sequence)</td>
</tr>
<tr>
<td>• Science and technology</td>
<td></td>
<td>• Science and other</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Laws and theories</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Postulates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Notion of scientific model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Role of Mathematics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Power and limitations of scientific knowledge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Science and other types of knowledge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Science and technology</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• {Differences between scientific areas/disciplines}</td>
</tr>
</tbody>
</table>
These two major axes are obviously interrelated. The division is to some extent artificial because the aspects properly epistemic and distinctive of the “nature” of knowledge produced come from a construction that is collective (intersubjective), historical and social. The theme of the origin of knowledge (2nd axis), for example, can be put in terms of how it has been seen along the historical and social evolution of science (1st axis). Likewise, a theme like “aims of science” involves both the relationship science ↔ society (1st axis), which historically shaped the goals associated with the construction of this knowledge, as well as the type of relationship subject(s) ↔ object(s) (2nd axis), the basis of this construction. This theme can also relate to the idea of “nature of explanation in science” (2nd axis), since the way explanations and justifications of scientific knowledge are given relates to the goals and objectives associated with this knowledge.

A theme that can be approached from different perspectives is “science and other types of knowledge”. Considered from a historical and sociological (1st axis) point of view, we might explore historical and social differences between distinct cultures, as well as the gradual consolidation of science as a body of systematized knowledge, differing over the centuries from other forms of knowledge. From an epistemological point of view (2nd axis), the proper methods and processes of science are crucial to understand the differences between scientific and other types of knowledge. Moreover, it is precisely with regard to the nature/content of knowledge produced that distinctive features of science might be explored, such as its conjectural character, the notion of truth (not absolute), the idea of ruptures and continuities, the nature of change in science, the ideas of prediction, internal consistency and simplicity as well as characteristics of scientific language.

We conclude these brief comments about the Table 1 by pointing out that the differences between scientific areas/disciplines is something to be addressed under the different axes and themes. Historical (1st axis) differences, as well as epistemological (2nd axis) differences, such as the various methodologies used in different areas (in vitro, in vivo, double blind tests etc.), would be the object of attention. In this aspect, contextual and specific aspects of the various areas could be better explored.

A further analysis might involve taking these axes and themes and describing in more detail what should be taught. This would lead us to something similar to the NOS tenets proposed by CV (although works of this kind do not address exactly these same axes and themes). In a sense, the work of Abd-El-Khalic (2012a, 2012b) follows this direction by suggesting a spiral curricular structure in which a certain aspect of NOS would be addressed at different levels of depth along the formal education at many school levels. This path is valid and may undoubtedly be a guide for curriculum development.

We believe, however, that the very arguments exposed in this work justify another approach. It is important to remember that structuring and designing curricula is a broader and more complex process that involves – or should involve – a range of social actors (educators, scientists, politicians, members of the school community, teachers, parents and communities in general, students) and not just science educators. Thus, these axes and themes themselves could be guides for curricular choices (with subsequent definition about NOS contents) which would be built from more particular/specific contexts provided, e.g.: by specific scientific areas and subject matter contents; by school level; by local, regional and national issues of interest, among others. In short: working from major axes and themes, the details would come up in a more contextualized manner. This contemplates, to some extent, the flexibility necessary to incorporate the plurality of views on aspects of NOS, especially with respect to the various scientific disciplines. Additionally, it prevents premature formulation of “general principles” on NOS that does not need to be present at that time. Thus, the use of themes would avoid many problems associated with the CV and the NOS tenets, providing a more open and plural approach in the treatment of NOS issues in school science curriculum4.

Certainly this detailing process will be informed by the knowledge built in science education area about these axes and general themes. We see here the fields of History, Philosophy and Sociology of Science

---

4 Certainly other perspectives are possible, such as, e.g., the notion of ‘structuring theoretical fields of the philosophy of science’ (Adúriz-Bravo 2004; Adúriz-Bravo and Izquierdo-Aymerich 2009; Adúriz-Bravo et al. 2002) which, although it has been developed in the context of pre- and in-service science teachers, could be another starting point for thinking about curricula designs. In a similar context (trainee teachers), Taber (2008, see Appendix) presents a document used in Cambridge that provides a basis for thinking about planning curriculum models to teach aspects of NOS.
feeding the discussion around these axes and themes. Without a reasonable minimum knowledge of these fields, the detailing of these themes would mean very little. Worse than that, it may result in a list of dogmatic assertions that mixes diverse views and does not become operational, being rejected in the future—and in practice—by science teachers in schools.

5. Conclusion
Notwithstanding its diverse meanings, the scientific literacy of the general population continues to be a goal of many those concerned with science education. Science should not be presented to students at schools in a dogmatic way and/or limited to the knowledge of science content—seen, wrongly, as a set of facts and claims about phenomena. In this sense, a scientific literacy should also embrace knowledge about science. Research in science education has advanced significantly in this direction, and we are today in a better position to inform educators in general, and curricula developers in particular, in relation to such metascientific content. As is characteristic of the humanities, the complexity and richness of ideas remains a virtue to be considered. In this sense, the search for a consensus view may be an arduous task. Our attempt in this work was to signal the difficulty of this consensus and some other issues that emerge from the so-called consensus view and deserve attention. We consider appropriate that the perspective of inclusion of NOS themes in science curricula has a wider and pluralistic starting point that, to some extent, incorporates what has been discussed in the literature. The approach of many groups, such as science educators, historians, philosophers, sociologists, scientists, educators in general, teachers and other members of school community, tends to be fundamental to the development of curricula that make sense of, and respond to, social demands.

Acknowledgements
The main author wish to thank Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES/Brazil) for financial support of the research project related to this publication (process number 4044-13-4).

References


Matthews, M. R. (2012). Changing the focus: from nature of science to features of science. In Khine M. S. (Ed.), *Advances in nature of science research* (pp. 3-26). Dordrecht: Springer.


Affiliation and address information

André Ferrer Pinto Martins
CE - Centro de Educação, Universidade Federal do Rio Grande do Norte
Campus Universitário, BR 101, Lagoa Nova
59072-970 Natal, RN, Brazil
email: andre.ferrer@pq.cnpq.br ; aferrer34@yahoo.com.br

Jim Ryder
CSSME - Centre for Studies in Science and Mathematics Education University of Leeds