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History teaches: Some educational projects based on the history of physics

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Summary. — We present some projects carried out in recent years and aimed at students of different levels (from high school to university), where we have adopted well-defined historical paths. The basic aim is to allow the students involved to develop appropriate physical reasoning skills, without the preventive request of a good standard preparation of the topics covered. The lines of action which were common to the various projects were intended to encourage the students to: 1) *think* like the given scientist of the past who is the object of the project, building step by step proper knowledge and reasoning; 2) *work* like that scientist, performing the original experiments; 3) *deduce* just as that scientist did concerning the subject matter; 4) *present* the results of their activity (including Physics demonstrations) to other students and, in general, to the general public, in order to test their ability to communicate what they have learned and discovered. These educational goals have always been accompanied by the desire to carry out historically consistent activities, based on the awareness of the key role that the history of physics can play in promoting scientific understanding at a deep level, even without requiring particular mathematical knowledge or advanced preparation. The enthusiasm of the students involved in the various projects, especially in demonstrating the result of their work to other students or in public events, as well as the prompt involvement of the aforementioned public (lacking adequate preparation or specific knowledge in the proposed activity), undoubtedly testify in favor of the success of the work presented here.

1. – Physics education through History of Physics

"The legitimate, sure, and fruitful method of preparing a student to receive a physical hypothesis is the historical method" [1]. Since Duhem's times, a long tradition has been established in incorporating history (and philosophy) of science in physics teaching [2-4], producing significant contributions [5] in helping students better understand the subject matter, since it is a common experience that history can provide useful expedients to be used to clarify conceptual knots or even experimental procedures or techniques, to ultimately give an answer to doubts of a different nature (see, just as an example, the historical approach in [6]). Also, it allows teachers to identify and prevent misconceptions of students, revealing the nature of physics as scientific activity and knowledge, and, finally, displaying the elements of physics as a culture [7]. Learning physics demands, indeed, is a complex and collective process [8] that can be fully revealed when the historical development of physics is disclosed: historical examples display *how science works*, which is a key point in science education [9]

As a matter of fact, history and philosophy of science have become a respectable physics education research trends in the last years [10], although no general approach has been developed in using history of science as a guide to help students understand the critical points of physics knowledge, nor consensus exists about the occurrence of change in students' attitudes towards science [11]. Indeed, the recognition that history of physics contributes to better understand given topics as well as grasp subtle details(1), usually faces with the fact that it adds complexity to physics teaching, since more elements are added to the discussion, and a wider range of skills are demanded [13]. The present situation concerning the incorporation of history (and philosophy) of science in science education is well summarized in ref. [14], while a still useful review of the specific contribution of the history of physics in physics education may be found in [15]. As pointed out in [16], it is not at all an easy matter to decide how to stage historical documents for a given public and for a cautiously selected partial goal. Nevertheless, a number of interesting researches have appeared in the literature, showing how history of physics can be helpful to teaching in multiple ways [17], and displaying different potentials of using history in physics education.

For instance (just to quote few examples and without claiming to be exhaustive), history can be useful in putting physics topics in context, by embedding them in the time in which they were developed, also linking them with other disciplines, especially with the humanities, whose teaching is intrinsically historical. This has been pursued especially in modern physics teaching, given the intrinsic difficulty of the subject, which moreover has the reputation of being awkward and counter-intuitive. In [18], for example, an educational approach was presented that invited students to explore the historical development and philosophical aspects of General Relativity within a digital learning environment, emphasizing the cultural and social relevance of physics and also linking General Relativity to students' previous knowledge of physics. Also, the possibility has been exploited of taking inspiration from reading original texts by the main figures or even founders of the given subject, which can be very useful in modern physics, as well as in any other field involving subtle conceptual steps. This has been recently applied in [19], where a teaching-learning sequence for teaching quantum physics has been developed, whose inspiration came from some of the fundamental papers about the quantum theory of radiation by Einstein.

Other authors have taken, instead, a different approach, starting from the assumption that a laboratory is the perfect environment to bolster student authentic learning, and convinced by the fact that history can help in creating that environment where students can "discover" and learn physics for themselves, in ways similar to how scientists did. In [20], for example, the author shows how a modern physics way of thinking can be built

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(1) It may be useful to consult several papers reported in [12].

in a laboratory by studying spontaneous dynamical path of reasoning, when adopting an Inquiry Based Learning strategy and Investigative Science Learning Environment (ISLE) methods to engage students in experimental explorative activities, in design and reflection, in multiple explanations able to develop scientific abilities and critical thinking. The incomparable role of experiments and analogical reasoning in creating new knowledge is well illustrated in [21], where hands-on experiments and models, framed within a generative educational model applying both to inquiry in science and design in technical disciplines, are proposed, pointing out their role as engines of intuition able to promote procedural knowledge on par with conceptual knowledge.

Being able to investigate phenomena, to evaluate assumptions and to test different ideas —that is, an interactive method of teaching—, certainly substantiates and contextualizes scientific knowledge and understanding, favoring the quality of argumentation and metacognition of students. In this respect, the history of physics may provide a number of useful examples where this emerges "spontaneously", as illustrated for example in [22], where a didactic unit of electrostatics was proposed by focusing on the reproduction of 18th century historical experiments, enabling students to have their own experiences, augmented by discussions about the development of concepts (and their specific experiments) and supported by original texts. Also, an epistemological dimension can be accessed through historical examples that lead students (and teachers) well beyond the simple goal of enhancing mastery of subject matter, but rather focuses on understanding the nature of science. A (non historical) example of how understanding the complexity and ambiguity of empirical work (obviously underlying any historical reconstruction) can emerge in a practical activity is shown in [23], where the students involved were let to engage in reflective processes on different levels, while offering them opportunities to think about different aspects of science such as documenting, communicating and verifying results and procedures. Historical instruments and (simple) experiments with them may also be used as an effective way to introduce students to the subject, as made in [24], where an approach to the understanding of the Venturi effect has been proposed to introduce the basic laws of hydrodynamics, correcting some typical (wrong) students' common-sense ideas about quantities related to fluids.

In all such approaches (and several other ones), an "integrated" strategy is evidently adopted, where scientific content and historical development overlap to some extent; that is, a didactic approach is used, integrated with the history (and philosophy) of science. However, this methodology somewhat suffers by the fact that it is still based on a *known* final result (at least for the instructor), obtained by linearizing the corresponding historical path, so that students' learning difficulties are treated *a posteriori* by letting them to just acquire knowledge (though through a more fruitful approach), rather than discover and learn real physics. As a matter of fact, indeed, history is far more complex than any didactic presentation, and the integrated strategy alluded above is the result — to some extent— of the apparent impossibility to present the full complexity of history in a didactic activity, thus providing again only (substantial and useful) disciplinary knowledge, but avoiding true epistemic knowledge.

2. – Historical vision as a guiding principle for teaching

Here we want to present a different approach, in the belief that the mentioned impossibility is only apparently existent, and can be overcome by adopting a complete and consistent historical perspective. Our basic research questions focus, on one hand, on students' responses to historically informed activities, on their expectations, as well as on changes in beliefs about physics and learning physics during a given activity. On the other hand, as it will become clear in the following, they focus also on increasing the effectiveness of the proposed activities while using interactive engagement methods with respect to traditional methods, as well as on learning achievements in terms of some inquiry process skills, conceptual understanding and content knowledge, after the inquiry intervention. Our pretentious goals when adopting a historical perspective then extend to allow students to form tentative explanations for the observed phenomenon using the knowledge acquired, consider effectively indirect cause and effect relations, consider effects of various variables on the same phenomenon, distinguish among more and less important influences of variables, and so on.

Our approach is embedded into an Investigative Science Learning Environment (ISLE) where, according to Etkina, students can "learn physics by practicing science" [25] just following a *real* historical path, suitably reconstructed but *not* opportunely linearized. Although —as in ISLE— our learning system also helps students in developing appropriate tools and abilities that physicists use in their work, nevertheless it is not aimed at *mirroring* processes by which physicists construct and apply knowledge, but rather it is aimed at *producing* actual processes by which scientists of the past have constructed and applied given knowledge. On the other hand, although —as in history of physics based activities— our approach is devoted to favor students' skills and curiosity on *how* people have reached a certain result, nevertheless students are here able to *realize* their ideas by actively participating in the learning process while practicing authentic physics reasoning. Then, our main goal is not to simply show how historical experiments, way of thinking and techniques can be used in education to support the study and practice of physics, but rather to show how the history of physics can successfully act as a basic *guiding principle* in active learning. The planning value of the resulting activities in training of training young people is, thus, clearly evident.

By enabling students to be able to think about and investigate phenomena, to discuss them in specific contexts, cope with multiple solutions and evaluate assumptions, as well as to test different ideas and solve real problems just as past scientists actually did, we can help students to develop proper skills and attitudes, not only simple knowledge. Indeed, students do acquire new knowledge in a similar way as scientists when approaching new problems, just by observing phenomena, measuring given quantities, elaborating tentative explanations and constructing experiments for their verification. Also, in such a way students are naturally led to think of science as a human endeavor, which is fully part of the undivided culture, not just a mere collection of rules and algorithms able to solve (theoretical and practical) problems.

The actual problem then is: how to achieve all this? In the following we will provide some different examples of activities that we have really implemented with different types of students in recent years. The basic proposal is to select key excerpts from original sources and then focus on the pedagogical lessons that can be extracted from them; of course, it is pivotal to develop specific activities within teaching-learning sequences allowing students to work on key concepts and techniques, and consequently learn them. All the proposed activities share the following common lines of action in encouraging students to: 1) *think* like the scientist of the past who is the object of the project, building step by step proper knowledge and reasoning; 2) *work* like that scientist, performing the original experiments; 3) *deduce* just as that scientist did, as far as the subject matter is concerned; 4) *present* the results of their activity (including physics demonstrations) to other students and, in general, to the general public, in order to test their ability to communicate what they have learned and discovered. Especially the level of achievement of the last goal is, evidently, a measure of the success of the activity.

Given the nature of the activities proposed, we deliberately devised high-performance projects for motivated students, that is, outstanding students with appropriate abilities in physical reasoning, though without requiring a good standard preparation. For motivated students, indeed, learning results are not basically influenced by prior experience and knowledge, and since initial conditions are thus independent of students' background, teachers can rely just on students' actions that are related to the acquisition of completely new knowledge. Skills and curiosity of such students are not always properly addressed, due to the notorious problems associated with teaching scientific subject matters, so that our choice was to balance the plethora of activities —of undoubted educational value— tailored for common students, who often do not take much interest in finding out more and better. And, in this respect, inquiry-based learning provides a unique approach where motivated students are able to excel [26], while stimulating and supporting their development, obviously requiring specially designed activities.

A few students (about a dozen, or even less) were then selected, from high school to first years university students (see the specific projects below), through a simple test asking few *Fermi questions* [27, 28] like the following: a) Give an estimate of the speed (in km/h) of your hair growth; b) How much carbon dioxide do you breathe into the atmosphere each year? c) Santa Claus is preparing to visit all the children of Earth who celebrate Christmas. How fast would he have to travel on Christmas night? According to what said above, indeed, the selection was aimed at choosing students able to demonstrate an appropriate ability in physical reasoning, rather than with a good level of scientific understanding.

Always without requiring any particular training in mathematics or other advanced education, the basic structure of any activity described below was as follows. The duration of each project covered a period of about five or six months, with scheduled two-hour (or more) weekly meetings.

The first part of each project was devoted to acquire the same mindset as any scholar from the age of the given author, who was the protagonist of the project (typically, from late XVII to early XIX centuries). The students were asked to address a given topic, brought to their attention by past scientists (natural philosophers) who had effectively posed and dealt with those problems. Here, the instructor adopted the role of a "master" of physics reasoning, as in ISLE, by creating the conditions to enable students to think like those scholars, often inviting to repeat simple, basic observations and experiences performed (or imagined) by the chosen authors. Reading the original texts was a crucial step, since it allowed the students to fully appreciate how "philosophical" reasoning was developing, as well as how it was presented to educated readership.

After that, a second part started, dealing specifically with the central work (and the main character) of the activity. After a short presentation of the given central problem and its historical contextualization, the meeting focussed on the basic experiments performed and/or described by the protagonist. In particular, a reconstruction of the whole series of key experiments was realized, without altering their original sequence nor adopting a (conceptual) "simplification". In particular, the instructor read the manuscripts where the scholar explained the chosen experiment, sometimes explaining the sense (given the often archaic language adopted), and then the students were asked to autonomously reproduce that experiment, by using the resources available or procuring the necessary material. Emerging questions of course produce a peer discussion, and students then share a partial conclusion for each situation, opening a new inquiry that is the first step for a new exploration. Group work was, then, an essential aspect of solving conceptual and experimental problems; as pointed out in [29], even modern research is usually performed by teams who must work effectively together, discuss problems, divide labour, and implement a common solution. During the activity, the students continued with their own interpretation of the results of experiment (sometimes stimulated by the instructor), and then compared it to the original one, as reported in the original texts. This structure applied to the whole series of experiments of the given activity. As the experiments were completed, a cumulative discussion of the different results achieved was also included. Note that we always stimulated an active role for students, emphasizing a learning process involving critical thinking and reasoning, development of skills and methods employed by scientists, as well as cooperative and collaborative works, with a certain degree of students' independence from teacher instruction, aiming at an effective learning through guided inquiry [30]. Our activities thus exhibit a relevant educational value in the way in which students assume responsibility of the experimental work, results and relative meanings.

Finally, a third part was devoted to the students' presentation of their whole path of experimentation and deductions/conclusions/interpretations to other students and to the general (non educated) public. Also, in some cases, the set of experiments was filmed (at the end of the given project): this was an important part of the activity as well, since a number of unexpected technical topics emerged and were clarified.

In the following we will report some details from three different activities implemented in recent years, from which what generally described above may be better appreciated. All such activities have been devised into an ISLE framework but, as it will be clear in the following, our specific methodology also involved a Predict-Observe-Explain (POE) inquiry-based learning model [31, 32], where students are explicitly invited to make predictions about the given problem at hand, then prove them through experiments and finally explain the results of their experiments. Our combined strategy proved particularly effective in all our historically-based activities, especially in allowing students to find out their initial ideas, generate discussions and further investigations, and then in motivating them to want to explore the given concept.

3. – The colours of Newton's *Opticks*

The first project that we present here was specifically designed for high school students (last years), and dealt with a major topic in the history of science, revealing for the first time the genius of young Isaac Newton as a follower of the Galilean experimental method. It concerned the Newtonian theory of colours, as deduced by the English scholar on the basis of his most famous experiments on prisms, and it does not require any particular training in mathematics or other advanced education (see [33] for further details).

The first part of the activity was aimed at reconstructing Newton's "philosophical" background in order to allow students to think like Newton about light, colours and vision, that is, to acquire the same mindset as any European modern-science scholar from the XVII century, with its roots in ancient Greek tradition, later evolved into medieval and renaissance thinking, before arriving at Galilei, his precursors and successors. In each meeting, the instructor posed a given topic investigated by a natural philosopher (also reading original texts, when available), favoring informal discussions and simple observations and experiences, often with no prior preparation. The list of natural philosophers discussing light, colours and vision, included: Empedocles of Agrigentum, Aristotle of Stagira, Euclid of Alexandria, Titus Lucretius Carus, Claudius Ptolemy, Avicenna, Alhazen, some scholars from medieval scholasticism and the renaissance period (including

Kepler), Galilei and other mechanicists and, finally, Descartes and its "modificationist" approach. The conclusion drawn in a dedicated meeting was that light is a homogeneous entity, not composed, but capable of different *qualities* according to its interaction with matter. Light is modified by refractions and reflections, and generates different perception of colour (this is the essence of Descartes "modificationism").

The second, most exciting part of the activity was then devoted to realize Newton's experiments involving prisms, from the simplest one to the most famous *experimentum crucis*. Since the aim was not to prove some (known) key result but just to experiment as Newton did (without any conceptual simplification or linearization), we did not discard some apparently spurious experiments with no specific relevance in regard to the "final" result, but rather we included every experiment performed by Newton related to the subject. The instructor encouraged students in a given direction, but left them free to realize their own "Newton experiment", with no other help. Reading a passage from original Newton's texts with the description and the result of the given experiment (without its interpretation) was followed by performing that experiment, according to the modes and methods identified by the students. Then they interpreted the results obtained and compared with original Newton's interpretation; once all the experiments were concluded, a cumulative discussion of the different results achieved was performed at a dedicated meeting. The experiments reconstructed were the following [33]:

1) a differently coloured line appears broken when viewed through a prism;
2) a prism forms an oblong image (with coloured edges) of a circular beam of light on a screen at a certain distance;
3) a second prism restores the circular shape from the oblong one;
4) red and blue appear differently when illuminated by the prismatic rainbow light;
5) the partition edge of a red and blue coloured card appears differently coloured through a prism; the edges of a small sheet of paper appear differently coloured through a prism (but not when illuminated by the rainbow light from another prism); colour ordering from a rainbow light is different when observed directly (by the eye) or (reflected) on a screen;
6) a prism produces no other colours from coloured light, but only shifts its position;
7) different colours from different prisms produce white light when they overlap;
8) coloured, oblong images from several beams fuse together to form one white image with coloured edges when the screen is moved away from the prism;
9) by rotating a prism around its axis, refracted coloured light gives way to reflected white light, while any subsequent refraction commences with a blue halo replacing the white light;
10) (*experimentum crucis*) prismatic red and blue are refracted by a second prism into different positions on a screen.

Students realized these experiments only with the aid of Newton's text, *i.e.*, without the instructor's intervention about possible "optimal conditions", and this often led to several repetitions of the same experiment, though under different conditions. Some experiments were performed in the laboratory, but others were conducted outdoors under direct sunlight (or even using artificial light sources). The students very soon realized how difficult it was to achieve even an apparently simple experimental result, this bringing them to a full appreciations of Newton's method. Note that no experiment was undertaken unless the previous one was completed; no cumulative original Newton's text was provided to the students.

The whole set of Newton's experiments was then also filmed at the end of the project(2); during this final stage, a number of unexpected technical topics emerged and were clarified, thus further challenging the students' abilities.

4. – An electrifying experience

We have then designed a project for high school students(3) aimed at reconstructing the experimental path on basic electric phenomena, from the beginning of the XVII century until the invention of the electric pile by Alessandro Volta, which marked a watershed in experimentation about electricity [34]. Again, no particular training in mathematics was required, but we preferred —as explained above— to stimulate motivated students to reason and work on original experiments, and eventually allow them to communicate what they learned to their classmates not involved in the project (or even to the general public).

Differently from the previous example, here the reconstruction of the "philosophical" background on the topic chosen, shared by the scholars at the onset of the XVII century, presented no particular difficulty, since it reduced practically to the strange property of amber, already known to ancient Greeks. Indeed, the discovery that a piece of yellow amber rubbed with fur is able to attract light objects, such as feathers, is traditionally attributed to Thales of Miletus. Thought to be a unique property of amber for many centuries, the phenomenon was not further investigated until William Gilbert inaugurated modern studies of it in the early XVII century. However, although the first part of this project practically reduced just to a short introduction, the second part of it largely compensated the time saved for two reasons. The first one is that the experimental path from Gilbert to Volta was not at all almost linear in its development, as in the previous case with Newton's experiments. This was due to the presence of many different actors/agents on the scene, each of them contributing with a different piece of experimental evidence, somewhat relevant for the continuation of the path, which in any case proceeded very slowly, through small steps [35]. The second reason is that, although apparently simple to realize, many (if not all) of the experiments hide a number of practical difficulties, often not easy to identify, which required multiple repetitions of the same experiment to resolve the difficulties that emerged. On the other hand, this occurrence led to an even greater active involvement of the students (and, often, even of the instructor!), both in reasoning and in experimenting, which certainly increased the cognitive success of the activity, along with a richer development of skills.

As above, in our historical reconstruction we did not discard some apparently spurious contributions by given authors, in order not to linearize a path that was inherently not linear. Also, each experiment was introduced by reading a passage from original texts

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(2) `https://www.youtube.com/playlist?list=PLTGvK6jMx5QCxKWsufvf0X6Z6yqAKIQ98`.

(3) We have implemented the project with high school students, but it can easily be adapted to primary school students as well.

by the given author, and then realized by the students according to their own design and implementation (of course with modern materials, often including plastic materials serving as insulators). Given the conceptual simplicity of the different experiments, the results obtained were interpreted contextually as the experiment was carried out. Above all, this was *required* by the emergence of a number of practical difficulties, as anticipated above, whose solution (and, then, the successful realization of the given experiment) necessarily required an in-depth discussion on what was actually happening, on the instrumentation used and on the conduct of the experiment([4]). Thus, in a sense, the interpretation of the "expected" results often preceded their practical realization. Finally, an analysis and a cumulative discussion of all the experiments performed, as well as of their particular meaning with respect to the global path explored, was performed at a dedicated conclusive meeting. The experimental path([5]) proposed to and realized by the students, according to the historical reconstruction adopted, developed around the following experiments:

1) plastic rubbed with paper, cotton fabric or hair attracts bits of paper or straw (the strange "property of amber");

2) (W. Gilbert) construction of a *versorium*([6]) to detect "electric" (amber, plastic, acrylic, some glass) and "non-electric" materials (common glass, wood, metal, rubber, natural magnet);

3) (N. Cabeo) the two ends of a rubbed plastic strip, folded in half, repel each other; the same applies when a rubbed plastic straw is brought close to a plastic*versorium* (electric repulsion);

4) (O. von Guericke) construction of an electric generator with a rotating plastic globe; floating feather experiment([7]); a small spark is produced with a finger touching the globe; crackling and luminescence are observed during the electrification of the globe;

5) (F. Hauksbee) cotton threads hanging along a wooden ring are drawn radially towards the center when an electrified plastic rod is introduced into the ring;

6) (S. Gray) small pieces of paper are attracted to a metal ball supported by a long twine —itself supported by a silk thread— in contact with rubbed plastic at a

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([4]) Just to quote an extreme example, the students and the teacher got stuck for almost two months on a specific experiment (despairing, therefore of its success), then discovering only by chance (or by intuition of the teacher) the cause of the failure. It was due to the fact that the experiment was implemented by means of a simple structure in dry wood, which was believed to be a perfect insulator, and which instead, in practice (and due to the very small potential differences involved), turned out to be a very peculiar Faraday cage... When the dry wood was removed (and the cage was "opened"), the experiment was immediately successful, without any difficulty.

([5]) A compendium of all the relevant experimental findings presented in the experiments reported below can be found in several historical sources; we have adopted the one in [36].

([6]) That is, a sort of compass, with a brass ferrule or a small piece of a plastic straw suspended on a nail.

([7]) A wadding flake is attracted by the rubbed plastic: after contact with this, the flake is repelled by the plastic and, floating in the air, can also be suitably "guided" by the plastic itself to move.

large distance; the attraction does not manifest itself if the silk thread is replaced by a metallic wire (electricity conducted at a distance); observed difference between *conductors* and *insulators*;

7) (C. F. C. Dufay) plastic strips rubbed between fingers, between PVC pipes or in hair repel, while they are attracted if rubbed between fingers and PVC, or between hair and PVC (detection of two different kinds of electricity); construction of an *electric pendulum*, made with a suspended plastic straw, to determine the kind of electric charge by means of attraction or repulsion;

8) (P. van Musschenbroek) construction of a Leyden jar made with a plastic cup, wrapped in an aluminum foil, containing water with a metal wire inside; experiments with it, electrically charged with a Guericke's globe;

9) (J. Canton) two small corks hanging from a plastic structure by means of conductive (silk) threads diverge from each other when an electrified plastic rod approaches them, while they reunite when the rod moves away(8) (*electric induction*);

10) (A. Volta) construction and use of an electrophorus, made with an aluminum baking tray (with a plastic handle glued in the centre) placed on a plastic plate electrified by rubbing it with a woolen cloth (or paper);

11) (A. Volta) a bimetallic arc produces particular gustatory(9) and tactile(10) sensations;

12) (A. Volta) construction of different column batteries (single column with 12 cells of 5 eurocent coins and aluminum foil discs interspersed with paper discs soaked in salted water; double column with a total of 30 cells of the same type; single column with 40 cells of larger copper-soaked felt-steel disks) and a "crown of cups" battery (a set of 6 cells, each consisting of a glass containing salted water acidulated with hydrochloric acid, in which a copper plate and a zinc plate are immersed); experiments with them.

Some comments are in order.

First of all, students noted that better electrostatic effects were revealed when plastic objects were rubbed with paper or, even better, on hair (preferably short). Experiment N.2 was preceded by the observations (referring to Gilbert) that a rubbed plastic rod also attracts cotton or copper threads, but attracts little or no silk threads or hair; also, it attracts an aluminum can as well, and even a thin stream of water flowing or a drop of

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(8) Also, two small corks suspended from one end of an electrically charged (insulated) tin tube repel each other, but a rubbed plastic rod held under the corks brings them together, as it gets closer to them.

(9) A student inserted his tongue between a 5 eurocent copper coin and an aluminum sheet (or a steel washer): if these were not in contact with each other, he did not feel any taste, but if the two metals touched , a "strange" taste was perceived ("acid"-like or "alkaline"-like depending on the copper-aluminum or aluminium-copper order of metals). Furthermore, the student could well perceive that the acid sensation had a continuous character, if the stimulus was prolonged over time.

(10) The tips of a copper-aluminum bimetallic arc, placed inside the mouth (on opposite sides of the buccal vestibule), produced a small "trembling" sensation faintly felt by the students.

water (or milk, detergents, alcohol) on a surface. All such materials are, conversely, not attracted by a magnet, so that, the students can conclude with Gilbert that the property of amber is not the same as that of a magnet or, in modern terms, that electric and magnetic phenomena are different.

Guericke's globe (originally made of sulphur, but effectively modeled here with a large plastic sphere) is quite an efficient electrostatic generator that proved useful for several experiments, included those mentioned in N.4, among which the most striking is certainly that of the floating feather. It allowed to reconstruct also the original Musschenbroek experiment with the aid of a Leyden jar (see Experiment N. 8): a metal chain was suspended from a wooden structure, with one of the two hanging ends resting on the globe, while the other was immersed in the water contained in the glass. After a hundred rotations of the globe, the Leyden jar was sufficiently charged to produce a very sensitive electric shock when experimenter's hands touched both the aluminum foil and the chain immersed in water. This was also made visible by touching the aluminum foil and the chain with a metallic arc (a thick metal wire bent in an arc) supported by a wooden handle: a very conspicuous spark was observed between the arc and the aluminum foil (or the chain).

Gray's experiments N. 6 are able to show that twine, metallic wire, wood, cork, etc. are conductors, while silk thread, fishing line, hair, resin, plastic, etc. are insulators. Also, though with some difficulty, the students were able to observe that a metal body (supported by a silk thread) attracts pieces of paper as it approaches, without touching, the rubbed plastic.

The realization and use of a Volta's electrophorus, that is the first electrostatic induction machine, presented instead no particular difficulty, but its use was particularly intriguing to the students. In fact, by electrifying the plastic plate just once, placing the baking tray on it and touching its inside with a finger, a small spark was obtained (and seen) when its outside was touched with another finger. This was obtained again every time the operations were repeated, even by no longer rubbing the plastic plate, thus clearly showing that the effects were not related to "production" of electricity, but rather to electric induction on the aluminum tray.

Experiments N. 11 evidently served to introduce the discovery of Volta's battery (just as it happened for Volta himself). However, they were preceded by a discussion on the well-known experiments of Luigi Galvani on frogs, also showing a video with their reconstruction (it was not possible to reproduce those experiments as well, due to lack of frogs and, above all, not having a "surgeon" at our disposal who could prepare them), with the obvious function of allowing the students to realize the distinction between the concept of *animal electricity* (Galvani) and that of *common electricity* (Volta), which instead led to the construction of the pile.

Several piles were finally built in Experiment N. 12, with gradually increasing intensity. This intensity was tested by the students exactly as Volta did (and, therefore, not using anachronistic light bulbs...), that is, in the case of column batteries, by using a copper wire to connect their base with the salted water contained in a glass: one hand was dipped into the water, while the other hand touched the top of the cell. Instead, for the "crown of cups" battery, it was enough for students to dip their hands at the same time into the first and last glass of the series. In this way, a more or less appreciable electric shock could be well perceived by the experimenters, which was particularly sensitive in the presence of small wounds on the hands, even causing a small painful sensation. For each type of battery, the students immediately noticed —"with their own hands"— the difference between a battery and the previously made Leyden jar, *i.e.*, a reduced intensity of electricity that was generated, however, continuously and not in a single pulse, as in the Leyden jar. Students also observed that, after prolonged use, the copper coins oxidized and the battery no longer worked; electricity production resumed normally after cleaning the coins with vinegar (mixed with salt). This oxidizing effect was greatly amplified in the "crown of cups" battery, where, in addition to the oxidation of the copper plates, the students noticed actual (heavy) corrosion of the zinc plates, both phenomena being associated with the observation of small "bubbles" developing from the electrodes and rising to the surface through the acidulated salted water.

All such unexpected effects, along with the peculiarities observed practically in any experiment performed, made the students' activity particularly interesting, as they were constantly stimulated to reason in an unconventional way and about completely new aspects for them. Furthermore, more than in the previous activity about Newton's experiments, here the presence of the instructor was purely as that of an external guide (for providing the original texts, suggesting materials to be used, etc.): the students' discussions, especially those concerning the continuous difficulties that emerged, were almost completely self-managed.

5. – Electromagnetic revolutions

As a sort of ideal continuation of the previous project, we have also developed a historical reconstruction of the path that led to the "birth" of the electromagnetism, with the key experiments of Ørsted, Ampère and Faraday [37]. Centered, indeed, around the remaking of 12historical experiments (with variants), the activity was originally designed for high school students (last year), and later adjusted to university students (first years) as well. The project setup closely followed those already described above, with the reconstruction of the "philosophical" background shared by the scholars at the onset of the XIX century practically coinciding with the results presented in the previous activity on the basic electric phenomena (with the addition of a discussion on the Newtonian-Coulombian viewpoint on central forces acting-at-a-distance)(11). Here, indeed, the basic starting point was the invention of Volta's battery, which allowed all the relevant experiments to be carried out: in addition to the experimental realizations with the different batteries described above, here more powerful batteries were required, which were realized as reported below. Although of different nature, a number of practical difficulties arose also during the realization of the present activity, which required several repetitions of the same experiment, often with somewhat different practical implementations, with the same benefits and drawbacks noted above.

Again, special attention has been devoted to not linearize the content of the activity, by making constant recourse to the original texts. Although the key ingredients of the historical case considered here were essentially experimental in nature, theoretical reasoning (and prejudices) played an important role, especially in Ampère. In order to avoid excessive and unnecessary mathematical complications, we chose not to dwell at all on this part based on theoretical calculations, so that, for example, no discussion was present either on the so called Biot-Savart law or on Ampère's calculations devoted to reconcile the Newtonian viewpoint with the emerging experimental results that seemed to deviate from it. Also, all those results —experimental and theoretical— obtained si-

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(11) Note that the groups of students who participated in the two different projects did not overlap, except for a single student.

multaneously by the same protagonists (Ampère and Faraday above all) and concerning terrestrial magnetism were not discussed at all as well. These certainly had a (vicarious) influence on the main topic of the present activity, but their detailed consideration would have gone very far, greatly weakening the practical effectiveness of the historical reconstruction, rather than strengthening it. Nevertheless, the students were constantly stimulated to fully appreciate the complexity of the subject in the appropriate places.

Electromagnetism originated thanks to the celebrated Ørsted's experiment [38] (or, as learned by the students, Ørsted's *experiments*) but, as anticipated above, the initial focus of the activity was on the fundamental device invented by Volta a couple of decades earlier, without which that origination could not have taken place. Then, we appropriately stressed on the relevance of that apparatus able to provide a measurable and controllable quantity of electricity, as opposed to that provided by the already existing Leyden jars (*i.e.*, condensers), which were useful only to study transient effects. After this, and before getting to the heart of the main topic of the activity, we introduced the students to the often confused experiments carried out with Volta's battery (always more and more improved) in the first twenty years of the XIX century(12). In particular, the water decomposition induced by electricity (discovered by W. Nicholson and A. Carlisle) and other chemical effects produced by the battery, including J. W. Ritter early experiments and especially the fundamental work on electrochemical reactions by H. Davy, were explicitly considered. Subsequently, an appropriate mention of the search for possible magnetic effects on chemical reactions (with the controversial Ritter's experiment on the oxidation of a magnet in an acid and the experiments by L. A. von Arnim on the different oxidizability of the poles of a magnet) introduced the students to the quest for possible connections between electricity and magnetism in several authors, such as N. Gautherot, S. P. Bouvier and Italian G. D. Romagnosi, who was (subsequently) attributed —wrongly— a priority over Ørsted's experiment. After having illustrated this amateurish situation [37], which well immersed the students in the actual situation of the historical period in question, the core of the project effectively started. The complete experimental path proposed to and realized by the students developed around the following experiments:

1) (A. Volta) construction of different batteries (column batteries with copper and aluminum (steel) discs; "crown of cups" battery with copper and zinc plates; powerful trough piles with copper and aluminum plates immersed in somewhat concentrated solution of salted water and hydrochloric acid) and experimentation of the effects produced;

2) (H. C. Ørsted) a wire connecting the poles of a tough pile rotates a magnetized needle (using copper, iron and brass wires above/below the needle and parallel to it; inclining the wire with respect to the earth meridian revealed by a compass or lying it in the same horizontal plane of the needle, or even perpendicular to this plane; using wooden, glass and terracotta tablets placed between the wire and the needle; employing a battery with a reduced number of cells or with an increased concentration of acid in the cells; using a copper, non magnetized needle);

3) (A. M. Ampère) an *astatic system* composed of two magnetized needles hanging from a nylon thread, placed (with opposite poles) horizontally at some distance

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(12) This connecting part consisted only in reading original texts and performing related discussions, without carrying out dedicated experiments.

above each other, lays at right angle (rather than just transversal to it, as in Ørsted) when a wire connects the poles of a battery;

4) (A. M. Ampère) two magnetic needles placed above the connecting wire and above the battery show the circulation of a *current* along the closed circuit;
5) (A. M. Ampère) a current carrying wire attracts/repels (rather than rotates) the poles of a magnetized (sewing) needle hanging vertically near it;
6) (A. M. Ampère) realization of "Ørsted experiments" with the magnetic needle replaced by another current carrying wire;
7) (A. M. Ampère) a magnet attracts/repels a current carrying coil (with many turns); similar effects with coil-coil interaction;
8) (F. Arago) a current carrying wire attracts iron filings (but not brass filings or sawdust); a solenoid magnetizes an originally non magnetic, iron needle introduced into it (as revealed by a compass);
9) (A. M. Ampère) parallel, straight current carrying wires attract/repel each other;
10) (M. Faraday) a vertical magnetized needle, floating on water, makes a circular motion around a vertical, straight current carrying wire.
11) (M. Faraday) a current carrying wire, bent in the shape of a crank, rotates around a magnet until he bumps into it;
12) (M. Faraday) a straight current carrying wire hanging vertically, and free to move around a vertical magnet inside an aluminum tray filled with salted water, rotates completely around the magnet when current flowing through that circuit (electric motor); construction of a *pocket rotator* (a device similar to the previous one, but pocket-sized).

In order for the experiments to be effective, quite a powerful battery was needed. In particular, Ørsted's experiments required a trough pile consisting of 16 cells (ice lolly molds were used) made of copper and zinc plates immersed in salted and acidulated water. Instead, for all the subsequent experiments, a pile was used made up of 20 cells, each composed of a rectangular aluminum tray (for food) in which a thick felt rectangle was placed, on which rested a copper plate of the same surface. The trays were then filled with a concentrated solution of acidulated salt water.

Note that, contrary to what usually found in textbooks, the students correctly experienced that in Ørsted's experiments the wire connecting the poles of a battery is able to rotate the magnetic needle and place it *transversally* to the wire, while only the astatic system devised by Ampère (to eliminate the action of the earth magnetism) allows visualizing the right angle effect.

The very appearance of the key concept of an electric current circulating along a (closed) circuit took place only starting from Experiment N. 3: the original Ørsted approach of just a "connecting wire" was, instead, heavily employed with the students in previous experiments to let them appreciate the conceptual mental change introduced by Ampère.

Experiment N. 6 was very difficult to realize, since it involved a very sensible thick aluminum rod, bent into the shape of an open rectangle and kept in horizontal equilibrium in its center by means of a vertical screw fixed to a base. Its terminals were immersed in small vessels with salted and acidulated water, ensuring the electrical connection with the battery. Once this system was placed under the connecting brass wire, also connected to the same battery, the students observed (after repeated attempts) a rotation of the aluminum wire around the screw, in one direction or the other depending on the connections with the battery. This experiment was very instructive, and suggested also to the students (after Ampère) that magnetic effects were generated by an electric current, as then confirmed by the subsequent experiments. On the contrary, Experiments N. 7 and N. 8 were very easy to realize, but turned out equally very showy and instructive.

The celebrated "Ampère experiments" N. 9 about two parallel current carrying straight wires (the only one known to students —and teachers— ascribed to Ampère) was again not at all easy to realize, the students succeeding in it only by using straight aluminum thick rods hanging vertically, and connected to the battery by means of thin copper wires (which became red-hot when the circuit was closed). The instructor properly emphasized that such experiments were "only" the culmination of a *long* experimentation by Ampère, aimed at understanding how electric current could generate magnetic effects.

All Faraday's experiments proved not very difficult to realize, although some care was required. The students were introduced to them by stressing the novel perspective adopted by the English scholar, at variance with that followed by Ampère and based on the Newtonian-like approach of direct attractions and repulsions. In such a way, they fully appreciated Faraday's approach (free from preconceived conceptual schemes) that naturally led him to realize that a current carrying wire was able to let a magnetic needle to rotate around it, as he finally proved (after some intermediate steps implemented in Experiments N. 10 and N. 11) by constructing the first electric motor. The experimental activity ended with the construction of a pocket device that Faraday built to be used with not a very powerful battery; it was basically exploited in order to "advertise" his discovery (Faraday sent it together with his writings to various scholars throughout Europe), and this served to illustrate to the students an often overlooked aspect of scientific research, namely the dissemination of the results obtained.

As for the activity on Newton's prisms reported above, the whole set of experiments about the birth of electromagnetism was also filmed at the end of the project(13), again revealing a number of unexpected difficulties (not limited to filming) that further challenged students' abilities (along with their curiosity and excitement).

6. – Educational evaluation notes

We were also interested in the learning outcomes of the projects, with particular reference to the results achieved by the students after activity, in order to test a short-term effectiveness of the guided inquiry intervention, as well as in the medium-term retention of the learning goals over the span of 6–8 months. For any activity we then devised some surveys aimed at investigating both the students' impressions of the projects and their effectiveness. The first aspect was addressed to the students, concerning their previous knowledge, their engagement into the project, project setting and its outcome. The second one was instead addressed to a small number of teachers evaluating students' activities during their public performances; it concerned the knowledge acquired by the

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(13) `https://youtube.com/playlist?list=PLTGvK6jMx5QCD2KcWqRv1JUyKUwBw0zDr`.

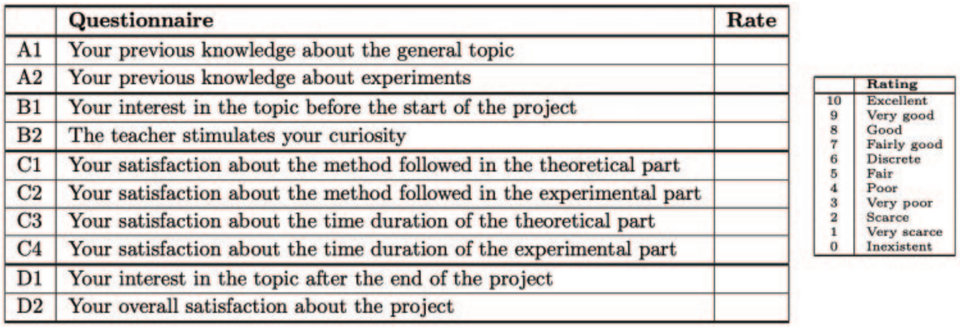
students, the competencies developed and the abilities mastered. Finally, a questionnaire was also proposed to the public visiting the presentation activities (usually taking place after some months), concerning their own science knowledge, science communication by the students and the outcome of the activity presented.

We have adopted external summative assessments in order to evaluate the relevance of the proposed activities in ordinary practice, in addition to physics education research, basically aimed at contributing to teaching practice; this can then be achieved not with internal but external criteria.

The first questionnaire was administered to the students participating to the given activity at the very end of the project. It is reported in table I and is divided into four parts investigating the students' previous knowledge of the topics treated, students engagement in the activity, project setting and, finally, the outcome of the project. Each question can be rated in the range 0–10, as reported in the table. In order to give an idea of the analysis performed and what can be deduced from it, as an example we have also reported the actual results of the survey for the first activity presented here, *i.e.*, that about Newton's prisms experiments. The scores in the rating results reported in table I for such activity refer to the sum of all the students' ratings (for each question) divided by the maximum attainable total (that is, 10 times the number of students), expressed as a percentage. The results reported in table I clearly show, for example, that despite a certainly poor knowledge on the topic at the start of the project (see questions A1, A2), the activity contributed to arouse a strong interest in it (questions B1, D1). The evident strength of the project was the continued stimulus of students' curiosity (question B2), as well as a good reception of the method employed (questions C1, C2), albeit a certain indolence towards the time duration of the theoretical part was endured (questions C3).

Learning outcomes were evaluated by means of external evaluators, not involved in

Table I. – *A typical questionnaire administered to the students involved in a given activity at the end of the project, divided into four parts. Part A: previous knowledge. Part B: students' engagement. Part C: project setting. Part D: outcome of the project. The explicit rating results refer to the first activity presented here about* The colours of Newton's *Opticks.*



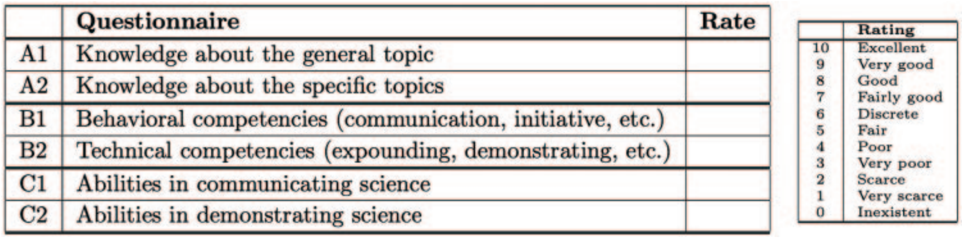
	Questionnaire	**Rate**
A1	Your previous knowledge about the general topic	
A2	Your previous knowledge about experiments	
B1	Your interest in the topic before the start of the project	
B2	The teacher stimulates your curiosity	
C1	Your satisfaction about the method followed in the theoretical part	
C2	Your satisfaction about the method followed in the experimental part	
C3	Your satisfaction about the time duration of the theoretical part	
C4	Your satisfaction about the time duration of the experimental part	
D1	Your interest in the topic after the end of the project	
D2	Your overall satisfaction about the project	

	Rating
10	Excellent
9	Very good
8	Good
7	Fairly good
6	Discrete
5	Fair
4	Poor
3	Very poor
2	Scarce
1	Very scarce
0	Inexistent

Rating results for activity I (maximum score for each item: 100)

Question	A1	A2	B1	B2	C1	C2	C3	C4	D1	D2
Score	61	50	82	96	71	89	65	80	91	76

TABLE II. – *A typical questionnaire administered to the teachers evaluating students' activity during the performance at Science Festivals, divided into three parts. Part A: knowledge acquired. Part B: competencies developed. Part C: abilities mastered. The explicit rating results refer to the first activity presented here about* The colours of Newton's *Opticks.*



	Questionnaire	**Rate**
A1	Knowledge about the general topic	
A2	Knowledge about the specific topics	
B1	Behavioral competencies (communication, initiative, etc.)	
B2	Technical competencies (expounding, demonstrating, etc.)	
C1	Abilities in communicating science	
C2	Abilities in demonstrating science	

	Rating
10	Excellent
9	Very good
8	Good
7	Fairly good
6	Discrete
5	Fair
4	Poor
3	Very poor
2	Scarce
1	Very scarce
0	Inexistent

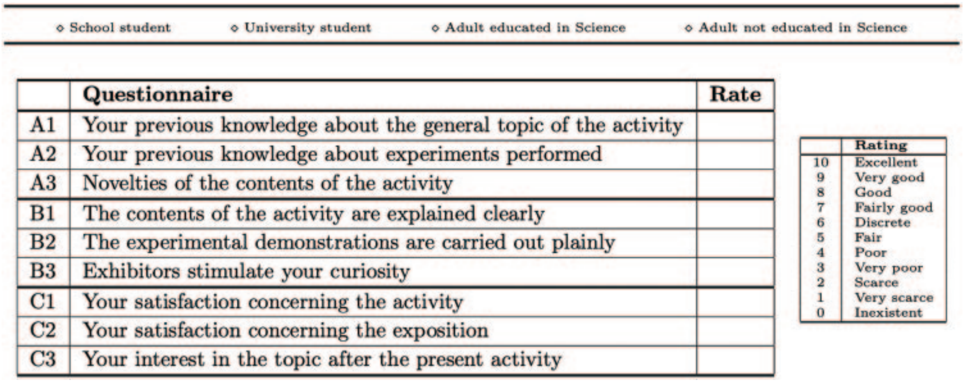
Rating results for activity I (maximum score for each item: 100)

Question	A1	A2	B1	B2	C1	C2
Score	97	95	84	89	77	85

the project at all, through a second questionnaire administered to them. The evaluators were picked among about 20 university teachers, with working interests ranging from general physics, to applied physics, theoretical and experimental physics, cosmology, astrophysics, etc. They mingled among the public during Science Festivals where the students presented the results of their activity, attended students' performance, even asking questions, and then filled up the questionnaire in table II. This was designed to survey about the knowledge acquired by the students, the competencies developed, as well as the abilities mastered by them. The explicit rating results in table II (referring to Newton's activity), again reporting the sum of all the evaluators' rating (for each question) divided by the maximum attainable total, expressed in percentage, evidently testify for the extremely favourable appreciation granted by the evaluators to the students involved in the activity. Interestingly, it was not just limited to the high level of the knowledges acquired, but also referred to students' skills in scientific communication and demonstration.

Finally, a third survey was usually conducted also among the public visiting the activity during the Science Festivals, by employing the specific questionnaire reported in table III. The visitors were grouped into four different classes, generally characterizing the public attending these kinds of Festivals: school students, university students and adults educated or even not educated in science. They were asked to say what scientific content they may have acquired during the performances, the way this content was communicated to them, finally expressing an opinion on their experience as a whole. The results usually obtained were somewhat different for the different classes participating in the survey. Indeed, as deduced from the explicit rating results for Newton's activity, while people were generally much satisfied about the activity and the students' presentation (questions C1, C2 in table III), the interest stimulated by the activity itself was raised at a very high level only in university students and in educated people, while it stayed a bit lower in not educated people and school students (question C3). This is somewhat

Table III. – *A typical questionnaire administered to the public visiting our activities at the Science Festivals, divided into three parts. Part A: science knowledge. Part B: science communication. Part C: outcome of the activity. The explicit rating results refer to the first activity presented here about* The colours of Newton's *Opticks. (The number of effective people visiting our activities at Science Festivals is greater of at least an order of magnitude, but only a limited number of them —attending the whole performance— are usually asked to participate in the survey, for easily recognizable reasons.)*



◇ School student ◇ University student ◇ Adult educated in Science ◇ Adult not educated in Science

	Questionnaire	Rate
A1	Your previous knowledge about the general topic of the activity	
A2	Your previous knowledge about experiments performed	
A3	Novelties of the contents of the activity	
B1	The contents of the activity are explained clearly	
B2	The experimental demonstrations are carried out plainly	
B3	Exhibitors stimulate your curiosity	
C1	Your satisfaction concerning the activity	
C2	Your satisfaction concerning the exposition	
C3	Your interest in the topic after the present activity	

	Rating
10	Excellent
9	Very good
8	Good
7	Fairly good
6	Discrete
5	Fair
4	Poor
3	Very poor
2	Scarce
1	Very scarce
0	Inexistent

Rating results for activity I (maximum score for each item: 100)

Question	A1	A2	A3	B1	B2	B3	C1	C2	C3
Group 1:	**95 school students**								
Score	58	39	91	88	95	84	91	95	85
Group 2:	**68 university students**								
Score	75	52	88	91	93	89	95	89	91
Group 3:	**121 adults educated in science**								
Score	65	41	90	79	88	81	92	93	90
Group 4:	**175 adults not educated in science**								
Score	56	25	95	92	85	87	89	85	81
Total:	**459 visitors**								
Score	62	36	92	88	89	85	91	90	86

in line with the (low) level of previous knowledge on the topic of the activity (questions A1, A2) for such less educated people. A general acknowledgment of the students' work was usually granted by the visitors (questions B1, B2, B3).

Notwithstanding the details mentioned, is seems safe to conclude that our projects generally encounter the favour of the students involved, and this was explicitly manifested in the presentation given to the evaluators as well as to the general public, which points out what the students really acquired as regards knowledge and skills in science communication.

7. – Final remarks

In the previous pages we have tried to give an idea about our approach to teaching physics, being guided by a consistent historical perspective that does not trivially linearize the complex path behind relevant discoveries, in order to allow students to develop the appropriate tools and abilities that scientists do use in their work. This is reached by letting students actively participate in the learning process while practicing authentic physics reasoning, just as occurred to the scientists in the past. Of course, our approach is well suited for high-performance projects devoted to motivated students, who do not necessarily have a good standard preparation (both in physics and in mathematics), but certainly they should have appropriate abilities in physical reasoning. This is also our deliberate choice to enthuse students who want to do (and learn) more and better, and for this reason our activities usually involve a small group of students, guided by an instructor to coordinate and stimulate their reactions (to set the goal, and not address the problem, which emerges from the original texts).

Here we have provided three different examples of our approach, but we have experimented several other activities tailored for students of different levels. For example, "the blazing story of a burning candle" (14), inspired by Faraday's famous Christmas Lecture [39], is a workhorse of ours that we have experimented with students of all levels, from elementary school to university, always with great success. Most recently, we have also proposed an advanced project for second year university students, "How hot it is, Monsieur Fourier!", on Fourier's experimental path on heat propagation (15) that finally led to his masterpiece on the analytic theory of heat [40].

A significant, common part of our activities was to test even students' communication skills, with presentations to other students, preparation of videos, dissemination activities, etc., that further challenged (different) students' abilities, and also provided a direct assessment of the success of the project, both concerning the activity carried out and for its presentation.

As a result, we can safely acknowledge a substantial contribution of any of our projects to the development of a strong interest in the students involved, whose curiosity was constantly stimulated by the method adopted. The excellent appreciation from teachers and external researchers, both for the high level of knowledge acquired and for communication and demonstration skills, further testified for the success of our approach.

This fruitful encounter between history, didactics and dissemination therefore provides an incentive to undertake other initiatives in this direction, which increasingly stimulate a critical knowledge of science and its applications.

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(14) `https://youtube.com/playlist?list=PLTGvK6jMx5QAUfH5HzoPe4cSIg6PDLwlx`.

(15) `https://youtube.com/playlist?list=PLTGvK6jMx5QBhFJ27J4n7JGxHCnZ0USMf`.

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