HISTORY OF PHYSICS AS A TOOL FOR TEACHING

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INTRODUCTION

It became a commonplace to agree that physics teaching presents a complex and interdisciplinary activity. Among the areas of knowledge essentially contributing to this activity we name Physics, the History of Science, Philosophy of Science, Cognitive Science and Pedagogy. Our appreciation of the nature of contribution of each from these areas incessantly changes reflecting the growth of our understanding of teaching physics. This essay is dealt with the History of Physics (HoP) and the understanding of its role as a tool of teaching physics.

First, I will mention the dimensions of contribution of the HoP to physics teaching as it became currently accepted, briefly elaborating on the relevant argumentation. I will, then, elaborate on the change in the perceived role of historical materials in light of the educational research and illustrate this change with examples from various domains of physics, optics in particular. Finally, I will describe the latest development in this subject, which suggests teaching physics as a discipline-culture. This step brought to the historical materials a new type of appreciation, as being an inherent part of physics contents also on our days. It is thus suggested that these contents could be taught in the regular instruction. The cardinal innovation of this approach is addressing the ideas and theories, which are normally considered as being obsolete and thus omitted from by the contemporary physics curriculum.

WHY TO TEACH PHYSICS USING HISTORY?

The discourse of advocating for using the HoP has a long history, starting from Mach[1] and Duhem[2] who argued, rather categorically, for so called *historical method* (or *genetic approach*) in teaching physics, already more than a century ago:

> The legitimate, sure and fruitful method of preparing a student to receive a physical hypothesis is the *historical method*. To retrace the transformations through which the empirical matter accrued while the theoretical form was first sketched; to describe the long collaboration by means of which common sense and deductive logic analyzed this matter and modeled that form until one was exactly adapted to the other: that is the best way, surely even *the only way*, to give to those studying physics a correct and clear view of the very complex and living organization of this science. [emphasis added][3]

Mach's textbooks in mechanics and optics that adopted this approach remain to be valuable and interesting teaching resources. Their claim was that including materials from the HoP in teaching physics causes (1) a *deeper understanding of the subject matter* by the learner. This claim is of the central importance for physics educators. In fact, the HoP may reveal the *important context* of the considered fragments of knowledge. For example, in the teaching of mechanics it is important to communicate to learners that the Newtonian approach removes from the stage the issues of friction and elasticity. This communication could benefit by the use of Newton's Principia. In fact, Newton originally considered the context of planets motion as material points that is without friction and elasticity. This very condition helped him to formulate his three fundamental laws, often masked in our regular environment by these two phenomena. Newton's concept of inertia becomes clearer if the teacher contrasts it with the previously introduced Kepler's and Galileo's inertia[4]. Newton discussed the conceptual points of central importance for introductory physics course: time-space description of movement, apparent and true physical quantities, the role of measurement in defining concepts, thought experiments[5], etc. Such points are scarcely mentioned, if at all, in textbooks, and the use of history brings them to physics class.

The second point raised by education researchers is the phenomenon of (2) *recapitulation*: a certain similarity between the individual growth of knowledge (ontogenesis) and the growth of collective knowledge of science (phylogenies).[6] Guided by this idea, the teachers can identify and anticipate misconceptions of students when become familiar with those occurred in the HoP. This similarity make relevant the argumentation and critique once used in the scientific discourse, helping students to understand the *critical points* of physics knowledge, usually difficult for the learner. Thus, considering the medieval theory of impetus, one finds a true similarity of this idea of the *charge of motion* with students' spontaneously developed understanding.[7]

The third point, extensively developed in science teaching research, is that the HoP reveals (3) *the nature of physics* as scientific activity and knowledge.[8,9] This aspect of the HoP has various aspects.[10] Thus, historical materials may reveal to the learners the method of enquiry. Physics as a discipline inherently includes it in its epistemological basis, as well as other methodological claims such as the need for empirical verification, operational definitions of basic concepts, logical rules (the ways of making inferences), and the philosophical ideas, such as reductionism, the role of mathematics, modeling, modulation and the correspondence principle. By describing the history of physical theories the teacher naturally introduces to the students these ideas when describing the activity of scientists, their ways of exploration and ways of demonstration. Such features of physics knowledge as being tentative, approximate, limited in validity, falsifiable and self-correcting naturally emerge when one observes the historical context. Normally such topics do not receive explicit teaching in physics class in other than historical context.[11]

For example, learning about the history of quantum physics through the historical narrative is much easier than starting with postulating of the new non-intuitive formalism reflecting a completely new vision of reality. The story about the instrumentalist approach introduced by the Copenhagen school and their furious debates with those like Einstein, Schrodinger, de-Broglie is exciting and much more appealing to the novice mind than any direct demonstration of quantum mechanics.[12,13] Likewise, presenting the history of special relativity reveals the nature of this fundamental revolution in physics. Students learn that Michelson-Morley experiment is only one from many arguments in favor of the new worldview, seeking covariance, symmetry and relativity in the description of reality.[14] Here too the students can be attracted with real story, debates of real people not less than by an adventure novel. The historical debate around the relativity theory in fact presents a convincing didactic method to teach the contents of the relativity theory. By presenting the historical debate to the learners one provides them with arguments that tackle the common tendencies of scienticism and dogmatism.

The forth point in our list is (4) *the culture of physics*. This aspect is not often addressed in regular physics teaching. It is, however, important in presenting physics to the next generation of its practitioners to describe more than the disciplinary contents. Physics teaching, intentionally or spontaneously, displays the elements of physics as a culture: the beliefs and ideology of generations of physicists. While presenting contents teachers often provide evaluative comments regarding the quality of solution and explanation, the features and requirements of physics products, such as parsimony, openness to criticism, the style and form, elegance and consistency, universality and objectiveness, and even fantasies and sentiments. Physics teaching seeks to tell to the future generation about its tradition, peaks of success and glory, spiritual intentions, a wishful image of itself such as seeking the all inclusive theory of the world or the ability to account for any phenomenon. Teachers of physics demonstrate to the learners the kind of expression style, appealing to feelings, spiritual, moral and ethical values, which should evoke in the learners sympathy and solidarity. In ancient terms, all these establish Ethos, Mythos and Pathos together creating what is normally called the *culture* of the discipline and, if known to the learner, humanize the image of physics. The culture of physics is universal, that is common for all people regardless their country, gender or race. The HoP provides a channel to teach this unique culture to the modern generation.

It is these aspects which enter the physics class when we tell to students about Galileo's trial, Newton's debates with Hooke, Fresnel's triumphal introduction of the wave theory of light, Einstein's thought experiments and his dreams about the unified theory of everything, the dramatic decisions of physicists who developed atomic weapons, and the passionate devotion of the physicists who promoted space exploration.[15]

The mentioned four aspects make physics teaching interdisciplinary keeping with the cultural standards established already in Greek science and kept through 2500 years of physics history.

Although one can add other roles of teaching HoP[16], it is more important to provide a different perspective which fortified the idea of using HoP drawing on the educational psychology.

SUPPORT FROM THE EDUCATIONAL RESEARCH

Cognitive science provided important considerations in favor of inclusion contents from physics history in regular teaching. Already in the sixties, within then prevailing behaviorist paradigm in psychology,[17] Schwab came out with the agenda of enquiry for science education.[18] This trend of thought put to the fore the core of the science: the method of *enquiry*. He criticized teaching science by informing about the knowledge and stated the need of teaching which exposes the structure of knowledge, the method of knowledge construction by imitating the real scientific research. Physics history which displays the process of creation of knowledge was perceived as suggestive for students. This approach was implemented first by Connant[19] and thereafter by Harvard Physics Project. The idea was to introduce the stories of activities of the prominent physicists from the past (Galileo, Newton, Faraday), tracing their line of thought in discovering the laws of nature[20]. However, besides providing valuable materials for physics teachers, we do not see that Harvard Project Physics materials were assimilated in the physics teaching.

At the later stage (the 80^{s}-90^{s}), physics educators rediscovered for themselves the phenomenon of cognitive *recapitulation*. Lead by this paradigm, researchers gave a close look on the development of physics, to the way in which physics theories replaced each other in the course of history. If the similarity takes place, the reasons for scientific revolution should be similar to those which course a conceptual change of an individual student in his/her learning of physics. Basing on this assumption, Posner et al.[21] formulated four conditions for a conceptual change to take place in the learner of physics (they investigated students learning the special theory of relativity). The conditions were: dissatisfaction with the previous knowledge, plausibility, intelligibility and fruitfulness of the new knowledge. Students were equated to scientists in performing a conscious reconstruction of knowledge. In a sense, the core of this account could be identified with the *cognitive conflict* between the old and new knowledge of the learner.

A number of researches discovered the similarity of physical ideas spontaneously developed by physics students (mainly in mechanics and optics) to those of scientists of classical Greece[22,23] and medieval science.[24] These findings suggested teachers to stimulate cognitive conflict in the learners regarding particular misconceptions using the *relevant* historical contents in teaching and class discussions.[25] Within this approach Galili and Hazan made a year long experiment. A special course of optics for high school students followed the trend of historical development of the knowledge of light and vision. The course, which in parts had a narrative form, presented the theories regarding the nature of light and vision in an unfolding manner, starting from the ancient Greece, through the Muslim and European medieval science, to the scientific revolution of the 17th century. Their approach showed the genesis of knowledge, making plausible its rationale, all within the limits of school teaching. The study sought two major goals: to encourage learning of the subject matter and better understanding of the nature of science, also presented as historically changed. In both aspects a significant success was assessed.[26, 27]

An important support for the use of the HoP came from educational psychology that revealed the principle of *variance.*[28] It was found that the differences between the subjects of learning could be more stimulating than the similarities between them.[29] These studies suggest the effectiveness of the strategy to teach a subject in variation of its meaning. Instead of saying "this way", it is preferable if teacher says: "not that way, and neither that way, but this way". Human cognition, very sensitive to contrasts, effectively learns the objective through a comparison between its variations, considered as possible options. For example, in order to teach certain physical conception, this approach suggests teaching several variations of this conception. The student learns the goal conception by discerning its idea by comparison between the presented to him/her alternatives. The HoP naturally provides such a "space of learning". In the case of optics, it is the competitive conceptions with regard to optical image. Their critical analysis encouraged effective construction of the concept of optical image and the awareness of its features as distinguished from the competitive possibilities.

EXAMPLE OF APPLICATION

Our study in application of the HoP in teaching physics took two trends. The first one was based on the traditional research, as performed in several countries, and investigated students' misconceptions in the course of their learning optics at school.[30] The study enabled us to establish a structure of students' knowledge. We found it comprised of several conceptions (schemes-of-knowledge). We then reviewed the history of optics regarding the growth of understanding of light an vision.[31,32,33,34] We found a certain parallelism between individual conceptions of students and the scientific conceptions in the course of history (Table 1). Keeping with the limits of the school curriculum, we then developed a new textbook, which presented the subject as an unfolding knowledge, and in doing so we paid a special attention to the rationale of the old physical theories, their meaning and justification.[35] Attention was also given to the process of maturation of the scientific method, the way of making sense of nature and its investigation, seeking explanation and adequate account. We have applied the new text in a year long course in 10th grade classes, followed up by an evaluation research. The results were promising. The following briefly touches on a few points of our experience.

Table I. Examples of conceptual parallelism in optics knowledge used in the experimental course

Historical conception practiced in the past science	*Student's conceptions practiced in the course of learning*
Pythagorean conception of vision: ''Active'' vision", Euclidean visual and light rays	Rays of sight, rays of light, rays reification
Atomists' conception of vision ''Eidola''	Image Holistic Scheme
Biblical–Medieval dichotomy of light as an entity and perception: lumen–lux dichotomy	Static light located in/around light sources, halos, bright sky, illuminated surfaces, light reification as a static entity
Al-Hazen conception of vision by means of light rays	Image Projection Scheme

Keeping with the history of optics implied significant changes in the way the subject matter was taught. Firstly, *vision* and *observer* were presented in connection from the very first lessons. This reflected the development of physics and, at the same time aimed to the frequent misconceptions of students regarding vision and the role of observer.[36] In a regular teaching, vision (the role of eye) is discussed in about the middle of the course, in the context of using lenses. The scientifically correct explanations are usually provided without competitive ideas, briefly and correctly. Light is considered as a physical entity, often independently from vision and observer.

Secondly, the history of optical image was interwoven with the account for vision. Its understanding reflected the major stages in the growth of optics. It appeared that a common naïve conception of image, held by many students before learning, corresponded to the holistic theory of Eidola, the theory of vision developed by "atomists" in the classical Greece. Quite surprisingly, however, the frequently appeared misconception of optical image among the students already instructed in physics[37] closely resembled the theory of vision by Al- Hazen, the prominent Muslim scientist of the 10-11th century.[30, 31]

A special attention was given to such topics as shadow and the speed of light. Although both these topics have a rich history relevant to students' difficulties (Table 1), they are commonly only briefly presented and considered to be too simple for the 10th grade. The concept of light ray was elaborated in its history, while it is never considered in instruction beyond its technical use. In fact, it served as the central concept in optics, starting from Euclid and up (including) Newton.[38] Our course showed how light ray was introduced, used and conceptually reconsidered to the familiar to us status by Kepler. In the wave theory by Huygens and thereafter, light ray served only as an auxiliary tool indicating light propagation. The confusion about light ray is involved in many misconceptions of students regarding the nature of light. After the re-evaluation of ray, our course introduced a conceptual alternative to it, which facilitated description of light: the concept of light flux. A similar step in the course of history was taken by Bouger and Lambert who established photometry.[39]

Light flux is often abandoned in the currently employed physics curricula for high schools together with the whole unit of photometry that gradually disappeared from introductory courses, leaving a hole in the conceptual structure of the discipline.[40] As often happens, such a vacancy was filled by naive conceptions manifesting themselves, for example, in the failure of many students to account for seasons and light illumination.

Importantly, we observed that despite the parallelism of misconceptions, in the history and in the individual learning, one can hardly draw on the *conceptual conflict* by an exposure of argumentation against certain conception. It is rather that the process taking place in students facing similar or different ideas and argumentation in the history presents a *conceptual resonance*. One can barely equate the debate between mature scientists sharing strong commitments of consistency, logic and role of evidence, with the way a novice young person renders knowledge and arrives to conclusions. The role of teacher's mediation is essential in the process of learning. This, however, does not discharge historical materials, but more accurately determines their role in physics teaching. The well chosen HoP materials attract attention of students, causing their solidarity with the scientists of the past. Students may sympathize to the views and beliefs of the scientists. Instead of "I got it wrong, my view is incorrect, I change my mind in favor of this view, because it is more powerful etc.", it might be more like: "Hm, it is interesting, it looks ok, it makes sense, it might be that…". Thus, the told story of Al-Hazen's theory, his arguments against the Greek theories of vision and, later on, the critique of his theory prepare student to accept Kepler's theory of vision. This is a rather "soft" conceptual change by a student, in contrast to the decisive change of mind by a mature scientist.

THE HISTORY OF PHYSICS WITHIN TEACHING PHYSICS AS A CULTURE

Within the second trend of our study we tried to answer the question to what extent the HoP presents a necessity in teaching physics, or it is merely optional? Suppose we face truly talented physics students who are immune to all possible misconceptions and correctly assimilate every word of their teacher in physics class. Do they need any of the HoP contents, which will take their valuable time, instead of them solving more problems, participating in more projects, and practicing physics knowledge in more contexts? Would then the aforementioned textbook in optics waist their time and decelerating their learning of physics?

The first response to these questions is that physics presents a culture and not a heap of facts, laws and rules of problem solving. Excluding history leaves students without the living body of physics, its culture, depriving the learner from the rich ideology of physics. In fact, such an approach would transform physics from science to a craft. This step would be unfair just to those who are talented and gifted and are expected to preserve the cultural tradition of physics.

There is, however, another answer, which states that depriving physics from history harms the understanding of the *meaning* of physics knowledge in the sense of its structure and syntax. To appreciate this aspect we had to consider the structure of physics knowledge.[41] The components of physics knowledge structure (laws, concepts, principles, theories, models, etc.) are frequently addressed in physics classes, but not so often the teacher presents the conceptual architecture, the hierarchy and interrelations between these components.

Any fundamental discipline comprising physics (classical mechanics, thermodynamics, electromagnetism, quantum theory) could be represented as incorporating elements of three groups. The first one includes principles, fundamental concepts and laws. Together, they comprise the *nucleus* of a discipline. From the rest of the elements, those that represent various applications of the nuclear elements such as for problem solving, modeling and explanations of various natural phenomena and laboratory experiments comprise the *body* of the discipline (Fig.1).

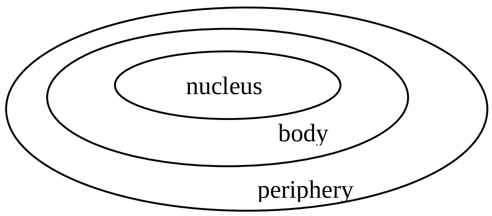

Figure 1. Schematic structure of a fundamental discipline in physics.

One, however, can recognize knowledge elements of the third type which belong to *periphery*. This area includes the knowledge which contradicts the nucleus of the discipline. Here one finds, for example, the principles and conceptions from the past, replaced in the course of history by newer theories, as well as the phenomena which cannot be explained basing on the principles of the nucleus. Periphery includes all the relevant knowledge of the subject domain, including misconceptions. The two first areas (nucleus and body) determine the *discipline* in physics, and the addition of periphery upgrades the discipline to the status of a *discipline-culture*.

In accordance to this view, we can characterize teaching physics which ignore periphery as *disciplinary* oriented, whereas teaching incorporating periphery contents, establishing a dialogue between the elements of different areas, presents *the cultural teaching*. Such a teaching leads to the creation of cultural knowledge of physics. Naturally the HoP contributes to all the zones of the structure of Fig.1: nucleus, body and periphery, but the contribution to the periphery is often missed in the currently prevailing physics teaching. For example, teaching mechanics rarely includes the concepts of Aristotelian and medieval physics leaves relativistic and quantum ones solely for future learning (the leaning that realizes only for a small number of students).

The mentioned experiment of teaching optics using genetic approach fits to the framework of cultural teaching. Being "cultural" obtains thus a concrete definition. It means addressing conceptual alternatives, the limits of validity and reliability in the presentation of any disciplinary content. The mentioned historically based textbooks written by prominent physicists demonstrate the cultural approach in teaching.[33, 34, 35]

In fact, within the cultural approach the historical contents, in a sense, cease to represent the past. The focus on the conceptual dialogue, emphasizing alternative possibilities, competitive interpretations, is made regardless the belonging to the past or future. Aristotle, Buridan, Descartes, Galileo, as well as Einstein and Bohr, appear in a vivid dialogue with Newton and thus change the whole atmosphere of teaching physics. We may mention here the recently reported new teaching unit of color, basing on a dialogue between Newton and Goethe, as an example of cultural teaching of this subject to physics students.[42] One can find other examples of cultural perception of physics in the activities of the international project on Pendulum. The project revealed this item of physics curriculum as a *cultural fractal*, that is including an extremely broad variety of aspects representing the culture of physics. The contents were drafted from the history of science.[43]

The important implication of cultural teaching of physics is clarification of the principle of correspondence between different physical theories which historically succeeded each other (such as Classical and Relativistic mechanics). Body areas of such theories may overlap (area C in Fig. 2), but never the nuclei (N1 and N2). Thus teaching the Newtonian summing of velocities in the relative motion emphasizes that although the numerical result can approach the one obtained using the theory of relativity, this should not mask the fact of essential confrontation of the nuclei of these theories. This understanding of the correspondence principle facilitates students' mature understanding of the HoP. It will help those numerous students who overlook the fundamental conceptual changes in physics and imaging the progress as a gradual advancement, as well as those who see the HoP as a series of theories in which every next link totally refutes the previous one. We tried this balanced presentation of different theories of light in teaching optics.

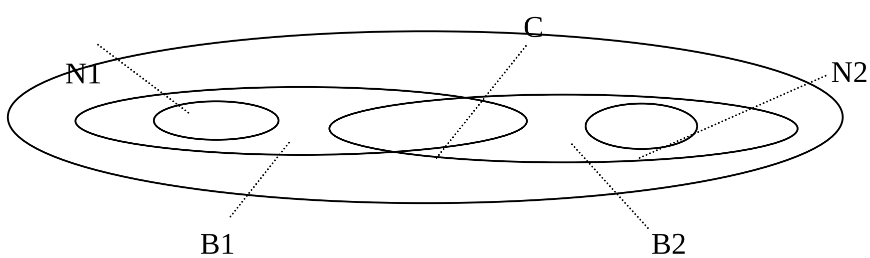

Figure 2. Schematic representation of the principle of correspondence between two fundamental disciplines in physics. The bodies of the two theories overlap in area C, whereas nuclei N1 and N2 remain well separated.

SUMMARY, IMPLICATIONS, SUGGESTIONS

From the beginning of teaching physics in schools (about 150 years) many educators recognized the high potential of the HoP as a tool for teaching. We have distinguished three stages in the appreciation of the kind of contribution that the HoP to the process of learning physics.

I. At the first stage, it was realized that the HoP can help students to better understand the subject matter by revealing the context of the general and abstract statements. The historical contents familiarize students with the way of doing physics, the nature of physics as a method of human exploration and learning about the Nature. Moreover, the HoP reveals to the learners, without explicit teaching, some essential concepts from the philosophy of science which are required for its genuine understanding and, not less important, provide the students with the inherent cultural values of physics.

II. At the next stage, within the tendency to focus on the practical application of physics and problem solving, science educators rediscovered the recapitulation of knowledge and therefore a possibility of drawing on the analogy between the growth of individual and collective knowledge. In their strategy of stimulation of conceptual change by the learner, teachers can use the argumentation employed by scientists in the past in illustrating the contents they teach and persuading their students to consciously reconstruct and build the new for them knowledge.

III. Finally, within the recently suggested perspective of discipline-culture, the HoP was recognized as playing an essential role in the structure of physics knowledge. Various contents from the past (from the periphery zone of the physics disciplines) provide and enrich the meaning of the claims physical theories (their nuclei). This is because comparison and contrast between the conceptual alternatives is required by human cognition in the process of learning. Moreover it creates a more mature knowledge which includes awareness of validity limits of the particular elements of knowledge.

All three stages equipped the physics teacher with a strong motivation to incorporate historical materials in a regular teaching.

Although the HoP was seldom totally rejected, it faces many objections. The first one is **lacking of time** of instruction. Our answer for this is that teaching physics should not be replaced by history, and neither the HoP is suggested to be added as a separate material. The historical contents should be interwoven in the regular teaching. This is the genetic approach introduced by Ernst Mach more than a hundred years ago. Similar to the water which does not expand when sugar is added, the teaching contents do not proportionally increase in volume when the teacher adopts the new knowledge taken from the HoP.

Lacking of the appropriate knowledge background was mentioned as another important obstacle. It is true that teacher training seldom includes the HoP. This can be changed. As to the in-service teachers, one may suggest various self training frameworks supported by workshops and professional meetings. There are textbooks, written by prominent physicists, who illustrate the cultural approach to teaching physics and thus provide necessary scaffolding.[44,45,46] Unlike the *classical* physics, the introductory textbooks introducing *modern* physics (the theory of relativity and quantum physics) often present the contents in a historical unfolding.[47,48] All these can adequately support the efforts of the teacher in the attempt to enrich and improve his/her teaching.

Another claim against the genetic approach is that the exposure to the erroneous contents, strange concepts, language and style could cause students' confusion. The results of contemporary research in physics education shows that there students spontaneously develop many misconceptions, often replicating the theoretical views from the past. Therefore, addressing history, including argumentations of competitive theories against certain views, can facilitate reconsideration of misconceptions and overcoming them, using the historical materials as the necessary scaffolding.

Finally, the need of involving history to the physics curriculum matches the discipline-culture paradigm which would may improve the quality and cultural validity of their physics education and attract more students in the modern society to learning physics. Such a step could bring an answer to Smolin's question "Why No 'New Einstein'?"[49] and support Churchill's saying, albeit in a different context, that "if we open a quarrel between the past and the present, we shall find that we have lost the future".

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