

JENARO GUISASOLA
EILISH MCLOUGHLIN

General editors

CONNECTING RESEARCH IN
PHYSICS EDUCATION WITH
TEACHER EDUCATION 3



INTERNATIONAL UNION OF
PURE AND APPLIED PHYSICS

Jenaro Guisasola - Eilish McLoughlin
General Editors

**Connecting Research in Physics Education
with Teacher Education 3**

I.C.P.E. Book

General Editors

Jenaro Guisasola

*Department of Applied Physics,
University of the Basque Country (UPV/EHU),
San Sebastian, Spain*

Eilish McLoughlin

*School of Physical Sciences & CASTeL,
Dublin City University,
Dublin, Ireland*

Published by The International Commission on Physics Education in cooperation with
University of the Basque Country (UPV/EHU) and Dublin City University.

***An I.C.P.E. Book* © International Commission on Physics Education 2022**

ISBN 978-1-911669-33-3

DOI: 10.5281/zenodo.5792968

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Chapter 4

Introducing Einsteinian Physics in High School and College

Irene ARRIASSECQ

*National Council for Scientific and Technical Research (CONICET).
ECienTec, Facultad de Ciencias Exactas,
Universidad Nacional del Centro de la Provincia de Buenos Aires, Argentina.*

Ileana M. GRECA

Department of Specific Didactics, Universidad de Burgos, Spain

Abstract: This chapter reviews various proposals for teaching Einstein's special and general theory of relativity in high school and college introductory courses and proposes two teaching-learning sequences for the last years of high school. They have been designed following a contextualized approach, within a theoretical framework that considers epistemological, psychological, and didactic aspects. It presents the teaching materials produced and some results from implementation in real classroom settings.

1. Introduction

Research has shown that although students are motivated and interested in relevant ideas from the special theory of relativity (STR) and the general theory relativity (GTR), they have great difficulty in understanding the core concepts of these theories [1, 2]. Moreover, limited training of high school teachers in this subject leads them to use the same textbooks they recommend to their students [3, 4] as their main resource. This aspect is important because, if teachers have not had the opportunity to analyze STR concepts in depth during their training, they will find it difficult to learn them from the textbooks they usually consult which deal with these theories very superficially and sometimes wrongly. At university level, although teachers are well qualified to teach this subject, there is no variety of didactic material, as most textbooks are based on just two proposals [5], as we will discuss below.

In addition, the area of research in physics concerning STR and GTR teaching—dealing with either students' and teachers' conceptions and difficulties, or with new approaches and teaching materials—is scarce compared, for example, with another subject as old, revolutionary, complex, novel in its time, and relevant, as quantum mechanics. A simple search in any database shows that, in terms of published articles, research in STR or GTR didactics barely totals a third of quantum mechanics didactics.

Therefore, two teaching-learning sequences (TLS)¹ were designed from a contextualized perspective in terms of epistemological, psychological, and didactic aspects [6–8], with which we have been working for more than a decade. These materials present a discussion of the relevant conceptual aspects of the STR and the GTR. They have been designed to help students to understand the profound changes that these theories have made in physics itself and beyond this science.

In this chapter, we first review the main strategies for approaching the STR and the GTR that have been published internationally and then present the TLSs, describing their structure and analyzing some of their activities. It should be noted that although these TLS have been developed to be implemented in high school, they can be used to introduce the STR and the GTR at undergraduate level.

2. Different strategies for teaching the special and the general theory of relativity

The visions that have shaped teaching on relativity derive from the opposing proposals for teaching the special theory of relativity (STR) in college introductory courses that appeared in Resnick's [9] and Taylor and Wheeler's [10] books [5]. As previously mentioned, given the scarcity of textbooks specially written for high school, these two books also guide the presentations in high school textbooks [5, 11]. Resnick presents the STR following a historical approach, which emphasizes the physical significance of the relativistic effects and their empirical corroboration. Taylor and Wheeler, on the other hand, move beyond the historical aspect and present a formal development of the STR that emphasizes the geometrical formulation using Minkowski diagrams. It should be noted that neither of them—nor the didactic texts inspired by them—consider the difficulties faced by students when first confronted with the STR and the GTR [11].

Therefore, as for other topics in Physics, a range of strategies have been proposed in an attempt to improve the STR and/or the GTR teaching-learning process. We are presenting, below, a brief selection of strategies that have been published since 1990 in journals included in the Web of Science database, organized according to their aim of improving class explanations, any possible demonstrations, and/or the types of representations [12]. Although what we present is not an exhaustive compendium, we consider that the selection is representative of the types of strategies designed to introduce the STR or the GTR at high school and university.

Proposals to improve how relativity is explained in introductory courses can be divided into four strategy types: using one or more concepts as the central axis for presentation, using examples of paradigmatic "objects", presenting the content in a way that students do not feel is "strange", and finally, introducing the relativity content from a perspective that considers historical and/or philosophical aspects. Thus, for example, Sandin [13] argues that the concept of relativistic mass should be used as the central aspect of teaching the STR because it brings consistency to introductory courses. Karam, Cruz & Coimbra [14], starting from common misconceptions, put into practice a strategy to improve students' concept profile of time to incorporate the notion of relativistic time.

Concerning the use of paradigmatic models, linked to teaching the GTR, two proposals stand out: Ehrlich's [15] strategy on the discussion of tachyons, given their speculative and controversial nature, and Muller's [16] focus on wormholes.

To reduce the "distortions of perception" students experience when faced with the STR, Dimitriadi and Halkia [17] propose a non-mathematical introduction, which avoids presenting the phenomena as odd and strange and terms considered difficult to understand or confusing, and which is based on simple examples that can be justified using the two axioms of the STR.

There are many wide-ranging proposals using elements of the history and/or philosophy of science (HPS) and, in most cases, their use is relevant not only for conceptual understanding but also for contextualizing and understanding the production of scientific knowledge. Levirini [18, 19] proposes presenting the idea of relativity through the different ways in which the concept of space can be viewed. She stresses that although the geometrodynamical interpretation of the GTR is widely accepted by physicists nowadays, since the assumption of a real space introduces a strong criterion for interpreting the basic principles of the GTR, the STR is still usually taught as the theory which overthrew Newton's absolute concepts, including the idea of a substantial space. She argues that it would be interesting to present the original view of the STR proposed by Minkowski, which could be considered a substantialist interpretation of the STR and, consequently, the key to building a consistent substantialist line running from Newtonian mechanics to the GTR. Guerra, Braga, and Reis [20] suggest discussing the relationship between science and other cultural productions to help students reach a more

meaningful understanding of how knowledge is built and therefore, a better grasp of the questions and solutions presented by Albert Einstein in his works. One last example of this kind of teaching comes from Provost and Bracco [21], who suggest using the explanation of the perihelion shift of Mercury, an interpretation which was a major success for Einstein in 1915 and which allows a critical discussion of ideas about physics that have contributed to the genesis of the GTR.

With respect to demonstrations, due to the very nature of the possibilities of performing relativity experiments, stand-out proposals include thought experiments (TEs) and laboratory-assisted ICT tools. Valentzas and Halkia [22] used Einstein's elevator and Einstein's train TEs as tools for teaching basic concepts of the STR to upper secondary school students. Wegener, McIntyre et al [23] developed and evaluated game-like virtual reality software, Real-Time Relativity, which simulates a world obeying special relativistic physics and is used as a virtual laboratory.

Finally, several researchers have worked on developing and evaluating different types of representation that might be useful for enhancing students' understanding. These include geometric tools, conceptual schemes, analogies, metaphors, and ICT-based tools. As an example of geometric tools, Zahn & Kraus [24] propose the use of sector models, which allow curved space to be described similarly to approximating a curved surface by plane triangles. They developed several sector models for high school and undergraduate students, for example, to introduce the notion of curved space using sector models of black holes. Kneubil [25] uses conceptual schemes, which emphasize visual patterns of knowledge organization, to discuss transformations in the meaning of the concept of mass between classical and relativistic theories.

Regarding the use of analogies, Prado, Area et al [26] explore some analogies between the STR and geometrical tools developed by the ancient Greeks. As an example, they solve the kinematics of one-dimensional elastic collisions with ruler and compass constructions on conic sections. Exploring the role of metaphors for teaching the GTR, Kersting & Steier [27] studied how conceptual metaphors found in the literature led students to conceptions of gravity that differ from what is accepted scientifically. Thus, they developed a teaching sequence that states the strengths and weaknesses of the rubber sheet analogy and addresses students' conceptual difficulties, aiding teaching of the GTR.

Finally, in recent years, there has been a notable increase in the development of ICT-based tools—simulations, games, and virtual reality films—to help students think about the true observational consequences of, for example, length contraction and time dilation, which can help to sharpen the understanding of these effects. Kraus [28] outlines the use of interactive simulations that adopt the first-person point of view, allowing observation and experimentation with relativistic scenes. Sherin, Tan & Kortemeyer [29] present an open-source toolkit for simulating the effects of the STR within the popular Unity game engine. In their game, the player only operates in the first-person view and therefore the scene cannot be viewed from any other frame of reference. The authors stress that their toolkit considers that what would be measured is not what would be seen: due to the finite time that it takes light to go from the source to the observer, length contraction does not necessarily make objects appear shorter, as Lampa [30] discovered and many textbooks wrongly state or implicitly discuss. Finally, Van Acoleyen and Van Doorselaere [31] developed a virtual reality film that takes students on a boat trip in a world with a slow speed of light, in the spirit of George Gamow's *The adventures of Mr. Tompkins* [32]. They show different relativistic effects (length contraction, time dilation, Doppler shift, light aberration) that come up during the boat trip. The immersive 360° experience allows students to specifically discuss the directional dependence of the effects.

In the next sections we present our teaching proposals for STR and GTR, that combine some of the strategies described here: conceptual emphasis; the use of the history and

philosophy of science; selected concepts as the central axis for teaching; examples of paradigmatic "objects"; thought experiments; and geometric and ICT tools.

3. Teaching Learning Sequence for the STR

3.1. Theoretical framework

Our proposal assumes that elements from history and philosophy of science, psychology, and didactics must be considered to develop a TLS. A contextualized approach makes it possible to determine the epistemological obstacles used to select relevant teaching content. This kind of approach can also be used to discuss production of scientific knowledge, the role of the socio-cultural context in which the knowledge is produced, and its repercussions inside and outside the scientific sphere, to generate students' interest in science [33, 34]. It should also include a strong conceptual emphasis on the topics addressed, which is essential for the historical-epistemological discussions to make sense. This perspective favors the achievement of curricular proposals which focus on training scientifically literate citizens who should construct knowledge of and about science during schooling.

The epistemological axis aids selection of the fundamental scientific ideas that students should meaningfully learn about the scientific topic in question. Because of its emphasis on the epistemological obstacles that must be overcome to understand a scientific theory, we focused on elements of Bachelard's [35] epistemology. Epistemological analysis of the STR content based on this framework [36] allowed us to delimit the concepts to be learned by the students: space, time, frame of reference and its associated notions of observer, simultaneity, and measurement, which are indispensable for the relativistic understanding of space-time. According to Bachelard's notion of obstacle, if students are to meaningfully learn the concept of time, then they must review the notion of time in classical physics, from which the relativistic notion is developed.

The psychological axis considers the principles used by students to conceptualize and learn content in a classroom situation, as well as the role of the teacher in this process. To this end, we synthesized several perspectives, Vergnaud [37], Ausubel *et al.* [38], and Vygotsky [39], to be used as complementary theoretical frameworks. Our main hypotheses were as follows:

- Conceptualization is at the core of cognition. Cognitive processes and students' responses depend on the situations they meet. As they progressively master the situations, they shape their knowledge. Such knowledge is relevant for conceptual analysis of the situations used by students to develop their schemata.
- To achieve meaningful learning, students must be willing to learn and have the appropriate subsumers for the situations being presented.
- In the school environment, the teacher is the main mediator for the acquisition of accepted meanings in science, by mastering different instruments, signs, and sign systems from those of the learner. Teaching takes place when students and teachers can share meanings. Thus, the teacher has the essential role of mediator, facilitator, and regulator of situations that allow the student to internalize instruments, systems, and signs that belong to the social language of school science.
- The meaningful learning that can be achieved in class is highly conditioned by the type of interactions fostered between students and teachers and among the students themselves, stimulating the exchange of accepted meanings within the students' zone of proximal development.

In the didactic axis, we included the choices about the specific sequencing of TLS, such as determining objectives and activities to achieve them. Regarding the objectives, we used Martinand's [40] conception of objective-obstacle. He argues that the objectives of science

education cannot be defined a priori and independently of the students' representations but must be based on the intellectual transformations that occur when overcoming a given obstacle. Therefore, it is necessary to analyze, among all the existing or possible obstacles for a given object of study, those that seem most surmountable for a given level and context, according to the students' representations.

3.2. Design and description of the proposal

To develop the TLS on the STR, we carried out a series of preliminary studies, such as a historical and epistemological analysis of the STR and the textbooks, and studies related to teachers' difficulties and students' representations.

The proposed TLS consists of five stages. The first stage is a historical-epistemological analysis of issues related to the notion of science, characteristics of scientific work, the evolution of ideas in science, influences of the social, historical, and cultural context on the emergence of scientific theories, and the validation of these theories. The second stage thoroughly reviews the concepts of classical mechanics that are necessary to interpret the STR, as well as any substantially modified by the STR and that constitute the epistemological obstacles for acquisition of new concepts. The third stage deals with the concepts of electromagnetism that conflict with classical mechanics and were taken up by Einstein. The fourth stage discusses the fundamental aspects of the STR, starting from the original 1905 article and using various situations to help students develop new mental schemata, because they face situations that require reformulation of classical concepts. The fifth part aims to introduce students to some aspects of Albert Einstein's life as a man, transcending the "myth" [41].

Based on the hypotheses of the theoretical framework, we designed, sequenced, and evaluated activities to complement the conceptual explanation. These activities include qualitative and/or quantitative problem-solving and the famous paradoxes, sequenced in increasing order of difficulty. The key concepts of the STR are incorporated at different stages of the TLS, using several representations (linguistic, algebraic, and graphical). Other activities proposed are reading articles and creating stories, comics, and concept maps. Regarding the reading, this comprises original texts for students to work on in class with the help of the teacher, and texts by specialists on the history of physics, dealing with conceptual issues that have had repercussions in non-scientific fields, such as art. This TLS takes the form of written material to be used by teachers. It has the structure of a textbook, with five chapters following the sequence described above.

To set out the expected outcomes clearly so that teachers could easily evaluate them, we considered the perspective of teaching for understanding [42]. According to this perspective, understanding is the ability to use what one knows when acting in the world, extending, synthesizing, and applying that knowledge in creative and novel ways. Thus, analyzing students' understanding requires ongoing diagnostic assessment of their performance, through tasks such as explaining, interpreting, analyzing, relating, comparing, and making analogies, which differ from other common classroom activities.

Activities are therefore only considered comprehension performances if they are elaborated on and demonstrate that students have reached important comprehension goals. These expected performances, based on what teachers can observe, will be indicative of achieving the goals. Table 1 presents the comprehension goals for learning the STR and those that the learner should have previously achieved, plus the proposed comprehension performances.

Table 1. Comprehension goals and performances

<i>Comprehension goals</i>	<i>Comprehension performances</i>
• Discriminate between the concepts of distance travelled and position.	- Decide on the concepts necessary to describe the motion of an object.
• Establish meaningful relationships between the concepts of observer, reference system, measurement process, and instruments.	- Construct a concept map with a personal synthesis of fundamental concepts for understanding and solving problems in classical mechanics, such as the following: invariance and independence of space and time, the impossibility of defining an absolute frame of reference, and the notion of simultaneity.
• Analyze the conceptualizations of space and time they have constructed and compare them against the major approaches to these concepts throughout the history of science.	- Draw a concept map interpreting the phenomena linked to electromagnetism, those explained by the theories of the time and those that raised problems.
• When analyzing motion, recognize the need to consider the frame of reference with respect to which something is said to be moving.	- Interpret a drawing representing motion from the perspective of two different observers.
• Recognize the need to use transformation equations when solving a problem that requires information from different frames of reference.	- Analyze the invariance of concepts such as "space" and "time" in different frames of reference at relative rest. - Distinguish phenomena that require a relativistic interpretation from those that are explained by classical theories. - Choose appropriate frames of reference to solve problematic situations related to the STR.
• Identify concepts relevant to making measurements, primarily of space and time, from different frames of reference.	- Critically read the introduction to the article published by Einstein in 1905 in the prestigious German journal <i>Annalen der Physik</i> under the title: On the electrodynamics of moving bodies.
• Discuss notions such as "synchronization" and "simultaneity" and link them to the need for observers to have the appropriate means of communication.	- Explain in different ways how they interpret, based on their readings and discussions with their peers and the teacher, the two postulates of the STR and compare them with other concepts analyzed in Newtonian mechanics, for example, frame of reference or unresolved questions at that time, such as the "ether problem".

3.3. Implementation and review of the proposal

The TLS was implemented twice, with students in the last year of high school in Argentina. In the first implementation, we worked with a group of twenty-seven students, in two one-hour classes per week. During the classes, the students carried out the various activities included in the didactic proposal, such as readings and text analysis, debates, comics, concept maps, exercises, and problems. In the evaluation, it was observed that the central ideas, the objectives, and most activities were adequate. However, the students showed difficulties in understanding the space-time concept, which involves the concepts of simultaneity, proper and improper time, and proper and improper length. Although we presented several situations that required

analysis and/or construction of Minkowski diagrams to explore these latter concepts, working with these pencil and paper diagrams was quite complicated and time-consuming. Therefore, in the second implementation, students worked with interactive Minkowski diagrams using applets, which facilitate conceptualization by making qualitative and quantitative estimations (Fig. 1 and Fig. 2).

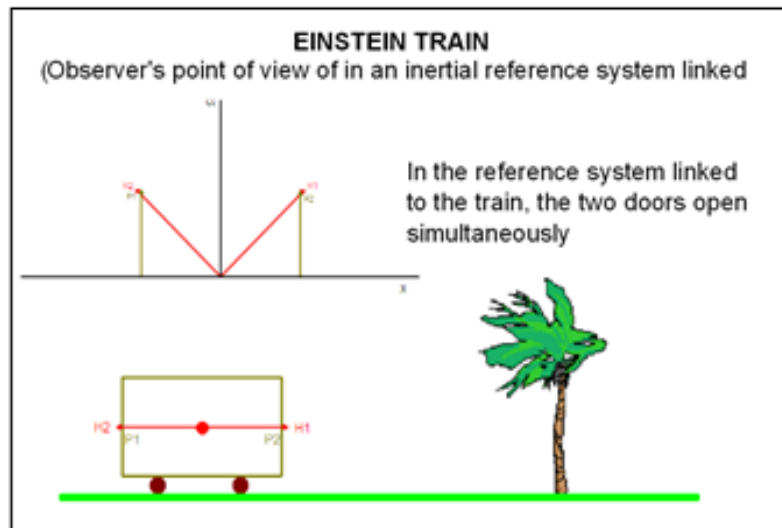


Figure 1. Opening of train doors observed from a frame of reference located in the middle of the train

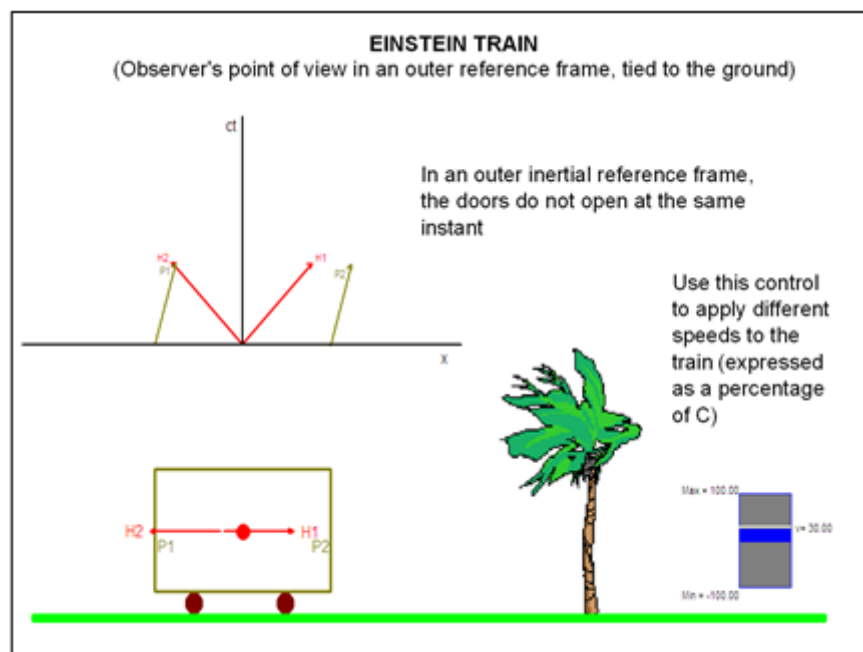


Figure 2. Opening of the train doors observed from a frame of reference outside the train

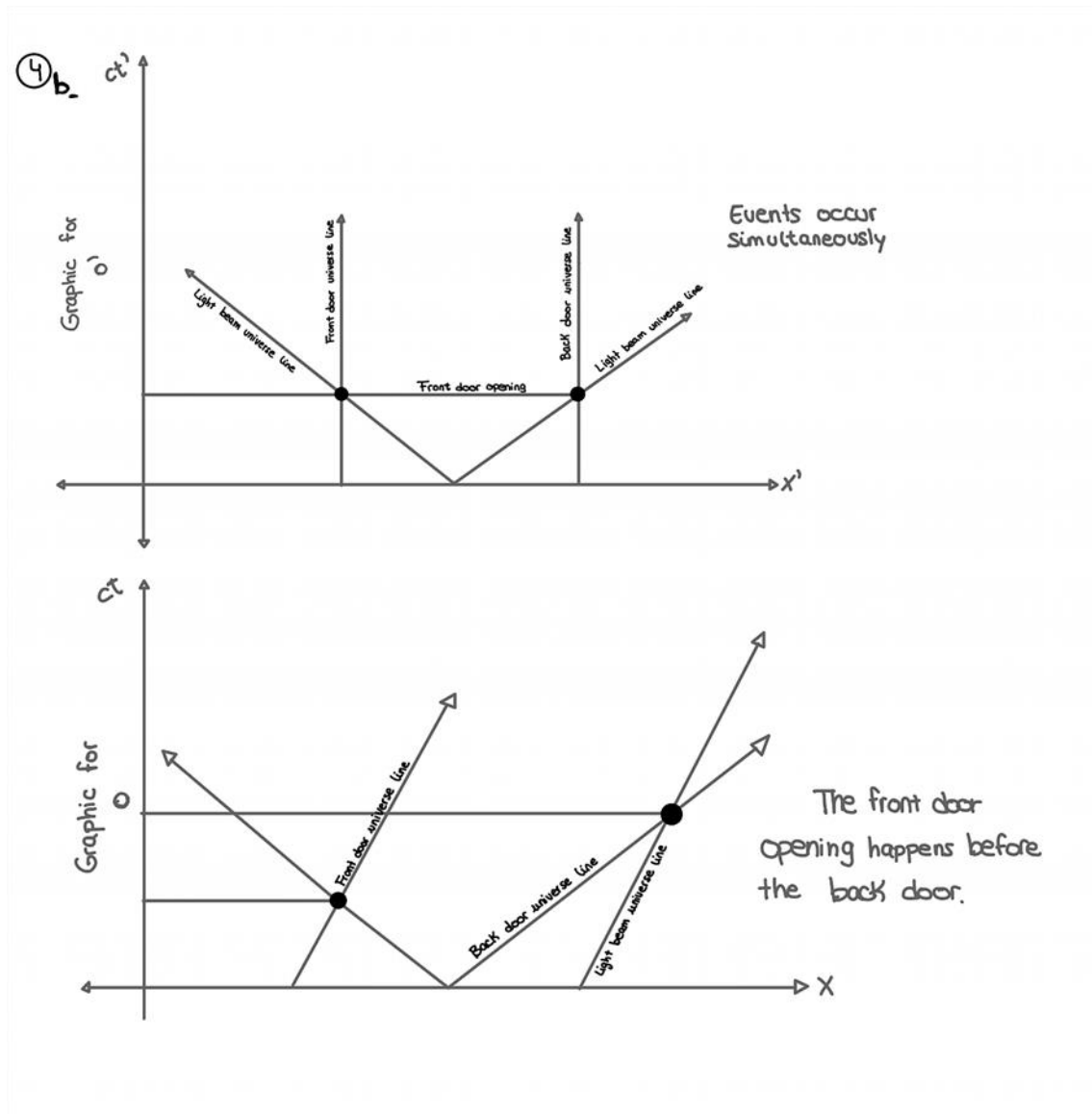
Below, we provide examples of how students worked on the following activities:

Activity 4: A passenger on a train, with constant speed relative to an inertial frame of reference located at the midpoint of the carriage, switches on a lamp and the beam of light travels towards the walls where two doors, P1 and P2, are located. The train has a mechanism that ensures that a door opens when the light hits a wall. The train is travelling at a speed of $0.5 c$.

a) Using algebraic operations, establish the possible simultaneity of the door openings for observers located inside the carriage (O') and another (O) on the train platform, for the case where the train speed is $0.5c$.

b) Using space-time diagrams, establish the simultaneity of the events.

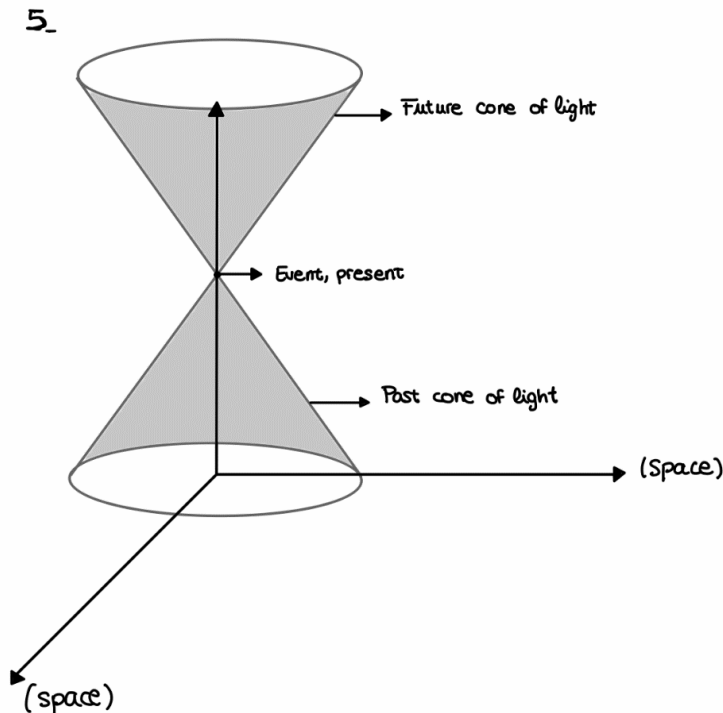
Solution for (b)



In Einstein's train (observer point of view O' within the SR) where events vary by the speed at which the train travels, they are always simultaneous and occur at the same time.

Talking into account the SR outside the train, observer O it is concluded that the higher the speed of the train, the farther apart events 1 and 2 are: The first occurs faster and the second takes longer. If the train equals the speed of light, event 2 never occurs. The higher the speed of the train, the closer the lines of the universe L_1 and L_2 are to the x -axis.

Activity 5: Represent the history of a quasar using a space-time diagram for events occurring in two spatial dimensions plus the time dimension. Describe the absolute past, present, and future of the event.



Present (event): a quasar emits light, a pulse of light at a certain time, at a certain place in space.

Future: As time goes by, the light pulse will expand as a sphere of light and after a certain radius.

Absolute past: The extinction of many stars that later came together and formed a mass called "Quasar".

3.4. Some results

The results obtained in the first implementation show that most students managed to achieve the objectives related to classical mechanics, such as interpreting time and space and analyzing these concepts from a philosophical and scientific perspective, considering the need to establish a frame of reference to solve problems that involve the concept of motion, and analyzing the close relationship between observer and measurement process. As far as the STR-related concepts are concerned, the students were able to recognize the concept of length contraction although they were unable to solve the problem. They also achieved the objectives related to historical and epistemological aspects. In particular, they were able to see that the STR is a theory with sufficient experimental verification, and were able to explain its technological applications, such as the Global Positioning System (GPS).

The results from the second implementation [43] show that most of the comprehension goals were achieved, in particular those related to classical mechanics (differentiation of the concepts of trajectory, distance traveled and position, analysis of the concepts of space and time, simultaneity of events, use of transformation equations in inertial frames of reference, and interpretation of the incompatibility of classical mechanics with aspects of electromagnetism) and others related to the STR (determination of time dilation and length contraction occurring in proper and improper systems, application of the Lorentz transformation equations to the calculation of velocity in different frames of reference, and calculations to determine the simultaneity of events). On the other hand, using the applets allowed students to understand and make meaningful use of Minkowski diagrams to represent space-time events.

In terms of comprehension performance, most students performed well or very well in most of the proposed activities. Particularly noteworthy was their understanding of inertial frames of reference and their interpretation of events from the perspective of different observers, their interpretation of the Michelson-Morley experiment, the resolution of activities that involved interpreting and relating the postulates of the STR, the use of Minkowski diagrams to establish the simultaneity of events in different inertial reference systems, and their understanding of the different experimental verifications, applications, and repercussions of the STR. On the other hand, the most difficult comprehension tasks were related to the selection of appropriate coordinate systems, use of transformation equations to represent motion from different frames of reference, problem-solving using transformation equations between frames of reference or using the Lorentz transform to calculate velocities of objects in different frames of reference, and algebraic problem-solving that involves establishing the simultaneity of events in different inertial frames of reference.

4. TLS for teaching the GTR

Understanding new scientific knowledge in cosmology and astrophysics over the last decade, constantly reported in the mass media, requires a deep understanding of GTR concepts—for example, the expansion of the universe, dark matter, black holes, and the measurement of gravitational waves. The latter topic, which constitutes a new empirical verification of the GTR, received wide media coverage in several countries, where time and effort was devoted to spreading the news of the first measurements. Astrophysicists tried to explain this finding to the public, why it so shocked the community of physicists and astronomers, what it implied for science and beyond science, not least for the perspective of the nature of science, and why it took a hundred years to detect these waves from the time they were predicted by Einstein. The news reached schools, and students from all around the world showed interest in the subject [44]. Many of them were also interested in films such as "Interstellar" and consulted their teachers about physics concepts mentioned in the film. Some recent Korean high school textbooks mentioned the film [44].

If it is considered relevant to teach the GTR in high school, the next question is how to do it. Historically, the GTR has not been taught, not even at university level, because it has been considered extremely difficult. The GTR is based on concepts of differential geometry, often expressed in the language of tensor calculus. In other words, it requires the use of a more complex level of mathematics than most undergraduate students can handle.

However, Christensen and Moore [45] argue that almost all undergraduate GTR texts published in the 21st century move away from the mathematical approach and focus on conceptual physics. This type of text follows the trend called the physics-first approach. This approach was proposed by Hartle [46], and his text *Gravity* is the most representative of its kind. It addresses the main concepts of the GTR at a mathematical level that does not go beyond

the first and second year of undergraduate courses. Two aspects of the book stand out: many examples of astronomical and cosmological phenomena and the emphasis on physical concepts, without the need to use mathematics in an initial approach.

Although the physics-first approach has only become widespread at university level in several countries, we believe that it can be implemented in high school classes if it is approached within an adequate theoretical framework. Based on assumptions like those described above for the design of the TLS on the STR, we have developed a similar project for teaching the GTR in high school.

4.1. Design and description of the proposal

To identify the most relevant GTR concepts to be dealt with in high school, we analyzed the current curricular designs in several countries, as well as the books *Gravity* and the popular text *100 years of relativity* [47], written by astrophysicists interested in disseminating the GTR beyond the scientific sphere.

We also considered the results obtained in a survey answered by students in their last year at a state high school in Argentina, after having dealt with the subject of gravitation and having seen the film "Interstellar".¹ This survey aimed to identify, among other aspects, which GTR concepts addressed in the film interest students most, and determine which concepts of classical mechanics students require to meaningfully understand GTR concepts.

The topics this analysis identified as relevant were: the principle of equivalence, curved space-time, the relationship between gravity and time, the relationship between matter and space-time, GTR empirical contrasts, black holes, gravitational waves, cosmological models, and technological applications. The proposed comprehension goals for the GTR are presented in Table 2.

Table 2. Comprehension goals for the GTR

1.– Interpret the principle of equivalence.
2.– Analyze basic aspects of non-Euclidean geometries.
3.– Characterize curved space-time
4.– Determine the relationship between gravity and time
5.– Determine the relationship between gravity and space
6.– Identify the relationship between matter and space-time
7.– Interpret the meaning of black hole.
8.– Recognize the variation of time in the vicinity of a black hole.
9.– Interpret the concept of gravitational waves.
10.– Analyze the different GTR empirical contrasts.
11.– Interpret different current cosmological models.
12.– Reflect on the different technological applications of GTR
13.– Interpret journalistic information linked to the GTR
14.– Debate on the GTR empirical testing process
15.– Investigate the role of female scientists in the GTR empirical verification process.

¹ The film "Interstellar", released in 2014, addresses several physics issues (black holes, wormholes, time dilation, gravitation, tides, etc.). It engages students, with special effects that led the film to win an Oscar. It was inspired by the work of Kip Thorne, one of the most renowned experts on the applications of the GTR to astrophysics, and the scientific consultant for the film. He wrote the book "The science of Interstellar", in which he uses scientific rigor to develop all the calculations necessary to simulate the visual effects of the physical phenomena involved in the story. In October 2017, he received the Nobel Prize alongside Weiss and Barish for their work on the LIGO Project to detect gravitational waves.

Regarding how to promote understanding, we propose the use of popular documentaries, newspaper articles with information on relevant scientific advances that directly or indirectly involve aspects related to the GTR, computer simulations, science fiction books, and films that deal with the subject, among other resources that are generally interesting for most students.

To exemplify our proposal, we selected the topic of gravitational waves. Table 3 shows the goals and comprehension performances identified for this specific topic.

Table 3. Comprehension goals and performances related to gravitational waves.

<i>Comprehension goal</i>	<i>Comprehension performance</i>
• Interpret the concept of gravitational waves.	- Differentiate the concept of gravitational waves from the other types of waves discussed in the workshop.
• Analyze the value of gravitational wave measurements as a GTR empirical contrast.	- Identify the experiments that made it possible to test the GTR.
• Interpret journalistic information related to gravitational waves.	- Solve the tasks proposed in the didactic sequence.
• Discuss the process of gravitational wave detection.	- Formulate specific questions for interviewing scientists specialized in the detection of gravitational waves.
• Investigate the role of female scientists in the process of measuring gravitational waves.	- Interview women in science (preferably linked to the subject of gravitational waves) and identify the main difficulties in their work, or for their female colleagues, just because they are women.
• Analyze the reasons why three scientists, out of the more than a thousand participating in the LIGO project, were awarded the Nobel Prize for detecting gravitational waves in 2017.	- Solve the tasks proposed in the didactic sequence.

As previously mentioned, high school physics textbooks that incorporate topics related to the theory of relativity are few and far between. It is even rarer to find teaching material for the specific topic of gravitational waves. For example, Hewitt's text *Conceptual Physics* [48] devotes half a page to this topic. In contrast, there are abundant academic and popular publications about gravitational waves, especially since their first detection announcement in February 2016. On the internet, we can find lectures by experts at various universities, interviews by specialized and non-specialized journalists with scientists working on the subject, material produced by popularizers, digital material produced by members of the LIGO Project itself, and popular videos.

For this reason, we have made special use of this material in our design. As there is so much material, we used the following selection criteria: the source (mass-circulation newspapers and periodicals, science channels of ministries of education or educational bodies); the communicators (interviewees should be either scientists who are experts in the subject or renowned popularizers); the style of communication (attractive and not too lengthy format, such as a TED talk or interviews with scientists with a layman's approach); and supplementary materials (descriptions of the experiment to detect gravitational waves, modelling and simulations of concepts linked to gravitational waves, space-time, and black holes).

Five activities were run to fit the determined goals and performances. Activity 1 consists of questions that seek to reveal the students' prior knowledge on the subject (What other

scientific concepts are gravitational waves related to? How are they generated? Is it important for science to detect them? Why? What facts might indicate that it is important for science to study gravitational waves?), the information sources they usually consult, and their interest in the subject. This first activity begins by considering aspects of the nature of science, such as who first proposed the existence of gravitational waves and in what context, how they are studied, the importance of studying them, the role of women in the study of this phenomenon, and the importance given to their detection in the media.

Activity 2 reviews the main characteristics of wave phenomena, which they have already studied, to subsequently distinguish which aspects of gravitational waves also have these characteristics. Activity 3 is introduced using newspaper headlines and screenshots of various television programs from the day of the report of the first detection of gravitational waves. In the same way, participation of an Argentinean scientist in the LIGO project is highlighted; information is presented about three scientists being awarded the Nobel Prize in Physics one year later for their work related to detecting the waves, plus headlines about subsequent detections. After the introduction, short videos are analyzed. Some of them are interviews or talks: a TED talk by Dr. Gabriela González, Argentinean scientist and spokesperson for the LIGO project; another TED talk, discussing the implications of the detection of gravitational waves in depth; two interviews with the same astrophysicist, one on a television news program by a non-science journalist and the other by a scientist; and an interview with an internationally recognized science communicator. The remaining videos correspond to an explanation of physical phenomena related to the gravitational wave: gravity as a space-time warp, black hole, black hole collision, and light bending in strong gravitational fields. As a complement, a series of popular articles are provided on the meaning of gravitational waves, the importance of their detection, the LIGO project, and the implications for astronomy.

In Activity 3, students should use the journalistic material to identify the concepts they consider most relevant and any they do not know. Then, they must reanalyze the instructions from Activity 1 and try to answer them. This activity emphasizes aspects linked to the way knowledge is produced and topics related to epistemology: what it means that gravitational waves are a "prediction by the general theory of relativity"; what the phrase "Einstein was right" means, as so often mentioned in the media; why scientists continue to measure gravitational waves after the first finding. In the final point of the activity, students are asked to assess the materials used, videos, and articles, in terms of their interest in the topic, or the lack thereof, and the material's potential to help them understand the physical phenomena.

Activity 4 focuses on other aspects of the Nature of Science linked to the sociology of science in general, and gender issues in particular. Students should investigate and discuss, based on reading three articles and any other sources they may choose to consult, what the Nobel Prize is and how important they think it is; what other types of prize they would compare it to, outside the scientific field; which country has won the most Nobel Prizes and what the reason for this might be; their opinion regarding how few women have won this prize; if they consider that it is more difficult for women to dedicate themselves to scientific work; and why the 2017 Nobel Prize in Physics was shared by three physicists and not awarded to only one person.

Finally, Activity 5 requires students to build a concept map that answers the focus question: Why is detecting gravitational waves important for science and society? We chose to use this powerful metacognitive tool because it has proven to be a very powerful instrument for sharing and exchanging meanings over the decades. In addition, the exchange of meanings displayed on the concept map is a further instance of learning and evaluation of what has been understood. The didactic sequence is set out in a written document, which includes the readings and videos.²

4.2. Implementation of the proposal and some results

The didactic sequence was implemented in a workshop called "Waves" for students majoring in natural sciences, who were in their fifth year at a high school run by the university, in the city of Tandil (Argentina) during 2018. This is a two-hour weekly course, and at the time of the study it was attended by twenty-three students. The results of this first implementation are encouraging in terms of student comprehension; they show the students have achieved the proposed goals for learning the generative topic of gravitational waves, as well as epistemological and sociological aspects of the nature of science. However, it would be necessary to extend the allotted course time, to allow for further debate in the classroom. With regard to the didactic proposal, given the students are meeting concepts such as space-time for the first time and need more time to grasp their meaning, an instruction was incorporated for Activity 2: after Activity 3, they have to rework their answers for Activity 2.

5. Conclusion

The STR and the GTR generate public interest and have scientific relevance inside and outside the field of physics. They have led to numerous applications in daily life, such as GPS or LCD screens. Therefore, it seems relevant to introduce these theories at high school and college. Nevertheless, their presence in textbooks and research in physics education is still scarce. Some promising proposals have been developed, for example, emphasizing conceptual aspects and reducing mathematical burden, or drawing on the history and philosophy of science. Other promising approaches are related to the increasing development of ICT-based tools—simulations, games, and virtual reality films—to help students think about the true observational consequences of both theories.

In this chapter, we presented two TLSs and their materials, which delve into topics of physics that, despite their importance, have not been sufficiently investigated in physics teaching. The materials have proved very useful to teachers with no undergraduate education or specific training in the subject, who have used them in high school as the main resource in their first approach to both the STR and the GTR.

We are convinced that it is possible to introduce elements of these theories at high school and university level using the materials we have developed, despite lack of teacher training and limited time. This approach seems not only to benefit students in the sense of bringing them closer to more "current" physics, but also to allow them to review and better understand classical physics concepts that go unnoticed in traditional teaching, such as the concepts of time, space, frame of reference, observer, simultaneity, and measurement.

In the twenty-first century, physics has been revolutionized by validation of theories that are already a century old. The media devote time in some cases, and space in others, to disseminating this progress. Students are often enthusiastic about these topics, which are often covered by films or science fiction novels. Although sometimes such material has strong scientific backing, at other times the emphasis is more on fiction than science, as these are cultural products for entertainment rather than education. For those who are interested, there are no bounds to the possibilities of accessing this information. The formats are very varied: interviews with specialists, short informative videos, longer documentaries with technicalities that require previous scientific knowledge, as well as popular ones. Notwithstanding this available material and huge student interest, in high school physics classes we only deal with a few topics from the beginning of the twentieth century at best.

It is a fact that most of us teachers lack training in this topic and teaching on texts that deal with contemporary physics is scarce. It is also true that with only the teachers' will, the students' enthusiasm, and the randomly chosen popularization materials without adequate didactic transposition, it is unlikely teachers will be able to convey certain concepts successfully. At

best, students will be able to describe the phenomenon in question but will be unable to understand the concepts involved. In this chapter, we have presented theoretical and methodological guidelines, used to develop the didactic sequences and the guides for teachers and students. They were developed within a theoretical framework that considers it relevant to address the conceptual aspects of the content plus the epistemological, psychological and didactic aspects, making it possible to implement these sequences at high school and undergraduate levels.

Notes

1. Both TLSs are available in Spanish.

For STR at

<https://drive.google.com/file/d/1jT7BUYoLu6GG3EVPSB0M4gbNx9Xf0T3a/view?usp=sharing>

And for the GTR at

https://drive.google.com/file/d/1F5RnF78igxUeS_hDAliQwWBDm052iL4h/view?usp=sharing

2. All this material is available in Spanish.

The TLS at:

https://drive.google.com/file/d/17Qt3lOh1CVx4EOduDfAbmx_lUC40Zmy_/view?usp=sharing;

The readings at:

https://drive.google.com/drive/folders/14cEpekIquSs0L7ws01-9L4_1eYYx6AaU?usp=sharing

And the videos at:

https://drive.google.com/drive/folders/1MwP7_-DVRNik9UCijTGJuoA-R3cnCPM2?usp=sharing

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