Results in physics education research as lenses for analyzing textbooks, recognizing critical details and fostering thinking. The case of teaching/learning special relativity

REVISTA DE ENSEÑANZA DE LA FÍSICA

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Abstract

The teaching of special relativity, both at the secondary school level and at the university level, is still strongly influenced by the approach designed by Resnick in 1968. This approach follows in some way the 1905 original paper of Einstein on "The electrodynamics of moving bodies" and it is still orienting, more or less explicitly, textbooks' authors.
In this paper I analyze how the educational tradition progressively transformed the presentation of the theory, from the original article to the current textbooks. In particular, I will show how such a transformation has progressively disregarded both *critical details* needed for understanding, and that *interpretative dimension* needed for making the approach comparable to other possible ones and, hence, needed for perceiving the cultural meaning of the theory.
The analysis is carried out using results in Physics Education Research (PER) as lenses and it is intended to provide teachers with tips for reading in the lines of textbooks and for recognizing some implicit interpretative choices.

Keywords: Special Relativity, Textbooks, Original papers, Teaching and Learning

Resumen

La enseñanza de la relatividad especial, tanto a nivel de escuela secundaria como de universidad, se encuentra aún fuertemente influenciada por el abordaje diseñado por Resnick en 1968. Este abordaje sigue, de alguna manera, la publicación original de Einstein de 1905 sobre "La Electrodinámica de los Cuerpos en Movimiento" y orienta, de manera más o menos explícita, a los autores de libros de texto.
En el presente trabajo analizo cómo la tradición educativa ha progresivamente transformado la presentación de la teoría, desde el artículo original hasta los textos actuales. En particular, mostraré cómo tal transformación ha progresivamente dejado de lado tanto *detalles críticos* necesarios para la comprensión, así como la *dimensión interpretativa* necesaria para que el abordaje sea comparable a otros y posibilitar así la percepción del significado cultural de la teoría.
El análisis se lleva a cabo utilizando como lentes algunos resultados de la investigación en educación en Física (PER), y pretende proveer a los docentes claves para leer "entre líneas" en los textos y reconocer algunas elecciones interpretativas en ellos implícitas.

Palabras clave: Relatividad especial, Libros de texto, Artículos originales, Enseñanza y Aprendizaje

I. INTRODUCTION

The teaching of special relativity, both at the secondary school level and at the university level, is still strongly influenced by the approach designed by Resnick in 1968 (Resnick, 1968). In particular, Resnick's approach can be seen at the basis of the widespread educational tradition that presents relativity following this outline: historical excursus about the state of physics knowledge at the end of XIX Century and discussion of experimental evidences which required a revision of Newtonian mechanics;

presentation of the postulates and of the relativistic effects (derived either from the Lorentz transformations or by thought experiments); explanation of experimental proofs and technological applications and, at the end, presentation of the main notions of relativistic dynamics.

Resnick's approach, in its early formulation, is recognisable as an educational transposition of the 1905 original paper of Einstein on "The electrodynamics of moving bodies", where both Einstein's operational approach and the main pillars of Einstein's argument are carefully respected and exploited. Unlike Einstein's original paper, Resnick's textbook pays a broad attention to the Michelson & Morley experiment (that in the original paper is not explicitly mentioned whilst it is usually widely discussed in textbooks[1]) and, of course, the experimental proofs and the technological applications are included and refer to the experiments realized as follow up of the theory.

Over the years, the distance between textbooks and the original paper become more and more evident, mainly on the rhetoric plan. The "voice" of Einstein somehow disappeared and a process of "de-personalization" progressively took place through which scientific language and arguments have gone. The argumentative tension of who has to persuade, by a scientific paper, the scientific community of the plausibility and relevance of the new theory disappears in current textbooks and language becomes factual, a linear and clean transmission of shared contents.

In this paper, I will focus on this special case of "de-personalization" and discuss some risks it can involve both for *understanding* the basic contents of relativity and for *appropriating* the cultural sense of the theory.

In particular, after a brief illustration of the process of de-personalization in the case of the teaching of special relativity through an approach *à la* Resnick (sección II), I will go through the first part of Einstein's paper and I will show how its transformation for teaching has progressively disregarded both *critical details* (Viennot, Chauvet, Colin & Rebmann, 2005) needed for understanding (sección III), and that *interpretative dimension* needed for making the approach comparable (*commensurable*) to other possible ones and, hence, needed for perceiving the cultural meaning of the theory (De Ambrosis & Levrini, 2010; Levrini, Fantini, Pecori, Tasquier & Levin, 2014) (sección IV).

The analysis will be carried out using the lenses of Physics Education Research (PER) and it is intended to provide teachers with tips for reading in the lines of textbooks and for recognizing some implicit interpretative choices.

In the conclusions, implications for teaching are discussed (sección V).

II. FROM ORIGINAL PAPERS TO TEXTBOOKS: OBJECTIFICATION OR IMPOVERISHING?

The transition from the original article to textbooks is extremely interesting from a cultural point of view; it is in fact a step in which crucial decisions are made about the image of physics that one wants to convey. Kuhn himself, who contributed so significantly to change the image of physics, opens "The Structure of Scientific Revolutions" by criticizing the identification of science with science textbooks:

> History, if viewed as a repository of more than anecdote or chronology, could produce a decisive transformation in the image of science by which we are now possessed. That image has previously been drawn, even by scientists themselves, mainly from the study of finished scientific achievements as these are recorded in the classics and, more recently, in the textbooks from which each new scientific generation learns to practice its trade. Inevitably, however, the aim of such books is persuasive and pedagogic; a concept of science drawn from them is no more likely to fit the enterprise that produced them than an image of a national culture drawn from a tourist brochure or a language text. (Kuhn, 1962)

In a 1996 paper, Clive Sutton argued that textbooks are the last phase of a process aiming at transforming language from an "interpretative system for making sense of new experience" into a "labeling system for describing, reporting and informing" (Sutton, 1996). The steps of the conversion

[1] The role played by the Michelson & Morley experiment in the genesis of special relativity and, in particular, in Einstein's personal process of invention has been widely investigated since the works of Shankland [Shankland, R. S., (1964). Michelson-Morley experiment. *Am. J. Phys.* 32 (1), 16-35; Shankland, R. S. (1973). Michelson's role in the development of relativity. Applied Optics, 12 (10), 2280; Shankland R. S. (1973). Conversations with Einstein. *Am. J. Phys.* 41 (7), 895-901]. Other very authoritative studies that discuss such a special relationship are: Holton, G. (1969). Einstein, Michelson, and the 'Crucial' Experiment. *Isis* 60, 133-97; Pais, A. (1982). "*Subtle is the Lord—": The science and the life of Albert Einstein*, Oxford University Press.

process are identified in the sequence of different kinds of publication: Journal →Handbook of research →Textbook, during which

> [...] some of the ideas and claims of individuals are built into the structure of thought of a larger community and converted into agreed public knowledge which merits the status of 'fact', or 'fact for the time being', or at least 'best available theory, which to all intents and purposes we can assume to be correct'. (Sutton, 1996).

The language, moving from the original papers to textbooks, becomes objective, definite, precise, needing the right word for the right thing; the voice of scientist is lost and the ideas become "labels":

> The more often [the ideas] are used, the more familiar they become, and the less tentatively they are expressed, so words inevitably start to function as labels for the things that people now feel sure about. A phrase like 'the orbit of the electron', which began as a mere figure of speech, becomes a label for a reality which to all intents and purposes is considered to exist. (Sutton, 1996).

In the transition from original papers to textbook the rhetoric deeply changes: from dialectics and confrontational, typical of knowledge that is being built, to the more simple rhetoric of information. It is through this transition that, according to Sutton, the process of objectification typical of scientific knowledge takes place: A claim becomes a fact accepted by the community; the arguments appropriately selected as the most convincing to support a thesis disappear and the language, from conjectural, becomes literal, denotative.

So, if it is true that, in the transition from the original papers to manuals, the process of depersonalization performs that function, inherent to physics, of more and more objectifying knowledge, it is equally true that different meanings can be ascribed to this process in teaching. On one hand, this process can be part of teaching so as to provide students with examples of how knowledge is constructed, what epistemological, sociological and personal aspects can be involved and how dramatic – and fascinating – the process of knowledge construction can be; or, on the other hand, the process can be only hinted to show the power of a science which, when freed from every element of subjectivity, can unlock the objective secrets of nature.

More or less consciously, teaching usually chooses the second approach. This positioning can mirror the epistemological choice of considering results more important than the process and any form of subjectivism far from the very essence of physics. However, in Gerald Holton's opinion, this choice is more than this and implements a "normative and moralizing" function attributed to science education: The function of getting students acquainted with the public norms of scientific profession, among which there is the norm of minimizing the personal involvement in scientific job (Holton, 1973).

In this paper, the process of depersonalization will be discussed mainly for its cognitive implications on learning and on thinking, even though I retain its consequences on the image of science very relevant.

In the case we are considering, the process that moved from the original paper of Einstein to the current textbooks *via* Resnick's approach led the following features of Einstein's choices to be removed and, then, lost: the care he took of building, step by step, the lattice of synchronized clocks needed to operationally define space and time in a frame of reference; his epistemological choice of presenting the theory as a beautiful, simple and coherent construction able to solve *theoretical asymmetries* and to offer a new *operational way* of looking at space and time, free from useless metaphysical entities, like the Newtonian absolute containers or the luminiferous ether.

In the following sections I will use the main results obtained in PER about students' difficulties in learning relativity to argue why such a process, if not carried out with care in teaching, can lead to "dangerous simplifications, that is hyper-simplified instructional descriptions and explanations that, by making the material seem easy, are dangerously able to distort the learning process as well as the content" (Levrini & Fantini, 2013). Two kinds of dangerous simplifications will be considered: i) the disregard of details that revealed to be critical for a global and deep understanding of the theory, and ii) the impoverishing of the argument to the point of presenting "ideas with a single sense" (Minsky, 1986). And, as Minsky claims:

> An idea with a single sense can lead along only one track. Then, if anything goes wrong, it just gets stuck--a thought that sits there in your mind with nowhere to go. That's why, when someone learns something "by rote" --that is, with no sensible connections--we say that they "don't really understand." The secret of what anything means to us depends on how we've connected it to all

> the other things we know. That's why it's almost always wrong to seek the "real meaning" of anything. A thing with just one meaning has scarcely any meaning at all. (Minsky 1986, p. 64)

III. WHEN "TEXTBOOK'S OBJECTIFICATION" DISREGARDS CRITICAL DETAILS

The original paper of Einstein includes a part titled "Kinematics", where a long discussion about the definition of time and space introduces to the implications of the postulates, the Lorentz's transformations and the relativistic effects. In the process of objectification, didactical tradition has progressively retained such a discussion a useless disquisition and textbooks progressively made it disappear.

In particular, much more extensively than in textbooks, Einstein takes care of providing an observer with an ideal tool, the lattice of synchronized clocks, needed to provide "judgments in which time plays a part" (Einstein, 1905).

The construction of the lattice occurs through passages which concern: i) the introduction of the concepts of *event* and *time of an event*, ii) the discussion of the problem of determining the *time of a distant event*, iii) the definition of a *procedure of synchronizing* clocks that are spatially distant.

In the following we reconsider these passages because, although they can appear pedantic, it is in these steps that some *critical details* can be hidden, that is details that, if neglected, endanger the understanding of key concepts and the achievement of a process of conceptual change, as several works in PER about relativity argue (Posner, Strike, Hewson & Gertzog, 1982, Hewson, 1982; Sherr, Shaffer & Vokos, 2001; 2002; Levrini & diSessa, 2008)[2].

A. Einstein's operational definition of time and space

In reading the second paragraph with the heading "Part kinematics", one realizes that the first choice of Einstein is to bring the concepts of space and time to their operational definitions - coordinates to be determined by the use of rigid rulers and clocks. In this context the concepts of *event* and *time of an event* are introduced and discussed. He writes:

> If a material point is at rest relatively to this system of co-ordinates, its position can be defined relatively thereto by the employment of rigid standards of measurement and the methods of Euclidean geometry, and can be expressed in Cartesian co-ordinates.
> If we wish to describe the *motion* of a material point, we give the values of the co-ordinates as function of the time. Now we must bear carefully in mind that a mathematical description of this kind has no physical meaning unless we are quite clear as to what we understand by "time". We have to take into account that all our judgments in which time plays a part are always judgments of *simultaneous events*. If, for instance, I say, "That train arrives here at 7 o'clock," I mean something like this: "the pointing of the small hand of my watch to 7 and the arrival of the train are simultaneous events[3]. (Einstein, 1905, p.39. Italics not added).

The motion of an object becomes a set of space-time events, where each event is defined through the measuring operations necessary to determine *position* and *time instant* in which the event occurs. The operational definition involves the use of both a measuring rod and of a clock. The *time of an event* is then "what is measured by the clock placed next event." But, as he writes immediately after, this definition is not enough to determine the time of events that occur in locations distant from the clock:

> It may appear possible to overcome all the difficulties attending the definition of "time" by substituting "the position of the small hand of my watch" for "time". And in fact such a definition is satisfactory when we are concerned with defining a time exclusively for the place

[2] In another paper I review a selection of papers in teaching/learning special relativity and, there, I deeply stress to what extent several studies carried out in PER, applying different research methodologies according to different theoretical perspectives, provide multiple cross arguments for supporting a common achievement: guiding students to *look in terms of events* is crucial for promoting deep understanding in special relativity (Levrini, 2014).

[3] Pay attention here to the fact that in this specific case simultaneity refers to two events that are supposed to occur *in the same position*. In this case, if they are simultaneous in one frame of reference, they are simultaneous in *all* the frames of reference. The relativity of simultaneity refers to couples of events that, in *none* frame of reference, can occur in the same position (they are related to a space-like interval).

> where the watch is located; but it is no longer satisfactory when we have to connect in time series of events occurring at different places, or – what comes to the same thing – to evaluate the times of events occurring at places remote from the watch. (Einstein, 1905, p.39)

The *time of an event* defined as above shows its limits "when we have to connect in time series of events occurring at different places, or – what comes to the same thing – to evaluate the times of events occurring at places remote from the watch". The problem arises because we are assuming that in nature there is an unsurpassable speed. For this reason the time of an event does not coincide with the *time of reception of the signal*, i.e. the time in which a clock, distant from the event location, receives the signal sent from the event itself. The clock receives the signal with a delay equal to d/c, where d is its distance from the event and c is the speed of light in vacuum.

To address the problem represented by the existence in nature of an unsurpassable speed and, therefore, by the necessity to distinguish between the *time of an event* and the *time of reception of the signal*, Einstein stresses:

> We might, of course, content ourselves with time values determined by an observer stationed together with the watch at the origin of the co-ordinates and co-ordinating the corresponding positions of the hands with light signals, given out by every event to be timed, and reaching him through empty space, But this co-ordination has the disadvantage that it is not independent of the standpoint of the observer with the watch or clock, as we know from experience. We arrive at a much more practical determination along the following line of thought. (Einstein, 1905)

Through this argument, based on the need to provide definitions - and measures - ideally independent of the position of an observer, Einstein finally comes to build the lattice of synchronized clocks (see Figure 1). This is the tool that each observer has to use to evaluate, in their reference system, the temporal order of events (if they are simultaneous or not), the spatial distance between two events and the length of a body. To construct the lattice, a definition of simultaneity for events that occur at different locations (based on the isotropy of the speed of light) is provided and a synchronization procedure is shown[4].

Thanks to the lattice, an observer is now well-equipped for measuring the time interval between two events, even if they are distant in space, since their time interval can be evaluated by comparing what the two clocks, placed exactly where the two events occur, sign. Furthermore, the observer is equipped to measure the length of a body, by applying precise operational definitions. Also for lengths, Einstein is very detailed and distinguishes the operational definition of the length of a body at rest with respect to the frame of reference from which the measurement is carried out and the length of a moving body:

> We now inquire as to the length of the moving rod, and imagine its length to be ascertained by the following two operations:
> a) The observer moves together with the given measuring-rod and the rod to be measured, and measures the length of the rod directly by superposing the measuring-rod, in just the same way as if all three were at rest.
> b) By means of the stationary clocks set up in the stationary system and synchronizing [the lattice of synchronized clocks], the observer ascertains at what points of the stationary system the two ends of the rods to be measured are located at a definite time. The distance between these two points, measured by the measuring-rod already employed, which is this case is at rest, is also a length which may be designed 'the length of the rod' (Einstein, 1905, p. 41)

[4] An operational way to synchronize two distant identical clocks is to place in C, a point at an equal distance from the two clocks, a transmitter of light signals. The clocks in A and B will be synchronized by making them to sing the same time when the signal from C reaches them.

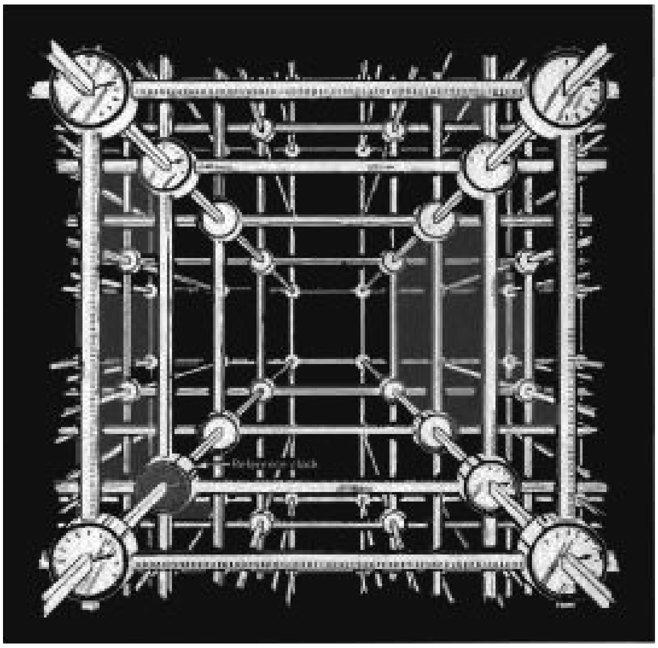

FIGURE 1. Lattice of synchronized clocks (Picture from Taylor & Wheeler, 1992)

So far, in Einstein's argument, the two postulates did not playe any specific role. The argument was developed to *re-arrange imagination* so as to make it suited to think of a world where an insuperable speed is assumed. Imagination is re-arranged so as to see a world where phenomena are fragmented in sets of events, space and time are coordinates to be established through a lattice of synchronized clocks, strictly interwoven, and where the assumption of an insuperable speed led space and time to be deeply interwoven – in measuring both the time of a distant event and the length of a moving body, rules and clocks are both necessary.

The concepts of space and time undergo their most drastic change when the postulates of the theory are introduced and their implications are analyzed. The postulates introduce new constraints – norms[5] – to be respected when phenomena and physics laws are considered from different inertial frames.

To derive the relativistic effects in the original article, Einstein follows the road of the Lorentz transformations, derived by the two postulates (as well as the assumption of homogeneity and isotropy of space-time). Thus, the relativistic effects are algebraically obtained as implications of such transformations. This road has the drawback that the formal steps may overshadow two rather important points for understanding the theory: the link between the postulates of the theory and relativistic effects (Posner et al., 1982); and the role of the operational procedures used to define time and length.

These two points can instead be highlighted if the relativistic effects are derived by thought experiments. Today, many textbooks[6] follow this path, where the relativity of simultaneity is discussed on the basis of the so-called "train paradox thought experiment" and the time dilation on the basis of the "light clock experiment". The length contraction is, usually, derived from the formal expression obtained for time dilation in the light clock experiment. Students' difficulties in understanding the thought experiments and the relativistic effects will be discussed in Section #3.3. Before doing that, I would like to go back to the lattice of the synchronized clocks and to provide a new argument to stress in what sense it was, for Einstein, a tool for arranging imagination.

B. The world seen from the patent office in Bern at the beginning of '1900

In the first paragraph of the book "Einstein's Clocks, Poincaré's Maps", the historian Peter Galison writes:

> At the heart of [Einsteinian] radical upheaval in the conception of time lay an extraordinary yet

[5] In the paper by Bertozzi and Levrini (2014) we discuss, from an educational perspective, the normative role of the postulates of relativity and its implications in changing the meaning of symmetry in contemporary physics.

[6] See, for example, the textbook of Halliday, Resnick, Walker, or Giancoli (2004).

> easily stated idea that has remained dead-center in physics, philosophy, and technology ever since: To talk about time, about simultaneity at a distance, you have to synchronize your clocks. And if you want to synchronize two clocks, you have to start with one, flash a signal to the other, and adjust for the time that the flash takes to arrive. What could be simpler? Yet with this procedural definition of time, the last piece of the relativity puzzle fell into place, changing physics forever. (Galison, 2003)

The book aims to reconstruct the material worlds in which Einstiein and Poincaré were respectively immersed at the beginning of XX Century and, in a sense, "the book is about that clock-coordinating procedure". The issue of clocks coordination, Galison claims, was

> at once lofty abstraction and industrial concreteness. It was a world where the highest reaches of theoretical physics stood hard by a fierce modern ambition to lay time-bearing cables over the whole of the planet to choreograph trains and complete maps. It was a world where engineers, philosophers, and physicists rubbed shoulders; where the mayor of New York City discoursed on the conventionality of time, where the Emperor of Brazil waited by the ocean's edge for the telegraphic arrival of European time; and where two of the century's leading scientists, Albert Einstein and Henri Poincaré, put simultaneity at the crossroads of physics, philosophy, and technology. (Galison, 2003)

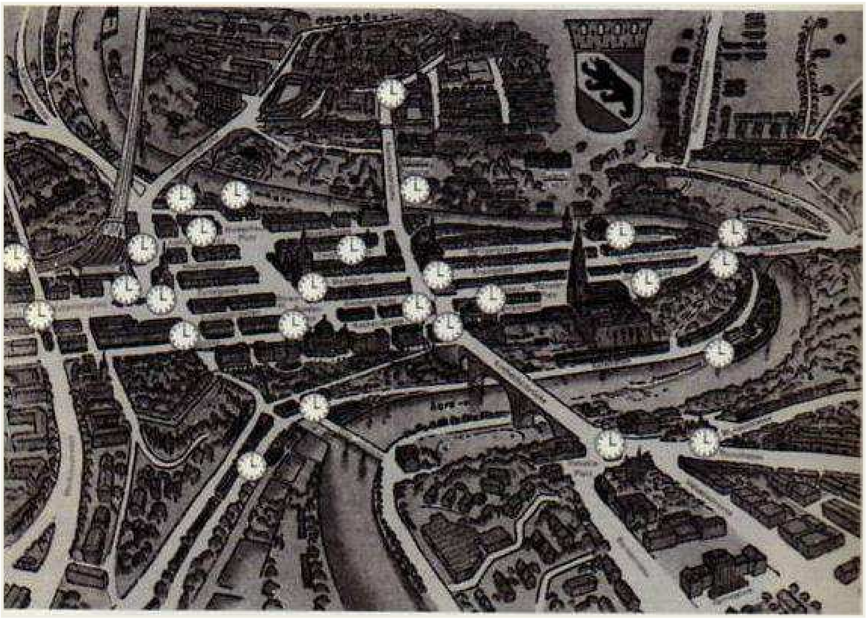

FIGURE 2. The network of the electric clocks of Bern (about 1905). Picture from the book of P. Galison (2003).

From the work of Galison, we learn that at that time, Bern was a modern city, proud of its network of electro-coordinated clocks (see Fig. 2) and we learn that, at that time the number of patents for electro-coordinating distant clocks increased over the first years of XX Century and, very probably, patents like the one reported in Fig.3 passed through the office where Einstein worked.

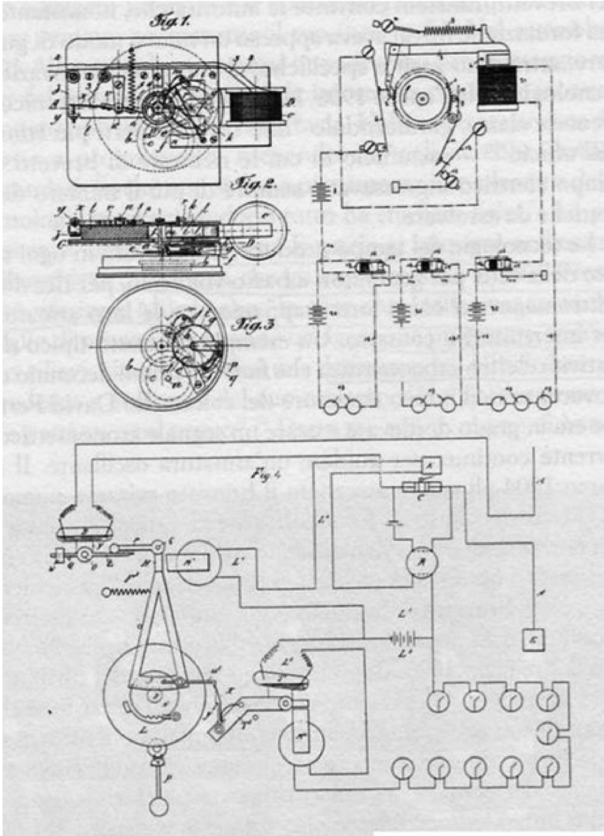

FIGURE 3. Patents for electro-coordinating distant clocks. Picture from the book of P. Galison (2003).

In this sense, the world where Poincaré wrote "the measure of time" (1898) and Einstein wrote "The electrodynamics of moving bodies" (1905) was a place where the theological, absolute time of Newton was very far. Time was a procedure, and its measure on a global scale, so strictly related to the issue of longitude, was a diplomatic issue of conventions (Galison, 2003).

It was in this cultural environment that Einstein, with his friends of the Olympia Academy, read Poincaré's articles and wrote, in his paper, the long discussion about the construction of the "ideal" lattice of synchronized clocks. Einstein was fascinated by the material world and his writings are full of objects (trains, magnets, compasses, clocks, rods…). But, above all, he was fascinated by the sense of wonder that he experienced in front of some objects:

> I encountered a wonder of such a kind as a child of 4 or 5 years when my father showed me a compass. That this needle behaved in such a determined way did not fit into the way of incidents at all which could find a place in the unconscious vocabulary of concepts (action connected with "touch"). I still remember – or I think I do – that this incident has left with me a deep impression. There must have been something behind things that was deeply hidden. (Einstein, 1949)

We can suppose that, also in front of the patents with the synchronized clocks, Einstein thought that "there must have been something behind things that was deeply hidden". And, in the case of special relativity, going behind meant to search for fundamental conjectures to be elevated at the rank of postulates and from which the world of events, coordinated by space and time relations defined by the lattice, revealed its own "wonderful" simplicity.

The processes of guiding the students throughout Einstein's arguments and inviting them to play this game of imagination have, in my opinion, a deep cultural value. Still, these processes are also crucial for helping them to address the well-known difficulties in understanding the relativistic effects, as I will argue in the next section.

C. Critical details

In Einstein's construction of the lattice of synchronized clocks, some details are worth to be stressed since they are critical for learning. They are: 1) the focus of the discussion on the concept of *event*; 2) the careful distinction between *time of an event* and *time of signal reception*; 3) the distinction between an observer, situated necessarily in a position of the frame of reference, and the lattice of clocks that allows an "intelligent observer" (Sherr et al., 2001) to measure the positions and the time of events in every point of the frame of reference, independently of observer's position.

In PER, the role of events is known since 1982, when Peter Hewson publishes a paper where he discusses in detail students' difficulties in understanding length contraction and demonstrates that length is usually treated by the learners as a constant, independent of the choice of the frame of reference. According to such a view, the length contraction is conceived simply as a distortion of perception. Behind such a tendency, Hewson claims, the metaphysical commitment of *mechanistic view* of the world can be acknowledged (Hewson, 1982). Like in the Newtonian world, extended objects are assumed to have fixed properties (a fixed length) and phenomena a fixed time duration. Length and duration are conceived the fundamental reality in nature. In the paper it is shown that a student, during an interview, went progressively though a process of conceptual change thanks to the interviewer who encouraged him to revise his metaphysical commitment. The factor trigerring the process was the interviewer's decision to introduce Einsteinian position so as"to present the point of view that *events*[7] were more fundamental and that length, for example, could be interpreted in terms of events, that is, something that is localized in space and time" (Hewson, 1982). This choice led the student to change his focus of attention. While he still believed that there is a reality independent of measurement, he changed his view of how reality manifests itself: it manifests itself by means of events and not by objects' fixed constant properties like length.

The tendency to consider the relativistic effects as perspective distortions has been identified in other studies that revealed students' resistance in giving up the idea of absolute time or absolute simultaneity (Scherr *et al.*, 2001). More specifically researchers from Seattle have observed that students often fail to interpret properly the 'time of an event' and the notion of 'reference frame': "We found that students at all levels tend to treat the time of an event as the time at which a signal from the event is received by an observer. Thus, they consider a reference frame as being location dependent." (Scherr *et al* 2002, p. 1239). This tendency is revealed through problems invented by the group of Seattle, like the "problem of the volcanoes" in all its variants that represents a delicious situation to be used in class. One variant is reported in Figure 4.

In this problem, all events and motions occur along a single line in space. Non-inertial effects on the surface of the Earth may be neglected.

Two volcanoes, Mt. Rainier and Mt. Hood, are 300 km apart in their rest frame. Each erupts suddenly in a burst of light. A seismologist at rest in a laboratory midway between the volcanoes receives the light signals from the volcanoes at the same time. The seismologist's assistant is at rest in a lab at the base of Mt. Rainier.

Define Event 1 to be "Mt. Rainier erupts," and Event 2 to be "Mt. Hood erupts."

A fast spacecraft flies past Mt. Rainier toward Mt. Hood with constant velocity $v = 0.8c$ relative to the ground ($\gamma = 5/3$). At the instant Mt. Rainier erupts, the spacecraft is directly above it and so the spacecraft pilot receives the light from Mt. Rainier instantaneously.

All observers are *intelligent* observers, *i.e.,* they correct for signal travel time to determine the time of events in their reference frame. Each observer has synchronized clocks with all other observers in his or her reference frame.

For each intelligent observer below, does Event 1 occur *before, after,* or *at the same time as* Event 2? Explain.

- Seismologist
- Seismologist's assistant
- Spacecraft pilot

FIGURE 4. Problem of the volcanoes in the explicit version of the spacecraft question (Scherr et al., 2001)

Also university students who learn relativity tend to answer that for the assistant and the spacecraft

[7] Italics are significant in the original text. They were not added.

pilot Event 1 occurs before Event 2, since they are focusing on "the time at which a signal from the event is received by an observer" and not on the "time of the events" and since they are confusing the observer with the frame of reference. Several years of personal experience with secondary school students, university students and pre-service teachers lead me to observe that, if learners are guided to analyze Einstein's argumentation and to re-arrange their imagination, they come very easily to recognize that, in a given frame of reference equipped with a lattice of synchronized clocks, the position of the observers does not play any role in the times of events, even though it influences the time at which a signal is received. Thus the learners arrive to conclude that the two events are simultaneous for both the observers at rest on the Earth, whilst Event 2 occurs before Event 1 in the moving frame of reference.

Also prior to my empirical tests, Scherr and colleagues, on the basis of their problematic results, produced a curriculum for university students that proved to be successful, being tested by means of a research methodology which employed pre-tests and post-tests with a large sample of students. The strategy implemented in their tutorials was, like in my trials, focusing on the concept of *event* and on Einstein's argumentation. In particular, two tutorials were designed by the team of Seattle. The first one aims at guiding students

> to develop the basic procedures that allow an observer to measure *the time of a single distant event*. These procedures form the basis for defining a *reference frame as a system of intelligent observers*. The tutorial then helps students to extend the intuitive notion of whether or not *two local events* are simultaneous by having them develop a definition of simultaneity for events that have a spatial separation. (Scherr *et al*. 2002, p. 1239, italics added).

The second tutorial aims at guiding students "to examine the consequences of the invariance of the speed of light through an analysis of the train paradox" (Scherr *et al*. 2002, p. 1239).

Hence, the tutorials were designed to guide students to the analysis of the Einstein's thought experiments, by a structured and operational concept of frame of reference as a lattice of rules and synchronized clocks or, as Scherr and colleagues say, as "a system of intelligent observers" (Scherr *et al.* 2001; 2002). The construction of such a system of intelligent observers implies emphasizing all the details that we found in Einstein's paper and that have been disregarded in the process of "objectification": i) the notion of time of a single event, measured by the clock situated in the same spatial position of the event; ii) the procedure of measuring the time of a distant single event, according to the constraint that there exists a limit to the speed of signals; and iii) the need to generalize the measurement procedure for the time of an event in order to devise an arrangement of observers and equipment that allows the position and time of an arbitrary event to be recorded.

Another paper, of Levrini and diSessa, contains an analysis of a single classroom episode in which secondary students reveal difficulties with the concept of proper time, but slowly make progress in improving their understanding.[8]

The concept of proper time is usually introduced, in teaching, through the light-clock thought-experiment. However the analysis and discussion of this thought experiment does not usually focus on *those specific* spacetime properties of *those couple of events* whose spacetime interval is called proper time (e.g. by defining proper time as the time interval measured by *two events occurring in the same position*). The light-clock thought experiment is instead used for defining proper time as the *time duration of a phenomenon* (the back and forth travelling of light ray) measured in the frame of reference *at rest with respect to* the light-clock. The works of Hewson mentioned above lead to foresee that students, in every other context where proper time has to be determined, do not search for a couple of events whose spatial coincidence determines the relevant frame but for an object (like the light-clock), or, slightly more complexly, for the "location of the phenomenon" whose duration is to be measured. This implies that teaching may reinforce the persistence of "classical ontological inferences" that take for granted the existence of phenomena as unproblematic things that have a place and a duration. This is what happened in the classroom episode analyzed in the paper of Levrini and diSessa, where it is shown, by applying the coordination class theory, that the students tend to maintain a classical ontology which led them to

[8] The concept of proper time, like the concepts of proper length and mass, is particularly tricky since its understanding is strongly dependent on the level of appropriation of the shift from a Newtonian space-plus-time to the relativistic spacetime. Its property of invariance is indeed an expression of the invariance of spacetime interval between two events. Also the invariance of mass is strictly related to the relativistic spacetime structure, being the module of energy- momentum 4-vector. This point is addressed very effectively by Taylor and Wheeler (1992) and it would be worth understanding why many textbooks and teachers still use the notion of relativistic mass (a mass dependent of velocity), in spite of the sharp criticisms known in literature (e.g. Adler, 1987; Warren, 1976; Whitaker, 1976).

coordinate the property of invariance as an inner, intrinsic, property of a phenomenon. Like in the other papers mentioned above, also this paper shows that what made students' perspectives change was a lesson where the teacher progressively encouraged them to shift their attention from "looking in terms of phenomena" to "looking in terms of events".

IV. WHEN "TEXTBOOK'S OBJECTIFICATION" CANCELS THE INTERPRETATIVE DIMENSION

In the textbook of Halliday, Resnick and Walker, "Fundamentals of Physics", the chapter on relativity begins with this sentence[9]:

> Relativity [is] the field of study that measures events (things that happen): where and when they happen, and by how much any two events are separated in space and in time. In addition, relativity has to do with transforming such measurements (and also measurements of energy and momentum) between frames that move relative to each other (Hence the name relativity) (Halliday, Resnick, Walker, 1997).

This sentence condenses the operationalist interpretation of special relativity that however is rarely explicitly discussed.

Operationalism got an epistemological status in the '20s, following the work of Bridgman. Referring to the early writings of Einstein, Bridgman proposed to characterize science, with respect to non-science, on the basis of the type of definition that can be given to "the physical concept" as a "group of operations required to measure": "we mean by any concept nothing more than a set of operations; the concept id synonymous with the corresponding set of operations" (Bridgman, 1927)

Operationalism became an important perspective for the teaching of relativity mainly because of the work of Resnick and his book "Introduction to Special Relativity", on which, as we have already mentioned several times, generations of students were formed. In the text, the inner meaning of relativity is expressed by this sharp sentence: "*Special Relativity is a theory of measurement and motion affects measurement.*" (Resnick, 1969)

The success of Resnick's proposal is probably due also to the choice of an operationalist approach that, although criticized by many physicists and philosophers as simplistic form of empiricism, has a great persuasive power because of the image of concreteness that seems to give.

The main criticisms addressed by physicists to Resnick's approach concern the limits shown by the algebraic-operational language when moving to general relativity and highlighting the formal four-dimensional structure according to which new relations among the dynamical concepts of mass, energy and momentum must be redefined. Moreover, according to some physicists, believing that the only concepts identified as *physical* were those related to their operational definitions was very limiting. In particular, the emergence of quantum mechanics and the acceptance of concepts such as wave function were put into serious trouble by the criteria used by Bridgman. Einstein himself, in the formulation of general relativity, could no longer move with an operationalist approach, so much so that Bridgman himself "accused" him of treason (Bridgman, 1949).

As anticipated, now in the textbooks for secondary school the operationalist perspective is only hinted. In fact there remain traces in sentences like the one shown at the beginning of this section and the language seems to refer to an epistemologically neutral presentation of the content. Maybe the process of de-personalization was, in this case, motivated by the will to put the content presentation well beyond possible epistemological critics but the result is that any interpretative dimension disappears and the "ideas are made follow single routes" (Minsky, 1986).

In any case, the presence of those few sentences and the choices of emphasizing the algebraic language and the relativistic effects do still echo a world and a physical view that is not immune from criticism by those who do not share the epistemological assumptions or sees the physical limitations of Resnick's approach. And, on the other hand, making the assumptions explicit does not necessarily mean to share them. It can also simply mean to understand them, to assess their implications and, mainly, to open the possibility for a "real" confrontation with other possible interpretations, such as the "geometric" one that, for more than twenty years, is arousing curiosity and interest among teachers and researchers in physics education. I am specifically referring to the teaching proposal of Taylor and Wheeler, whose first

[9] In Italy, there is a version of this textbook for secondary schools. The chapter of relativity is very essential and it starts with the sentence reported here.

edition was published in 1965 and it became the other main reference for teaching special relativity both at university and at secondary school in the western world. In Italy Taylor and Wheeler's approach has been chosen only by an *élite* group of teachers, even though the 1992 version of Taylor and Wheeler's book was conceived to be used by a wide range of students and teachers. The result is that it is still perceived by the teachers as a strongly innovative curriculum (De Ambrosis & Levrini, 2010).

The two curricula are deeply different, since they focus on different concepts (relativistic effects or invariant quantities and relations), use different languages and reflect different interpretations of special relativity. In particular, Taylor and Wheeler's proposal offers an elegant and conceptually transparent non-historical reconstruction of the theory, by relying heavily on a geometrical formulation of special relativity. The geometrical approach allows the properties of invariance of the theory take on a leading role with respect to relativistic effects and the openness to general relativity is considerably facilitated.

The geometric perspective of Taylor and Wheeler grounds its roots in the work of Minkowski and, in particular, in the invention of spacetime diagrams that textbooks usually present as an effective tool to visualize the relativistic effects already found algebraically. An analysis of the original work of Minkowski (Levrini, 2002) allowed instead to find out the epistemological underpinnings of that linguistic choice and to grasp that geometry was chosen to emphasize the absolute and invariant character of spacetime, assumed as "the world":

> The word *relativity-postulate* for the requirement of an invariance with the group G_c [Lorentz's group] seems to me very feeble. Since the postulate comes to mean that only the four-dimensional world in space and time is given by phenomena, but that the projection in space and in time may still be undertaken with a certain degree of freedom, I prefer to call it the *postulate of the absolute world* (or briefly, the world-postulate). (Minkowski, 1909)

A comparative analysis of original works of Einstein and Minkowski, in addition to highlighting the historical roots of the relativity of the main educational traditions, allows the two teaching proposals to be anchored to the historical debate on the concepts of space and time in physics. In particular, the comparative analysis of the original papers shows that the postulates of the theory admit also an absolute "substantialist" spacetime position (the idea for which space and time are real containers) next to the "relationalist" positions of Einstein and Poincare, according to which space and time are nothing but relations between events elaborated by humans for understanding the world (Levrini, 1999). Indeed, already at the very beginning of the conference that Minkowski held in Cologne in 1908, entitled "Raum und Zeit" (published in 1909), he stressed that the most significant result of special relativity was not to have removed from physics the two absolute containers of Newton (the spatial and temporal). The core meaning was that the theory had led to unify them in a unique spacetime container to which he attaches the properties of *reality* (substantivalist assumption) and of independence of any observer (the principle of invariance).

> The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality (Minkowski, 1909).

The comparison of the two approaches, algebraic and geometric, through the analysis of their historical roots, has been discussed both in classes of secondary school students and in context of teacher education. The aim was to switch on, through a contrastive strategy, the interpretative dimension and allow thinking to move across different contexts and perspectives.

In the case of secondary school students, a fine-grained analysis carried out by applying the coordination class model (diSessa & Sherin, 1998) to classroom data provided a theory-based explanation of why *multi-perspectiveness* and, in particular, learning from multiple contexts and definitions, can be a good instructional technique to work around documented difficulties in conceptual change in relativity (Levrini & diSessa, 2008).

In the case of teacher education, our analysis allowed us to argue that teachers' process of appropriation of a less familiar approach, like the Taylor and Wheeler proposal, requires the teachers to acquire criteria to make this proposal explicitly "comparable" with proposals more familiar to the teachers (that of Resnick) (De Ambrosis & Levrini, 2010).

For the teachers, the discussion about the progressive loss of the interpretative dimension of the Resnick approach was very lively and passionate and the analysis of the historical roots of the two main approaches very appreciated. It indeed allowed the teachers to put the proposals on the same ground and to compare them as different choices of content reconstruction, inspired by different global views of the theory and of its teaching, thus overcoming the tendency of evaluating them as “orthodox/heterodox” alternatives. This awareness guided teachers to critically review not only textbook proposals, but also their own teaching ways, by removing the absolute value they often assume (De Ambrosis & Levrini, 2010).

V. FINAL REMARKS

In this paper, I went through the first part of the original paper of Einstein and I read it through the lenses of Physics Education Research. Such lenses allowed some critical details to be recognized and the interpretative dimension restored.

The analysis can be interpreted and used as a proposal for reconstructing some meanings readable in the lines of the most widespread textbooks’ approach; meanings that have been lost over time, but which are necessary to understand the basic concepts of relativity and grasp the peculiarities of a possible interpretation of the formalism of a theory. The analysis can also be interpreted as an attempt to delve into the reasons of Resnick’s approach (1968), approach that, in a sense, did the history of the teaching of relativity and that can now be regarded as the "traditional" approach, against which the peculiarities of other innovative approaches, such as that of Taylor and Wheeler, have to be analyzed.

The reflections I carried out ground their roots in the belief that the teaching of relativity, as for every other area of physics, purchases special cultural value and didactically effectiveness if it enables students to compare multiple interpretations and approaches to the same content. The reason is very simple and regards the fact that, since the meaning of the concepts is complex, a content organization that somehow respects the complexity of meaning, has to foresee rich and well-connected meaning-networks since:

> “too many indiscriminate connections will turn your mind to mush. But well-connected meaning structures let you turn ideas around in your mind, to consider alternatives and envision things from many perspectives until you find one that works. And that's what we mean by thinking!” (Minsky 1986, p. 64)

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