A TEACHING-LEARNING SEQUENCE FOR THE SPECIAL RELATIVITY THEORY AT HIGH SCHOOL LEVEL HISTORICALLY AND EPISTEMOLOGICALLY CONTEXTUALIZED

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ABSTRACT. This paper discusses some topics that stem from recent contributions made by the History, the Philosophy, and the Didactics of Science. We consider these topics relevant to the introduction of the Special Relativity Theory (SRT) in high school within a contextualized approach.
We offer an outline of a teaching-learning sequence dealing with the SRT within this frame of reference. Such a sequence was tried out on a group of high school students in Argentina. The results obtained seem to indicate that the proposal has been effective as regards the motivational aspects and the understanding students gained of some of its concepts.

1. Introduction

The Special Relativity Theory (SRT), together with Quantum Mechanics, marked a new era in Physics as they gave rise to a new form of looking at the extremes of the natural world (the extremely fast; the extremely small) which changes and improves the classic image of the world. At the same time a new way of seeing physics theories developed. As a result of the development of the SRT, invariant and the principle of relativity became requirements for theories instead of properties of them (Sánchez Ron 1985). Even more, the influence of the SRT has exceeded the scope of Physics in such a way that the impact it made on the society of 1920's can only be compared with the one produced by Charles Darwin's *The Origin of Species* (Pearce Williams 1989), which implies that the knowledge of the SRT is necessary in order to understand a great part of the cultural productions of the 20th century.

For these reasons, with the consensus in science education about the need for updating the Physics syllabus, the SRT is a necessary topic, and its inclusion in high school is recommended in almost all national syllabus reforms. Furthermore, in the last years several proposals for its incorporation have been presented. At secondary level education we can mention Hewson (1982), Solbes (1986), Fabri (2001), Aleman Berenguer and Pérez Selles (2000), Levrini (2002), Perez and Solbes (2003); at college level, Angotti et al. (1978), Scherr, Shaffer and Vokos, (2002) and for upper elementary school children, Astin (2005). Also, some researchers have focused on the design of specific simulations for helping in teaching (Salgado 2004, Fraunford 2008). The results of the implementation of some of these different proposals have been quite varied. In a review, Villani and Arruda (1998) classified them as ambiguous since some results obtained would suggest that the "enthusiasm" for learning the SRT could help overcome the difficulty that this entails but, according to some less optimistic results, the students do not interpret the relativist concepts taking the new concepts provided by the SRT as a starting point, but in the framework of their spontaneous beliefs. What is more, according to those results, the students' acceptance of this theory would be just temporary as it is opposed to their deep convictions (Villani 1992).

In fact, the difficulties of introducing the SRT in high school are certainly numerous and not only related to the abstract nature of its concepts. Considering the students' everyday experience, the traditional Mechanics taught in high school, which is considered to be more intuitive than the SRT, is also abstract and the large amount of research on this topic shows the difficulties students have with it. Perhaps the most serious ones are the teachers' own professional training in the SRT, which is basic and quite formal, and the debatable way in which textbooks, which are the teachers' main resource, introduce the theory by giving distorted conceptual, historical and epistemological views. That is the case in several countries such as Brazil, Spain and Argentina, where similar researches have been conducted (Pérez and Solbes, 2003; Arriassecq and Greca, 2007). Having in mind the scientific and cultural importance of the SRT and the students' interest in the contents related to it, which, as Ausubel (1991) points out, is one of the main conditions for meaningful learning, we consider it necessary to produce specific teaching materials, for teachers and learners, with substantial discussions for this level of teaching, on conceptual, historical and epistemological aspects of this theory. In this paper we present one example of this material, a teaching learning sequence, within a contextualized approach (Matthews 1994; Duschl 1997; McComas et al. 1998), designed for introducing the SRT at high school and the results obtained from its application in a group of students in Argentina. In this country, the SRT is included in the official science syllabus, but teachers usually do not deal with it because of lack of time. However, the results of our previous studies seem to show there may be other reasons for this as discussed above.

It is worth stressing that we consider that one of the main objectives of the research into the teaching of Science –and Physics in particular– is to improve classroom practice. Thus, the research and development activities should be closely linked to each other. Moreover, when developing improvement strategies, we should give same attention to both the topic of interest associated with Physics as an academic discipline on the one hand and the students' learning needs and capacities on the other. In this sense, this paper picks up the idea of educational reconstruction (Duit 2006), according to which the person who produces teaching materials, the teacher or curriculum developer. should reconstruct the structure of the scientific content from a teaching perspective. This does not mean a reductionist view that assumes that the structure of the teaching content should be simpler than the scientific one to make it comprehensible to the students. On the contrary, this structure should be somehow much more complex than that of the scientific content in order to facilitate students' conceptualizations.

2. Some guidelines to deal with the SRT at secondary school adopting a contextualized approach

Several authors draw attention to the benefits of introducing Physics topics at secondary level from a modern historical and epistemological point of view, which is called a contextualized approach. Matthews (1994) points out that, among other factors, introducing topics related to the history and philosophy of science (HPS) in the teaching of science can humanize science and facilitate the linking of science with personal, ethical, cultural as well as political problems. In a similar way, Hodson (1986) and Kragh (1989) argue that this approach would allow students to understand the difficulties, obstacles that needed to be overcome and the cultural, philosophical and technological contexts which are different from the one in which the scientific theories were produced. It would also help them to interpret science as a human activity carried out by people who make partial contributions by answering questions asked in certain periods. They would then appreciate the fact that seldom is there "only one discoverer". They would understand that scientists, in every historic moment, did not think in our "actual terms" since they used the logical, methodological and epistemological tools and the traditions predominant in their environment and their time. Furthermore, this would encourage the development of reasoning skills and critical thinking, and also contribute to a better understanding of scientific concepts (Matthews 1994; Duschl 1997; McComas et al. 1998), aspects which are all necessary in order to fulfill the aims set up for teaching science at secondary school.

Nevertheless, it has to be made clear that when using the HPS as a teaching tool to provide scaffolding for a complex topic, oversimplification should be avoided. In the case of history it is necessary to overcome the distorted view that high school textbooks sometimes give, the so called "pseudohistory", the main feature of which is to reinforce commonsense stereotypes about science and the work of scientists (Allchin, 2004). In the case of the philosophy of science, there are some well known differences between contemporary epistemological theories concerning the construction and the structure of science (Jiménez Aleixandre 1995; Duschl 1997). However, there exist some consensual ideas about the nature of science which could be introduced at school (McComas et al. 1998; Adúriz-Bravo, Izquierdo-Aymerych, and Estany, 2002; Adúriz-Bravo and Izquierdo-Aymerych, 2009).These include the tentative character of scientific knowledge, the methodological pluralism and the wide variety of points of view from which observations are made. We can also mention the close relationship between science, society and technology as well as science as a historical and social undertaking in continuous evolution.

Even though the whole Physics syllabus could be approached from this viewpoint, the SRT is too special a topic to be dealt with in this way. As Holton points out (1982), certain breakthroughs in the field of science have had important consequences in other fields to such an extent as to bring about substantial changes in the culture of that particular period. In the same way as Newtonian Mechanics and Optics have influenced artists, thinkers, philosophers, and politicians, some of Einstein's scientific works have had a significant influence on other fields like philosophy, visual arts, or literature. Pérez (2003) has adopted a similar approach for his proposal.

Taking this point of view into account, we shall describe briefly some aspects we consider necessary for introducing the SRT in secondary school, that have been broached in our teaching-learning sequence through historical narratives, short biographies, scientific and authentic news articles and research and discussion activities. A more detailed discussion of this can be found in Arriassecq (2008). It is worth stressing that the available literature on the topics here addressed is quite large, as Relativity is one of the most studied theories from the point of view of the so-called specific history and philosophy of physics (just to mention a few of the most emblematic books: Eddington 1920, 1945; Capek 1961; Jammer, 1970; Newton-Smith 1980; Holton 1982a, b; Pais 1984; Whittaker 1989; Pearce Williams 1989).

2. 1 HISTORICAL CONTEXTUALIZATION OF THE SRT

A proper historical contextualization of the beginnings of the SRT should involve an overview of what Physics was like at the time, and those contributions by researchers that paved the way for this theory. The conditions of Physics until 1905 could be discussed for this purpose.

The description of the Newtonian Mechanics program represents an interesting aspect in connection with this. The Newtonian idea of the universe was that of corpuscles moving freely in a vast and uniform vacuum, affected by forces (distance or contact forces) obeying the laws of Mechanics. Since the birth of this idea, for almost two hundred years, its proponents had been convinced they had the right theoretical framework within which they could explain "every" phenomenon in nature, including the optical, caloric, magnetic, electrical, chemical, and even biological ones. To put it briefly, "At the same time, Mechanics gained precise meaning. It became the theory that asserted that any observable phenomenon could be explained through Newtonian Mechanics applied to the corpuscles that made up the universe and which were the only real elements found in space and time" (Boido 1996, p. 357).

However, during the last third of the nineteenth century, the Newtonian program turned out to be incompatible with the Physics of the time, especially with the Physics related to electromagnetic phenomena. As a result, several scientists contributed to a new view of nature. For example, whereas the Newtonian Mechanics program proposed the corpuscles as the only real elements, Faraday suggested that the only real physical entity was force. According to him, the world was a field of forces where some of them exerted pressure on the contiguous ones, the particles being the points where forces converged. Since in the explanation offered by Faraday there is no action-at-a-distance, every change in one of the points in space would bring about a change in the contiguous ones. Another important contribution was made by Maxwell, who developed a theory based on the results of experiments on electrical and magnetic phenomena which had been carried out during decades. This was a unified electrical and magnetic theory, condensed in four equations that made it possible to demonstrate that the interaction between electrical and magnetic phenomena can create permanent electrical and magnetic movement in the form of waves that propagate at the speed of light. In accordance with the mechanics principle that established that waves required a material medium to be propagated, Maxwellian waves also needed a corporeal medium so that their vibrations could support the electromagnetic forces of the theory. It is important to note that Maxwell had restated the notion of ether in the Newtonian theoretical building, for the sake of the Mechanics in his theory. This hypothetical medium was eventually called “electromagnetic ether”, and its detection became a major topic of research.

There is another key characteristic of the electromagnetic theory proposed by Maxwell that is related to what we mentioned above and contributed to the development of the SRT. This is the fact that its equations enable us to deduce that, from the point of view of an observer placed in that hypothetical ether, the waves are always propagated at the same speed, irrespective of the speed of the source of those waves in relation to the observer. This concept contradicts the Galilean transformations accepted by the Newtonian Mechanics Program. How did scientists react to this obstacle? One of the choices they had was to dismiss Maxwell equations. However, such equations had already “passed” all the experimental tests. Another possibility was to consider Galilean transformations to be wrong. This was not easy since it would have involved revising the whole Newtonian Mechanics because Newtonian laws are invariant in relation to Galilean transformations.

As a result, a middle ground was established. Only when applied to the ether at rest or to all the reference frames that were at rest with respect to the ether, were Maxwell equations to be considered valid. In the case of reference frames that moved at constant speed in relation to the ether, Maxwell equations had to be modified and the speed of light would be calculated through the Galilean transformation. This confirmed that such ether could be discovered. This assumption was the starting point for the well-known experiments conducted by Michelson and Morley. After repeated experimental failures, some studies were carried out in order to modify the Mechanics program without altering the fundamentals of such. It was precisely Lorentz who was in charge of these attempts to modify the theory by proposing new equations about light transformation known as the Lorentz’s transformations. These were not compatible with Galilean ones and provided an explanation for the results of the experiment conducted by Michelson and Morley.

A more “epistemological” influence can be detected in the origins of the SRT. This influence was due to Mach’s criticism of Newtonian Mechanics. As Holton (1982) points out, this influence is demonstrated in two crucial points of an article by Einstein published in 1905. In the first place, Einstein insists, right from the beginning of his article, on the great importance of a profound epistemological analysis in order to solve Physics problems, especially those regarding the meaning of the notions of time and space. The second point that denotes Mach’s influence is the fact that Einstein identifies reality with what can be perceived through the senses.

Such was the context in which the SRT was conceived. When the old view of the cosmos was being questioned due to a number of empirical, theoretical and epistemological problems, the SRT offered possible solutions to them although they would mean a change in the concept of the universe.

Apart from this historical contextualization regarding scientific matters, it is important to highlight the general historical context, which will provide for an understanding of the influence the SRT exerted outside the field of science. The SRT as well as quantum Mechanics, which is another great theory that caused a revolution in science, were conceived at the beginning of the twentieth century. That was a period of big political, artistic and scientific changes which had in common the aim of finding new ways to approach reality, moving away from the old conceptions.

2. 2 EPISTEMOLOGICAL REFLECTION ON THE ORIGINS OF THE SRT

As it has been stressed at the beginning of this section, from an epistemological point of view, there are several aspects present in current debates which are worth discussing. Such aspects include the reflections on the origin of a theory, its empirical consequences, its applications, the role of the scientific community in the development of a theory, as well as the influences of scientific production on society (Arriassecq and Greca, 2007).

2.2.1 The role of experimentation in the genesis of the SRT

There is evidence that confirms that the role Michelson's experiment played in the genesis of the SRT has been minor and indirect. This evidence derives from a detailed analysis of many studies in the field of the history of science, both general and scientific, that include letters, interviews, statements, and autobiographical accounts. However, this opinion was not popular among scientists. In fact, until recently, the scientific community regarded the SRT as a huge theoretical success and the long-expected correct answer to Michelson's experiment as well as the natural continuation of such (Villani 1981). This conception, influenced by the scientists' empiricist view, is reflected in textbooks and reference books. This view is shared by even brilliant books such as Berkley's *Physics* and Feynman's *Lectures on Physics*, as well as others of recent publication.

In spite of this, a detailed revision of the genesis of the SRT suggests that, even though Michelson's experiment had not been carried out, this fact would possibly not have influenced the development of the SRT. Even before 1905, through Lorentz's work, Einstein had learned of several vain attempts at determining the movement of the earth in relation to the ether. However, according to some authors, it was not a concern for contradictory experimental results but an aesthetical dissatisfaction what led him to write his article. There was a need to have a new viewpoint to solve the theoretical contradiction that arose when Maxwellian electrodynamics gave an explanation for the effects of motion between a magnet and a conductor, depending on which of the two is at rest or in motion. That need was the starting point for the development of the SRT. In fact, the first paragraph of Einstein's article in 1905 is devoted to accounting for the asymmetry between observable phenomena (that depend only on the relative motion of the magnet and the conductor) and the decided difference generally appreciated in both cases (whether the magnet or the conductor is either at rest or in motion)[1].

Suggesting that Einstein used Michelson's experiments as a starting point for developing the SRT, helps to create in students a distorted view of scientific activity, favouring in this way a completely empiricist conception of science. In view of all the evidence that disproves this, from an epistemological point of view (Mathews 1994), it would be unwise to support such idea.

2.2.2 The originality of the SRT

Einstein's work[2] generated important controversy. In fact, there are as many arguments in favor of the originality of his theory, as arguments that claim that it is the logical corollary of other scientists' work. In our opinion, this fact provides another possibility to deal in class with epistemological aspects whose discussion can favorably influence the idea of science that students form throughout the learning process.

The knowledge of theories that dealt with the same issues as the SRT can help to understand the revolutionary aspect of this theory, no matter how much influenced by other scientists Einstein was. Moreover, it should be noted that historians have not reached complete agreement on which works were really known by Einstein before the publication of his theory. The purpose of discussing this topic is to illustrate that, following a historical and epistemological contextualized view of the teaching of science, it would not be right to introduce the SRT as the invention of a scientific genius. On the contrary, we should point to the existence of other scientists working at the same time on the same problems. In other words, we should stress that no scientific theory is developed in a conceptual vacuum.

It also would be interesting to analyze with the students the kind of explanation the SRT provided the scientific community with. Battimelli (in Villani 1981) believes that the distinguishing feature of Einstein's theory lies in the fact of offering a new strictly theoretical model based on some fundamental principles in order to account for things that require a scientific explanation. This paradigmatic explanation radically changes the usual way in which models were established within the Mechanics program by reconstructing the properties from the interaction between the main components. Since the development of the SRT, a new paradigm of explanation has been adopted in Physics. According to it, the properties of phenomena observed in an empirical way and considered to be universally valid principles are the starting point of the theory[3]. This discussion allows us to point out to the students the continuous evolution of scientific theories, as regards not only its concepts but also the kind of explanations the scientific community accepts as valid.

2.2.3 Reference to the experimental verification of the SRT

The fact that a successful or failed verification could be definitive or not is questioned from an epistemological viewpoint –some of the best-known epistemologists, like Popper, Kuhn, Lakatos and Feyerabend, do not agree on this matter. Nevertheless, there is no doubt about the decisive role of empirical verifications in Physics. In the case of the SRT, great effort has been made to prove its validity. Given the particularly counterintuitive aspects this theory reveals to those who approach it for the first time (see, for example, Rossie and Hall 1941), attention should be drawn in class to the different phenomena that have been used to support the SRT (in our proposal, the atomic clock, the mean lifetime of muons in movement, and the superluminal jets are discussed),

However, it is necessary to stress that these experimental verifications were carried out in a later context than the one in which the SRT originated, because the necessary technology was not available in 1905. At the time of the SRT, such theory was not empirically superior to Lorentz'. In fact, that was the reason why Einstein was not awarded the Nobel Prize for this theory but for the photoelectrical effect and Feyerabend argued that the Lorentz's program was abandoned due to the development of Quantum Mechanics and not to the SRT.

This point is especially useful for challenging the naïve empiricist concepts students have about science.

2.2.4 Reference to applications of the SRT

Without taking sides in the epistemological discussion about "the context of application" of a theory, it is important that students reflect upon the fact that the SRT not only deals with theoretical issues but mostly provides for the interpretation of different phenomena –we have given examples from subatomic particles, sources of nuclear energy, to the Global Positioning System (GPS). For this reason, the SRT is not regarded as a metaphysical thesis but as a physical theory that deals with empirical matters.

2. 3 IMPACT OF THE SRT ON OTHER FIELDS

There are but a few theories that, like the SRT, have transcended the scientific field and have had a sometimes strong influence on other areas, some of which students can hardly imagine. These include philosophy, where it led to broad discussions, and the arts. As it was previously pointed out, the fact of drawing attention to these aspects contextualizes scientific knowledge and proves that this activity is not restricted to the scientific field but influences, and it is influenced by, other areas. However, students can realize this only if the teacher encourages discussion of these issues.

2.3.1 Impact on the scientific circles

Scientists' reactions to the SRT varied considerably from one country to another. Students should be encouraged to notice that this aspect shows that science is affected by the social and cultural characteristics of a country, and that these can influence, either in a positive or negative way, the promotion and support lent to an emerging theory.

We can appreciate this by analyzing the reactions in the countries with the most scientific production like Germany, France, England, and the U.S.A. The German scientific community carried out a systematic analysis of the SRT between the years 1905 and 1941. Von Laue wrote the first book on the SRT in 1911, despite the divergent opinions and a sometimes wrong interpretation of the theory, with Max Planck, at the time editor of *Annalen der Physik*, playing a crucial role, supporting and promoting the SRT, in England the SRT was regarded as an attack on the concept of ether which was of central importance for the British Physics of the time. This fact, as well as the mounting interest for Rutherford's newly created atomic theory, made the SRT go unnoticed for years. Also in France and the U.S.A., for different reasons, there was no considerable impact. In France, for instance, Poincaré never mentioned the SRT. It is argued that he considered it to be only a minimal part of his theory. On the other hand, in the U.S.A. the SRT was regarded as absurd and rather impractical.

2.3.2 Impact on philosophy

Many philosophical issues deal with concepts of central importance that have been modified by the SRT. These concepts pose questions such as, what kind of object do we refer to when we talk about space and time? , are they, or is the combination of them, a substantial unit? or, do they address groups of relationships among things different from themselves? Or, as Kant believed, could they possibly be shapes the mind imposes on a non-spatial and non-temporal world? Accordingly, it is interesting to consider the different possible answers science can give to these philosophical questions and see how they changed as a result of the development of the SRT. Although discussions of time and space began twenty five centuries ago, nowadays such discussions will inevitably take Einstein's work into account (Boido et al. 1998). For this reason, students should be shown this close relationship between philosophy and science which dates from the very origins of science.

2.3.3 Impact on the arts

It is worth analyzing the influences of science on the arts, especially the influence of Physics on the conception of modern art, as reflected in the avant-garde art that has developed since 1910.

At the same time as SRT developed, some artistic movements emerged supporting unconventional conceptions of space and time, sometimes finding inspiration in non-occidental cultures like those in Africa and Oceania. Those cultures do not have a Euclidean conception of space (a plane with straight lines) nor the idea that time passes at the same speed for everyone regardless of who measures it. For example in painting, cubists distorted shapes, breaking in this way with the Renaissance tradition of drawing in perspective. Another artistic movement that developed in Zurich at the same time as Einstein was teaching in that city was Dadaism. This movement broke with the occidental values ascribed to reality. Essentially, they opposed to the rationality that is alleged to have led Europe into the First World War.

As a result of this, many art critics and historians tried to link the influences of the SRT and general relativity with some characteristics of the many avant-garde movements between the year 1910 and the Second World War. On some occasions the art critics were the ones who established the influences, as in the case of cubism, and on others the artists themselves publicly stated that fact, as in the case of Dali. This fact does not necessarily mean that there was a direct influence, or that a linear connection could be established between the relative aspects of art and Physics. Nevertheless, this points out the importance of reflecting with the students on the fact that the development of the SRT, as well as the other theories in different periods of time, takes place within a particular scientific, social, cultural, and political context. Despite the difficulty in identifying how the interaction between these contexts takes place, it is evident it does happen [4].

2.4 CONCEPTUAL ASPECTS OF THE SRT

A contextualized approach requires a careful conceptual treatment for the historical and epistemological discussions to make sense. This section presents the concepts that demand special attention when introducing the main ideas of the SRT. It is worth noting the mathematics involved in the kinematic part of the SRT seems to be relatively simple for the students (Arriassecq and Greca, 2006). Problems arise in the comprehension process of the main concepts and the changes these introduce in the classical way of thinking. Limited research work has been done on the students' and teachers' understanding of concepts specifically connected with the SRT, most of which deals with concepts related to the notion of *relativity* within the Galilean context of *relative movement*. Also, there exist many studies aimed at particular aspects of the SRT, such as proper time, simultaneity and reference frames even though these are mainly found within the sphere of university education, and to a lesser extent at secondary level (Saltiel and Malgrange 1980; Hewson 1982; Posner et al. 1982; Villani and Pacca 1987; Panse et al. 1994; Ramadas et al. 1996; Aleman Berenguer 1997; Pietrocola and Zylbersztajn 1999; Aleman Berenger and Pérez Selles 2000; Scherr, Shaffer and Vokos 2001; Martins and Pacca, 2005; Levrini and diSessa 2008).

As a result of the difficulties the students face when they have to understand the fundamental concepts of the SRT, they either interpret them within a classical conceptual framework, which leads to a misinterpretation of the phenomena, or they learn definitions and formulae by heart. Unfortunately, both in textbooks and in class, the content of the SRT is usually presented in a strictly mathematical way that, although easier, makes students unable to grasp the concepts involved and appreciate how they radically differ from their classical equivalents. On the other hand, this conceptual understanding is vital for a contextualized view of Physics. The reach and consequences of a scientific theory can be seen only by understanding what the ideas expressed in the theory mean and to what extent they are novel and different from other ways of understanding physical phenomena.

For the selection of the most relevant concepts to be discussed with the students, we have adopted Bachelard's view. In his fundamental postulates, Bachelard (1991) argues that new knowledge can be acquired only by drawing on previous learning, which is always false and acts as an epistemological obstacle for scientific progress. These obstacles originate in subjective knowledge and have to do with intuitive aspects, first experiences and general knowledge, and even interests and opinions of an affective nature. With regard to the SRT, the concepts of *space* and *time* are, according to us, essential in order to understand such theory and its consequences. However, the student has already developed over the years his own definitions of such concepts. These constitute pedagogical obstacles for learning the SRT, since they originate in "basic experience" and have never been analyzed from a scientific point of view. When we say in our Physics classes "it is divided by *t*", "*t* is measured", "a particle is analyzed in a particular point in space", "the distance covered by a moving object is measured", etc., we rarely mention who takes the measurements and how he does it. The same applies to time. Therefore, concepts of space and time become pedagogical obstacles to be overcome by students in order to understand the theory. At the same time, we consider that from an epistemological point of view, it is not possible for students to build the concepts of space and time in the SRT unless they previously have the notions of "reference frame", "observer" and "simultaneity" within the frame of classical Mechanics.

A summary of the results of a survey (Arriassecq and Greca, 2006) which clearly shows students' conceptions of the terms mentioned above is presented in *Table I*. In the third column we indicate which obstacles should be overcome by students in order to acquire new knowledge within the framework of the SRT. Owing to these obstacles it seems necessary to help students to get insight into the notions of reference frame and relative motion within the framework of classical Mechanics. It is also important to discuss the concepts of space and time and the notions associated with them such as simultaneity and observer as well as to introduce the concept of space-time (which we propose it be done with a qualitative use of Minkowski's diagrams). In the teaching-learning sequence developed we encourage the discussion of some of the paradox associated with the SRT (the best-known "twins' paradox" and the "length contraction paradox") and explain the reason why in fact they are not such (Arriassecq 2008).

3. Design of a Teaching Learning Sequence

In order to design a specific teaching learning sequence we adopted a theoretical framework that takes into account three components which are seen as complementary. These are the epistemological, the psychological, and the pedagogical one. In the epistemological component, as it has been stated in the previous section, Bachelard's approach is adopted. According to Bachelard, a deep epistemological analysis of the intrinsic problems of a given theory is the starting point for conducting research into such. Following Bachelard (1991), the epistemological analysis of the content of the SRT was taken as starting point (Arriassecq & Greca 2002). This analysis helped us to define the central concepts we intended students to interpret and build within the frame of this theory. Such concepts are the concepts of space, time, and the notions associated with reference frame, observer, simultaneity, and measurement, which are essential to the relativist understanding of space-time.

The psychological component was defined by basing it upon a synthesis of various perspectives on the development of concepts which help to interpret how students are able to conceptualize some particular content in class. Some aspects of the theories constructed by Vergnaud (1990), Ausubel et al. (1991) and Vigotsky (1987) were especially taken into account for this purpose. The conceptions detailed in *Table I* are the result of a specific study (Arriassecq and Greca 2006) of the operational invariants, which derived from Vergnaud´s approach and that students have developed in Mechanics. These are related to the concepts that, as it has been stated above, we suppose are vital for the understanding of the SRT. Such study was conducted before the design of the teaching sequence and, as we shall explain next, played an essential role. By adopting Vygostky's and Ausubel's approaches, we considered elements related to the role the teacher should have and how the teaching material should be organized in order to promote students' meaningful understanding of relativistic concepts (Arriassecq 2008).

Although some important teaching consequences stem from the theoretical references previously mentioned, we judged it necessary to adopt a more specific teaching approach. We have therefore followed Martinand (1986) who proposes for the design of a teaching sequence, the notion of "objectives obstacles". This means that the intellectual progress to be achieved within a teaching context should correspond to the overcoming of epistemological, psychological, and methodological obstacles. In this way, the teaching objectives, especially in science education, should not be defined *a priori* and regardless of the students' mental representations, which is what usually happens. On the contrary, they should correspond with the intellectual transformations students undergo when a certain obstacle is overcome. In a similar way to Bachelard, Martinand stresses the need for not regarding the obstacles as a negative aspect of learning, which could lead to a block preventing students from achieving the desired objective, but as a dynamic and motivating aspect. It is necessary to evaluate from this perspective all the actual and possible obstacles, and decide upon the ones that could be overcome at the given level, within the given content and context in which they are expected to be confronted. In this way, basing it on the difficulties students present in the conceptualization of time, space, observer, simultaneity, measurement, and reference frame, we made a list of *obstacles.* These should be overcome by the student with the teacher acting as mediator within the classroom context, in order to achieve meaningful learning of the SRT. These obstacles appear in the third column of *Table I. Objectives* related to these obstacles are shown in the fourth column.

Taking into account these results and the theoretical framework adopted, a *teaching proposal* has been developed, for the Argentinean context, in order to deal with the SRT. Such a proposal comprises five stages. In the first stage, questions of a historical and epistemological nature are discussed. These refer to the notion of science, the characteristics of scientific work, the evolution of ideas in science, and the influences of the social, historical, and cultural context on the birth and validation of scientific theories. In the second stage, the concepts of classical Mechanics which are necessary in order to interpret the SRT or which are even substantially modified by the theory are thoroughly revised. Then, we deal with the concepts of electromagnetism that come into conflict with Classical Mechanics and which are later reintroduced by Einstein in the SRT. Afterwards, we discuss the fundamental aspects of the SRT introduced by Einstein's original article of 1905. Although students read only the principal suppositions and consequences of the SRT, by analyzing such an article from different perspectives, they are able to build new schemes in order to deal with situations that demand the reformulation of classical concepts. This text is intended to work as an organizer (Ausubel 2002), since it has a global hierarchical structure showing the relationships and connections among the SRT central concepts. Finally, in the fifth stage of the proposal, it is intended that students get acquainted with some aspects of Albert Einstein's life as an ordinary man, which go beyond the "myth". As regards Einstein's life there is a lot of written material. A very careful selection of articles was made and those selected have been recognized by the community of the history of science as scientifically rigorous (Pais 1984; Holton 1982a). The different stages of this proposal and the estimated time each will take are detailed in *Appendix A*. This proposal was presented in the form of a written unit using a kind of language in accordance with the students' age but which does not lack scientific rigour. The aim was to provide teachers with a specific text for the introduction of the SRT from a contextualized viewpoint. A summary of the topics that have been dealt with and produced as written support material for this proposal is given also in *Appendix A.* The expanded Spanish version is available on the Internet [6].

The key concepts of the SRT are reintroduced at different stages when the proposal is put into practice, using a range of representations, such as the algebra and graphics in Minkowski's diagrams. This kind of representation allows qualitative estimates that include the possibility of comparing the measurements made by different observers, of deciding upon the simultaneity of events, and so on.

Each stage involves various activities in which the obstacles (Bachelard 1991; Martinand 1986) are present. These are essential for our theoretical framework since most of the discussion takes the situations-problems (Vergnaud 1990) as a starting point. Such activities require the use of different kinds of tools (written and oral expressions, concept maps, graphic representations, calculations, etc.). How these activities are going to be developed (individually, in groups, as debates with the teachers or among different groups, etc.) depends on the intellectual progress achieved by the students. This is an indicator of whether they have already overcome the obstacles. As it can be seen, the evaluation is supposed to be a continuous process that starts with the diagnosis of the students' representations and the formulation of the objectives. Each class the teacher introduces one of these objectives and measures the progress already achieved. His or her role is therefore that of a provider of information and mediator in the process of learning. This is a decisive role in the implementation of the teaching proposal.

In summary, taking into account the previous knowledge of the SRT that Argentinian secondary students have, we expect them to,

– recognize the need to link the concept of observer with that of reference system.

– start associating the concept of observer with the process of measuring (of great importance to the SRT) and the instruments used. The aim is that students could see that "to observe" means more than "to look carefully".

– employ the Galilean equations of transformation to solve problems which require information from different reference systems. They should also give an adequate answer to questions raised within the context of classical mechanics, even when they could prove really complex. .

– to apply Lorentz equations of transformation to solve simple problems within the SRT which require information from different reference systems regarding space and time.
– to become aware of the fact that the concepts of space and time within the SRT can no longer be used with the meaning they had within classical mechanics.
– to recognize the limits to the possibility of classical mechanics and electromagnetism to solve physics problems.
- identify some of the main consequences of the SRT, such as the relativity of the concepts of simultaneity, space and time, and also to redefine the concept of mass.
- use Minkowski's diagrams to represent and interpret the concept of space-time.
– become familiar with experimental verifications of the SRT as well as with its technological applications.
– understand the role that Michelson's experiment played in the origin of the SRT.
– gain deep insight into Albert Einstein's character/life supported by historical and epistemological evidence. Such insight should transcend the classic narrow stereotype that lacks many characteristics of a "human" kind and is the only one present in classrooms and means of communication.

4. Implementation of the teaching proposal

4.1 CONTEXT OF APPLICATION

In this section we describe the results of the implementation of the teaching proposal that has been designed to teach the SRT and has been carried out with students in the last year of secondary school in Argentina.

A qualitative methodological approach has been adopted for this analysis. Such analysis demands a detailed description of the contextual aspects involved. In this particular case, these aspects, which are briefly described below, relate to the institution where the investigation was conducted, the authorities, the teacher, the group of students, and the kinds of relationships that existed among them, as well as the kind of work which both teacher and students were used to. They also refer to the work strategies they applied, the estimated time the proposal would take, and the adjustments that it was necessary to make considering the particular circumstances that could not be anticipated.

The students that took part in the investigation were in their third year at a traditional secondary school of the town of Tandil in Buenos Aires province. The class had a scientific orientation. The group was composed of twenty seven girl students who had two weekly hours of Physics. The topics of Physics they had dealt with in the two previous years involved Newtonian dynamics and kinematics; in third year, they had dealt with topics concerning optics (especially geometry) before approaching the SRT. The school authorities gave us enthusiastic support over the course of the investigation. We consider it important to highlight that in order to conduct the investigation within the selected class, an agreement was made both with the teacher and with the students in which the role of the researcher (the first author of this paper) in the classroom was established; she would be an observer and not a participant. This kind of relationship was considered necessary for the students to work comfortably, in a relaxed way as they were used to. Fortunately, the intended work atmosphere was generated and the students were not inhibited when working, even when the researcher approached them with the tape recorder in order to record some discussions.

As regards the qualifications of the teacher in charge of the subject, she holds a bachelor's degree in Physics and Mathematics and has ten years' teaching experience. When this proposal was implemented, she had not done any postgraduate courses, neither on this specific content nor on pedagogy; the courses she had attended were the training courses offered by the Ministry of Education or the local university. With regard to her knowledge of the SRT, this teacher, just like other teachers in this town, had only been formally instructed in this topic when doing Modern Physics, which is only one subject of the course of studies at the teaching training college. On several occasions, the teacher said that due to her lack knowledge of the topic she felt insecure, even though she was ready to face the challenge of approaching it. Every time she asked for support, this was given to her through meetings in order to discuss particular aspects of the written material or the proposed activities.

It is necessary to point out that although we explained the way to use Minkowski's diagrams to approach the concept of space-time, we were not able to implement it during that period of classes. One of the many reasons for this was the teacher's decision. Anyway, a version is available on the Internet.[6].

4. 2 A GENERAL OVERVIEW OF THE RESULTS OF THE IMPLEMENTATION

In order to evaluate the application of the teaching proposal, we did a supplementary analysis of data gathered from different sources – initial test, post-test, activities done by the students (solutions given to the proposed activities, written tests, concept maps, stories, and comic strips), field notes, and audio-recorded classes. As many of the activities were done in groups (6 groups in total), the evaluation was carried out on each group as a whole. Because of limited space, only some general results are described. A detailed discussion of this analysis can be found in Arriassecq's doctoral thesis, in press.

The results of the analysis of the activities selected to evaluate the teaching proposal, seem to indicate that, even though the circumstances were not the most favorable ones[5], many of the proposed objectives would have been achieved. This can be appreciated in the fact that students overcame some of the epistemological obstacles that had been detected in the description of the initial profile of the group that took part in the investigation. The results obtained show that the students were able to modify some concepts they used when dealing with Classical Mechanics matters which were not correct from a scientific point of view. If these modifications had not been made, the topics of the SRT would not have been incorporated in a meaningful way.

The results obtained in the last test given to all the twenty seven students are supplementary to the ones obtained by evaluating the different activities. However, they reflect the results from the overall analysis of the students' output. We tried to confront the students with problems which allowed them to use their perceptions and make their operational invariants explicit in order to find a solution. These were the most significant results:

Regarding the concept of reference system, more than half of the students admitted the need of a reference system to solve a problem involving the notion of movement. When asked to deal with a matter in relation to a certain reference system twenty students gave the right answer.

The total number of students answered that the measurements taken by two observers in relative motion within inertial systems and at relative speed are different. However, again half of the answers justifying which measure would be smaller were incorrect. This seems to indicate that the students recognized one of the consequences of the SRT, length contraction, but could not tell within which reference it takes place.

As for the notion of simultaneity within the SRT, twenty four students chose the correct option available: the simultaneity of two events can be established even when such events do not occur in the same place.

It seemed the students were clear about the "reality" of length contraction and time dilation since all of them answered correctly the question concerning this point and twenty three students gave the right answer in another section dealing with these concepts.

All the students stated that the SRT is not pure theoretical speculation but a theory with enough experimental verification and acceptance by the scientific community.

Also all the students stated that the SRT has technological applications and admitted being familiar with those with more implications to daily life such as the GPS.

Nearly all of them (twenty six) explained that the SRT did not originate in answer to the failed attempts by Michelson and Morley.

As regards the "creation" of the SRT, more than half of the students answered that it was not developed by Einstein exclusively. That is, even though he proposed it, he did not do so in a conceptual vacuum but with contributions by other scientists.

Most (twenty six students) agreed on the need to redefine the concept of observer within the context of the SRT. There was also agreement on the fact that simultaneity is a concept relative to a reference system in the SRT and that two simultaneous events do not necessarily occur in the same place.

They also seemed to have modified their conception of space as it was no longer considered to be a receptacle (twenty six students).

The analysis of activities related to Classical Mechanics concepts (initial test, problem solving, concept maps, devising stories and comic strips, and the final test) would suggest that the obstacle of conceiving the concept of time in Physics as we do in daily life, or reducing this concept to only its units of measure –the answer given in most cases in the pre-test related to this concept– has been overcome. At the same time, the debate on the history of the concept of time led the students to add complexity to the concept, becoming aware of the difficulties that a pragmatic view of such would entail. The students' answers to different activities and their comments in class –as, for example, the following excerpt from the last class on the SRT– seem therefore to indicate that the objective of analyzing time from different perspectives (philosophical, scientific, etc.) has been achieved.

> *"We realized that not only does time have a more specific meaning in physics but also differs according to whether it is used in Newtonian Physics, to which we were used to, or in the SRT. The thing is we can't "perceive" the differences with our senses… for instance the dilations" (Student 3).*

As we stated in our teaching-learning sequence, we intended to discuss in class the essential relativistic concept of space-time with the use of Minkowski's diagram. However, as we previously explained, the teacher decided not to do this. For this reason, there are no results concerning this concept.

The concept of simultaneity, approached in class through some activities, was not selected by the students in the concept maps. Nevertheless, there seemed to be a favorable development of other concepts connected with this one, such as reference frame, observer and measurement, which are fundamental to the SRT (five out of the six groups). In the answers to the initial questionnaire –with results similar to the ones obtained in other groups of students where the test was applied (Arriassecq and Greca 2006) –, the first of these concepts was not taken into account in order to approach different proposed situations and the second one was reduced to the idea of a person who "watches" or, to put it redundantly, "observes" (only four out of the twenty seven students considered the concept of reference system to solve the problem and twenty of them had a narrow conception of observer). After the implementation of the proposal, these conceptions were modified coming closer to a scientifically accepted one (all the students used the concept of reference system to solve problems and twenty out of twenty seven formulated a more complex notion of the concept of observer) as can be seen in these excerpts:

> *"the movement of an object can only be described by adopting a reference frame" (Student1);*
> *"in order to determine the speed of an object both a reference frame and an observer are required" (Student 2);*
> *"the observer who intends to describe some physical phenomenon should adopt a reference frame and use the appropriate instruments for each kind of measurement" (Student 3);*
> *"if an observer has to record times, he needs instruments that are synchronized with those of another observer in order to compare results" (Student 4).*

The rest of the concepts that have been selected following the epistemological analysis, are within the conceptual field of the SRT, and have been evaluated according to the results obtained from the students' concept maps of the SRT, comic strips or stories, and a final test. As regards the concept of space, it has been initially detected that the students' representations agreed with the Platonic model that states that "space is the place that bodies occupy". A radical modification of such interpretation of the concept of space was made, as we can appreciate by comparing the initial test with the final one in which twenty six out of twenty seven students disagree with such statement.

All the four groups that made concept maps of the SRT were able to identify relativity both in space as in time in relation to the adopted reference frame As regards the comic strips, five of the six groups stated the same as it was expressed in the concept maps (See figures 1 and 2)[7].

The comic strip (figure 2) suggests that the group of students identified one of the postulates of the SRT (the speed of light as a limit), considered it important to adopt an inertial reference system, and recognized some of the consequences of the SRT. (One of these consequences, the fact that the concepts of space and time are relative, is illustrated in four of the six cartoons).

Nevertheless, there should have been more detailed specifications as regards the instruments used in the different reference systems.

As for the concept map given as an example (figure 1), according to the answer given by the group (which was not always reflected in the graphic representations), the following are the concepts they considered as relevant ranked in order of hierarchy: SRT; postulates; inertial reference systems; time dilation–length contraction; simultaneity; synchronization – common time system; technological applications.

The students in this group (as well as three other groups out of a total of six) correctly identified in their concept maps the two postulates on which the SRT is based. They also recognised the need to adopt an inertial reference system in order to measure especially time and length. It was clear that these vary according to the reference system selected; that is, they identified two consequences of the SRT: time dilation and length contraction. They also pointed out another consequence which is the relativity of the concept of simultaneity. They recognized its importance in time measurement and associated it with the concept of synchronization of the instruments used in time records. They perceived the relationship of this last concept with the common time system as well.

They made reference to the technological applications of the SRT. However, in their description they confused them with the empirical verification of the theory.

Even though the concepts of observer and of instruments are implicitly formulated in the description of the map, it should be noted that they were not regarded as relevant.

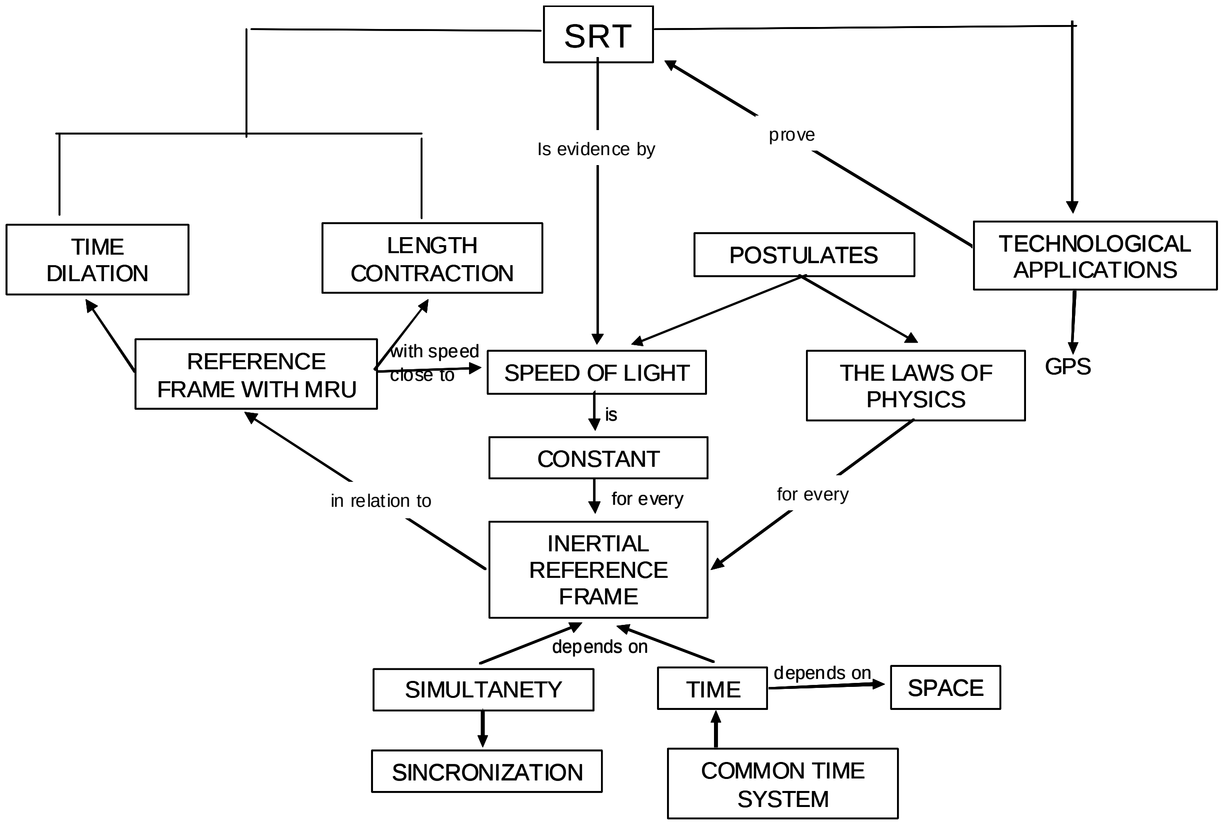

Figure 1: Concept map created by a group of students.

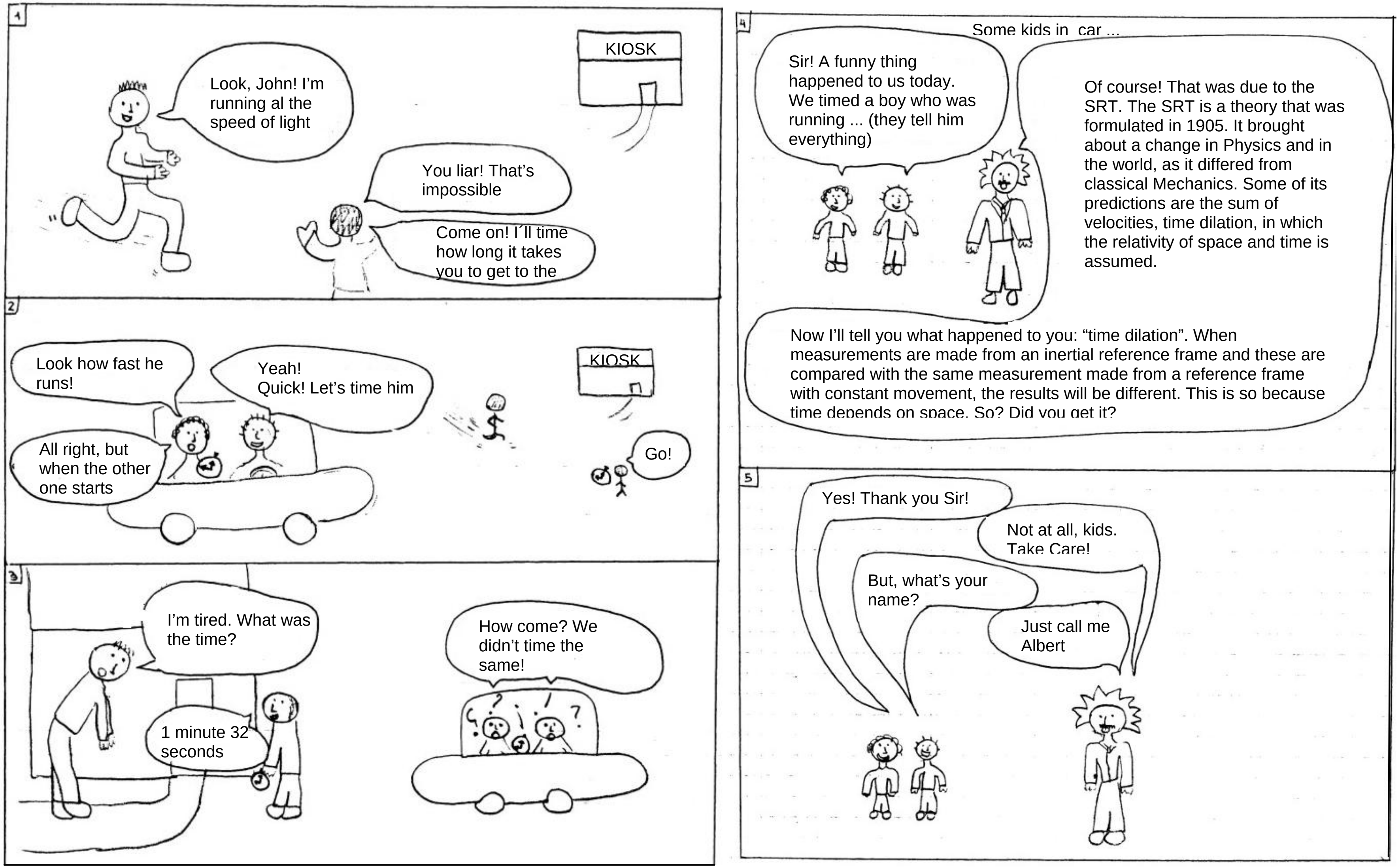

Figure 2 Comic strip created by a group of students.

In the answer to a problem in the final test, all of the students answered that the measurements of a certain length depend on the reference frame adopted by the observers, but half of the answers that offered an argument for which the measurement would be smaller were incorrect. One student wrote the following argument for this,

> *"Length is a magnitude that contracts when measured within an inertial reference system at a speed close to that of the light. This means that when the sailor measures the length of the ship aboard which he is travelling he will get a smaller value than that measured by an observer who is at rest in relation to the coast".*

This shows that, even though there is evidence that the students are able to notice one of the consequences of the SRT, which is length contraction, they are yet not capable of solving specific problems that involve this concept.

As regards the concept of simultaneity, out of the four concept maps made by the groups of students, two considered this concept as relevant, and established appropriate connections with other concepts, showing an understanding of the relativity of simultaneity as a consequence of the SRT. One of the other two groups did not even mention it, and the other one, although placing it on the concept map, did not establish important connections with other concepts. On the other hand, only one group mentioned and made correct use of this concept in the comic strips. In the final test, twenty four students selected the correct option that stated that the simultaneity of two events can be established even when such events do not occur in the same place. In spite of the fact that this point could suggest that the obstacle detected in the initial test would have been overcome –the students used to think that events could be simultaneous provided they occurred in the same place– we are aware of the fact that there was not enough time to deal with different cases of simultaneous events both within the field of Classical Mechanics as within the field of the SRT as it was stated in one of the objectives. We believe that this is the reason for the different answers in the final test and for the fact that this concept did not appear as relevant in all the maps, stories and/or comic strips.

With regard to the concept of postulate, it seems that the two main postulates of the SRT have been identified and appropriately connected with other concepts of the SRT. In the final test, almost all the students (twenty three and twenty seven students respectively) gave a correct answer to the items that involved the concept of postulate, which seem to indicate that they have been able to incorporate the meaning given to this concept within the context of the SRT. In the stories and comic strips, two, out of the six groups, included them in their productions, two mentioned only one of the postulates and the two other groups did not take them into account. However, there was no opportunity to see if, from an epistemological perspective, more appropriate meaning was given to this concept than the one expressed in the initial test.

The same applies to the concept of scientific theory. Even though there are no elements to assert that they have modified the concepts from an epistemological point of view, there seems to be evidence that the obstacle initially detected –a narrow view of scientific theories– has been overcome, at least in relation to the example they dealt with, the SRT. All of the students answered –in the final test– that the SRT is not a mere theoretical speculation, but an experimentally verified theory accepted by the scientific community. Also all of the students asserted that the SRT has technological applications and had knowledge of one of them with more implications for daily life such as the GPS. Apart from that, almost in all the answers (twenty six) it was asserted that the SRT did not emerge in response to Michelson and Morley's failed experiments. As regards the "creation" of the SRT, a bit more than half of the answers stated that the theory had not been formulated exclusively by Einstein although, as we have already suggested, there could have been a problem either with the interpretation or with the formulation of the instructions, since the ones who argued for Einstein's exclusive authorship also added that he did not construct it in a conceptual vacuum and that there were other scientists who made contributions to the SRT.

As regards the personal aspects of Einstein's life – a stage of the proposal which could not be dealt with in the time we expected –, the students highlighted the most "scandalous" aspects of his private life and they seemed to have intended to "compare" his professional performance with his personal attitudes although that was not what the material was intended for. It seems as if they were unable to realize that these are two different spheres, and that was precisely the idea that was intended to be conveyed through the discussion but there was no opportunity to facilitate this in an appropriate way. The students assumed that being bright, dedicated, creative, successful, renowned, etc. "guaranteed" a successful private life, too. Another aspect that was contrary to the nature of the proposal and appeared in connection with this point was the fact that two groups considered two characteristics of Einstein's work –his "solitary" work "isolated from the problems of society"– as desirable for scientists in the present.

Finally, it is important to point out that the intended work atmosphere was achieved. The students worked comfortably, even when the researcher approached them with the tape recorder in order to record some discussion. A very good rapport was established among all the participants during the months the research was conducted. There were no problems of misbehaviour and they all worked in a responsible way. From the beginning until the moment when they were interviewed at the end of the classes, the students expressed great interest in the topic.

5. Final comments

This paper is aimed at contributing to the incorporation of topics that are relevant to the science syllabus at secondary level providing a contextualized framework for science education. Despite difficulties with the application, the overall results achieved by this group of students in terms of the learning of concepts that are central to the SRT seem much more positive than the ones obtained when approaching the SRT in a way we could call traditional. That was the case for a similar group of secondary students on whom we conducted a previous study and who had a textbook as the only teaching resource. (Arriassecq and Greca 2005**).**

Therefore, we consider it is really possible to introduce elements of the SRT in secondary school by using the material we have designed, in spite of the teachers' lack of knowledge of the topic and the little time available. Apparently, this introduction to the theory proves profitable for students not only in the sense that they are introduced to more "modern" Physics –even though it is more than one century old!– but also because it seems to allow them to revise and gain a deeper understanding of classical concepts such as the concepts of time, space, reference frame, simultaneity, observer and measurement, which go unnoticed in traditional teaching practices.

On the other hand, the question that necessarily arises is whether this proposal proves too lengthy (and too ambitious) to be carried out at secondary level in the present circumstances. In other words, is it possible for other teachers to apply this proposal? If the content of the SRT is dealt with during the last term of the last school year, as it was the case this time and seems to be standard practice, at least in Argentina, the answer will be negative. The proposal should then be abridged at the risk, of course, of omitting some fundamental elements of its epistemological, educational, and psychological conception.

However, considering how relevant it is for students to develop a better understanding of classical concepts that emerges precisely from contrasting them with the relativistic ones, it would be desirable that teachers become convinced of the importance of dealing in detail with the SRT and not leaving this topic for the end of the last year of secondary school. From this perspective, the whole proposal could be put into practice since, according to the outlined results, it does not present students with any "insurmountable" difficulties in understanding such topic, except for the problems any new topic may pose.

In spite of these problems, the experience we have gained through sharing this material with teachers working at secondary level –one of whom was the teacher in charge of the class in which the proposal was put into practice– indicates that the material is relevant to them. It gives them a more global view of the SRT, of its central concepts and their relationship with classical ones and of the historical and epistemological aspects involved in its development.

We believe that studying historical cases such as the SRT, and placing them in the time such theories were formulated, would prevent students from adopting a distorted view of scientific methodology and from considering scientists as “super geniuses”. Therefore, students would be allowed to see how different ideas become more powerful concepts that together build conceptual frameworks like scientific theories. Apart from that, this approach makes it possible to appreciate the contributions made by several historical characters towards the creation of a new scientific conception, even though later they were not successful, or did not receive the recognition of their peers at the time they developed their ideas. We consider it important to stress once again that the introduction of the SRT can not be restricted to a historical and epistemological approach that does not include a conceptual discussion especially of those concepts regarded as relevant and which precisely give sense to such approach.

Table I. Concepts, Students conceptions, obstacles and objectives.

CONCEPTS	STUDENTS' CONCEPTIONS	OBSTACLES	OBJECTIVES
Time	• The notion of time is hard to define. • Time is a unity. • Time is an absolute concept. • Time is a relative concept. • Time is symbolized on a clock. • Time can be regarded as the independent variable of a system of coordinate axes. • Time can not be represented. • Nowadays it is not possible to travel in time for technological reasons. • It is not possible physically to travel in time.	• Students assume that the concept of time science deals with is the same as the one we daily refer to. • When students refer to the concept of time from a supposed scientific point of view, they commit mistakes such as confusing the terms magnitudes and units. Apart from that, they do not establish relationships between these concepts and the meaning of the process of measuring time magnitude.	• To analyze the concept of time from different perspectives: from a philosophical, a scientific, and a psychological point of view. • To appreciate the range of possibilities of graphically representing time magnitude. • To identify the concepts involved in the process of measuring time. • To interpret the concept of time within the paradigm of the SRT recognizing the differences with Classical Mechanics.
Space	• Space can not be represented. • Space is the place occupied by objects and the empty space in between.	• Students' conceptions of space coincide with the platonic model.	• To redesign the space model built, adapting it to meet the requirements of Classical Mechanics. • To interpret the concept of space within the paradigm of the SRT recognizing the differences with classical Mechanics.
Space.time			• To use Minkowski´s diagrams to represent and interpret the concept of spacetime.
Observer	• The observer can be an individual or an instrument that faithfully records facts.	• Students relate the notion of observer to the idea of a person who "observes" in the sense of "watching" or "looking at".	• To redefine the notion of observer adapting it to the SRT.
Simultaneity	• Two events are simultaneous when they occur at the same time and place.	• Students consider that simultaneity of events take place only if such events occur in the same space.	• To analyze the different possibilities of simultaneous events within Classical Mechanics. • To analyze the different possibilities of simultaneous events within the SRT.
Measuring	• The instrument is the most important feature in the measuring process.	• The observer's role in the measuring process is not regarded as important by students.	• To appreciate from a Physics point of view that within the context of the SRT "to see" is not the same as "to measure". • To study the relation among the measurement process, observer, and instruments.

Appendix A. Summary of the topics that have been covered and produced as written support material for the teaching proposal.

FIRST STAGE *(Estimated time: two-hour class plus the amount of time the student devotes to reading and doing the activities outside the classroom*). It comprises one activity and one text discussion.

1- Introduction
2- Scientific knowledge: its origin and some distinctive features.
2.1 Aristotelian cosmology.
2.2 The main characteristics that differentiate scientific knowledge from other kinds of knowledge.

SECOND STAGE *(Estimated time: two classes of two hours each plus the amount of time the student devotes to reading and doing the activities outside the classroom*). It consists of ten activities and text discussions.

1. Revision of the main concepts of Newtonian Mechanics which are necessary in order to interpret the SRT.
1.1 The concept of motion within Physics. Activity 2.
1.2 The concept of speed. Activity 3.
1.3 Change of reference frame
1.3.1 Equation corresponding to the identity transformation
1.3.2 Equation of transformation for stationary reference frames which are separated by a constant distance
1.3.3 Galilean equations of transformation
1.4 The concepts of space and time
1.5.1 Application of Galilean transformations to calculate the distance between two points
1.5.2 Application of Galilean transformations to calculate the speed of a body in motion
1.5.3 Application of Galilean transformations to calculate the acceleration of a body in motion
1. 6 Galilean relativity principle

THIRD STAGE *(Estimated time: a two-hour class plus the amount of time the student devotes to reading and doing the activities outside the class)*. It consists of one activity

1. The aspects of electromagnetism linked with the SRT
1.1 Brief account of the concept of ether
1.2 Maxwell's theory and its incompatibility with Galilean equations of transformation

FOURTH STAGE This stage comprises a total of six activities and text discussions.

1. Special theory of relativity
1.1 Let us start from the beginning: the "origins" of the SRT
2. How can we define and measure time?
2.2.1 The role of simultaneity in the measurement of time
2.2.2 Operational definition to establish the moment when an event takes place
2.2.3 Synchronization of clocks
2.2.4 Relativity of simultaneity
2.2.5 Determining the time when an event occurs from the point of view of an observer who is in motion with respect to it

(Estimated time: a two-hour class plus the amount of time the student devotes to reading and doing the activities outside the classroom)

3. Determining the length of an object from the point of view of an observer who is in motion in relation to it
4. Lorentz's equations of transformation
5. Transformation of velocities within the SRT

(*Estimated time: a two-hour class plus the amount of time the student devotes to reading and doing the activities outside the classroom)*

6. New relation between the concepts of space and time within the SRT: space-time
5.6.1 Minkowski's diagrams
5.6.2 Applications of Minkowski's diagrams

(Estimated time: a two-hour class plus the amount of time the student devotes to reading and doing the activities outside the classroom)

7. Experimental verifications, applications, and impact of the SRT
5.7.1 The origin of the SRT
5.7.2 Experimental verifications
5.7.3 Technological applications of the SRT
5.7.4 Impact of the SRT on different fields

(Estimated time: a two-hour class plus the amount of time the student devotes to reading and doing the activities outside the classroom)

8. Albert Einstein, a man *(Estimated time: a two-hour class plus the amount of time the student devotes to reading and doing the activities outside the class)*
It comprises an activity and text discussions.

Notes

[1]In the introduction of his article "On the electrodynamics of moving bodies" (*Annalen der Physik*, vol. XVII, pp. 891-921) Einstein says, "*Take, for example, the electrodynamic interaction between a magnet and a conductor. The observable phenomenon here depends only on the relative motion of conductor and magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of the two bodies is in motion. For if the magnet is in motion and the conductor is at rest, and electric field with a definite energy value results in the vicinity of the magnet that produces a current wherever parts of the conductor are located. But if the magnet is at rest while the conductor is moving, no electric field results in the vicinity of the magnet, but rather an electromotive force in the conductor, to which no energy per se corresponds, but which, assuming an equality of relative motion in the two cases, gives rise to electric currents of the same magnitude and the same course as those produced by the electric forces in the former case.*"

[2]See, in this regard, a very interesting presentation in Villani's work (1981-1985), in which this author introduces also the reason why Einstein's program succeeded in contrast to Lorentz's, even though at the time there was no empirical evidence for or against one of these theories.

[3]Apart from these points, the "ideas" the SRT generated in the scientific community can be the starting point to analyze the originality of the theory. From the perspective of a physicist such as Feynman (1963) the most relevant ones would be the fact that ideas that have been supported for a long period of time and have been clearly demonstrated could be wrong, the fact that "strange" ideas, such as time dilatation when one is in motion, can not be abandoned a priori, whether one likes it or not, and the fact that it is necessary to notice the symmetry in laws, which is the way in which laws can be transformed and remain the same. This last approach has characterized the research into the physics of particles and fields.

[4]However, it should be made clear that the influences attributed to the SRT in art and other cultural expressions sometimes brought about unfortunate results, to the extent of distorting concepts of key aspects of the SRT, leading to a terminological confusion. "Physical relativity", a term which has a clear meaning within the context of the theory, was misunderstood as "everything is relative", that is to say that all points of view on a matter are equally valid and that "truth" or "reality" is the combination of all the views expressed on such phenomenon. This was probably the most serious misunderstanding that the success of the SRT caused outside the field of Physics. Even though you can adopt this epistemological posture, such view does not emerge from the SRT, in which nature laws remain the same regardless of the reference frame used. For this reason, the SRT is universally valid and even more "absolute" than classical Physics.

[5]The two periods of Physics were divided in two different days. One of those days was Monday to which all the national holidays were moved. Therefore, many classes were missed. On the other hand, several activities typically done by students in their senior year (trips, special days) and other institutional ones (teacher training courses) took place on the days assigned to Physics classes.

[6]http://www.exa.unicen.edu.ar/~irenearr/propuesta didactica 2008.pdf

[7]Both the concept map and the comic strip have been translated from Spanish into English.

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