Special Relativity: A field where "minds-on" (thought) experiments could be proved valuable didactic tools

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Abstract. *In the first part of this study we investigate how the TSR is introduced in physics textbooks and in books popularizing physics theories. Our findings show that physics textbooks use mathematical formalism and complicated terms. On the other hand, popular science books use more comprehensible examples but they are often limited to the descriptive and peculiar character of these experiments. Thus, a careful design is needed to make the proper didactic transformation and to design educational material, drawing ideas and material from both of them.*

In the second part, we describe a teaching sequence, which has been developed in order to teach the TSR to upper secondary education.

Keywords. Books popularizing physics, Physics textbooks, Theory of Special Relativity, Thought experiments, Upper Secondary Education.

1. Introduction

Nowadays, the members of the science education community seem to agree that there is a need for updating the content of current physics curricula. In upper secondary education, this includes twentieth century physics theories. In that direction, a major problem emerged is how the mentally demanding theories can be introduced in science classrooms. This work attempts to explore ways of teaching the theory of Special Relativity (TSR) to upper secondary school students. This theory is recognized as a major constituent of "modern physics" (physics of the 20^{th} century) and also displays advantages in its teaching, namely that Einstein himself used thought experiments to clarify its meaning and consequences.

2. Methodology

In the first part of this study we investigate how the Theory of Special Relativity (TSR) is introduced in physics textbooks and in books that popularize physics theories. The purpose of this study is to trace the conceptual course and the examples that are used when dealing with the TSR. In that context, we have focused specifically on the two axioms of the theory and on the consequences relevant to the relativity of space and time (relativity of simultaneity, time dilation, length contraction). Based on the findings of this research, a teaching sequence has been designed and educational material has been developed in order to introduce the TSR in upper secondary education and to investigate the students' learning processes.

The books that were analyzed are presented in Table 1.

These physics textbooks were selected due to their extensive use in upper secondary education and in introductory university courses. The fact that some of them are considered as reference books was also taken into consideration.

As far as popularizing science books are concerned, the large number that deal with the TSR led to adopting as a criterion of selection whether the writer was/is famous physicist and/or famous as a popular science book writer.

Table 1: The books that were analyzed

A. **Physics textbooks**
1. Allonso M., Finn E.: *Fundamental University Physics (volume 1).*
2. Berkeley Physics Course: *Mechanics, (volume 1).*
3. Ford K.: *Classical and Modern Physics (volume 3)*
4. Halliday D. & Resnick R.: *Physics.*
5. Hewitt P.: *Conceptual Physics (volume 2).*
6. Ioannou A., Ntanou G., Pittas A., Raptis S.: *Physics (for 12^{th} grade Greek Students selecting Science and*

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Technology Orientation). 7. Ohanian H.: *Physics (Second edition, expanded) (volume 2).* 8. Serway R.: *Physics for Scientists & Engineers (volume 1).* 9. Taylor E. & Wheeler J.: *Spacetime Physics.* 10. Young H.: *University Physics Extended Version with Modern Physics (volume 2).*
B. Books Popularizing Physics
1. Einstein A.: *The theory of Relativity* 2. Epstein L.: *Relativity Visualized.* 3. Feymann R.: *Six not-so-easy Pieces*. 4. Gamow G.: *Mr Tompkins in Paperback.* 5. Landau L. & Rumer Y.: *What is Relativity* 6. Stannard R.: *The time and Space of Uncle Albert.*

3. Results

In the analyzed textbooks, we trace two main approaches. The first one is based on the qualitative approach of the theory, with the mathematical formalism coming afterwards. In the second approach, the theory's mathematical formalism is presented first, through which the basic ideas of the TSR arise.

To be specific, the most characteristic approach (A3, A7, A8, A10) is the following: The Einstein's principle of Relativity (1st axiom) is introduced and analyzed using simple paradigms. Based on this, the invariance of the speed of light (2nd axiom) arises. At this point, Galilean transformations are used in order to specify the problems that arise with the invariance of the speed of light, with historical information being given. The usual topic used is Michelson-Morley experiment and the rejection of the ether at the beginning of the 20th century. Einstein's "train paradox" thought experiment is described afterwards, and the relativity of simultaneity is introduced. Using the same set-up and a light-clock, the relativity of time (time dilation) follows and with the use of simple mathematics the mathematical formula is proven. At the end, the relativity of length (length contraction) is introduced as a consequence, through the use of a thought experiment (observers who measure a length) and the relative mathematical formula is also derived. In A9 we find something slightly different: at the beginning a "parable of the Surveyors" is described and the unity of spacetime is discussed. Afterwards, the same course is followed, but length contraction comes before time dilation.

In textbooks A5 and A6, the theory's historical development and the Michelson-Morley experiment are given at the beginning. Afterwards, the theory's axioms are introduced and time dilation and length contraction arise, using the light-clock without referring to the relativity of simultaneity.

In all of the above textbooks, the chapter of Special Relativity continues with the introduction and the elaboration of Lorentz transformation.

On the contrary, in the textbooks A1, A2 & A4, the elaboration of the TSR begins with the mathematical formalism. In the textbooks A1 and A4 there is no chapter dealing exclusively with the TSR. We find the basic points of the theory in various chapters. In textbook A2, the axioms are introduced in two different chapters, whereas in the chapter titled "Theory of Special Relativity: Lorentz transformation" the theory's consequences are derived from the Lorentz transformation.

A common theme we meet, though, in all textbooks dealing with the TSR in a qualitative way, is the use of one or more thought experiments. The most common one is "Einstein's train paradox", which is used for the elaboration of the relativity of simultaneity as originally introduced (A8, A9, A10), or with small changes not in the procedure but in the set-up –e.g. spaceship (A7) or jet-aircraft (A3) instead of train-. This shows that thought experiments can become important educational tools in order to familiarize secondary school students with physics theories of the 20th century [1]. This becomes crucial especially in relation to secondary students, who are not familiar with complicated mathematics –even when they can apply them, they don't know the idea behind them [2]

The popular science books writers approach the TSR in several ways, considering their time and their public.

Specifically, Feymann's approach (B3) is meant for special readers because he uses instruments which are not familiar to everyone (coordinate systems, mathematical formalism) while also making a number of historical reports.

In B1, Einstein himself approaches the two axioms developing philosophical arguments and giving historical evidence. Afterwards, however, he uses a thought experiment to introduce the relativity of simultaneity where he bases the relativity of time. Using the same example he arrives at the relativity of space.

A similar approach is traced in Landau's & Rumer's (B5) book. The examples they use are much simpler and they deal with the first axiom in a more comprehensible way. They use a thought experiment to show the difficulty that arises with the speed of light. In this way they introduce the 2nd axiom and through the use of the same set-up (train that runs in a relativistic speed), they derive the theory's consequences.

In "Relativity visualized", Epstein follows the historical development of the TSR in order to derive the axioms, including a lot of pictures and simple examples. Afterwards, he presents the consequences using thought experiments which take place in spaceships and which are explained at the end.

This point has been traced also in B4 & B6 where emphasis is laid on the consequences of the theory. Through tales of imagination, written in a very attractive way, the protagonists are transported in places where relativistic effects become obvious. The explanations are given indirectly, but the main point is "what happens" and not "why it happens". This poses the risk of these stories being read as fairy-tales or science fiction and not as scientific texts.

As it is obvious, thought experiments are widely used in science popularizing books as well. They are often limited to a descriptive approach and they do not venture towards scientific explanations, which are important for the introduction of the theory in the typical education.

Taken into consideration the above, the related bibliography [3], [4], [5] and a pilot study for the difficulties students face in basic concepts of the TSR [6], a teaching sequence has been designed for the introduction of the TSR. For this purpose, didactical material was designed, combining and drawing ideas and material from all the above approaches.

The conceptual course we followed was the one we found in most textbooks and which we described in page 2 (qualitative approach of the first axiom – reference to the difficulty that arises with the speed of light and subsequent introduction of the second axiom – combining the two axioms, introduction and elaboration of the theory's consequences: relativity of simultaneity, time dilation, length contraction). At the same time, we put aside the mathematical formalism and the complicated terms used by most of the textbooks. Instead, we utilized the examples and the thought experiments that are introduced in the science popularizing books, retaining the set-up (train which moves in relativistic speed) in order to make the picture simpler to the students. In addition, taking into consideration that the concept of the ether is not familiar to the students, the Michelson-Morley experiment was not included. The same subject (the problem that came up historically when the scientists had to combine the principle of Relativity and Galileo's transformation with the speed of light) was developed using the thought experiment we met in B5.

Another crucial point was to avoid presenting the consequences as odd and strange phenomena, and rather to come up with simple examples and justify them using the two theory's axioms. In this way we tried to overcome the difficulty of students classifying them as distortions of perception [2], [7]. More specifically, the steps we followed in order to deal with the consequences were the following:

- Presenting the thought experiment which takes place in a train of vast size moving with a relativistic speed.
- Students had to explain the thought experiment and its results, using the 2nd axiom.
- They were expected to elaborate the thought experiment by comparing and reversing the role of the observers (the one moves with a uniform speed and the other one is stationary) in order to apply the 1st axiom, and finally,
- they were asked to come to the conclusion.

The teaching sequence we designed consisted of 5 meetings. The research method used for the empirical study was that of *teaching experiment*, through which teaching and learning processes are investigated [8]. The sample was 40 students in the tenth grade, from three schools of Athens, working in groups of 4.

At this point, we analyze the data we gathered

- from the questionnaires students answered individually before and after the procedure (pre- and post-test and follow-up test) and
- from the discourses / interviews which were recorded during the meetings.

4. Conclusions

The results of the study, up to this point, are positive since students seem to be able to grasp the basic ideas of the TSR. They work with the TSR's axioms and they can deal with its consequences. This proves that Special Relativity is a field where thought experiments are valuable didactic tools.

Appendix

Books that were studied

A. Textbooks

1. Alonso M, Finn E. Fundamental University Physics, Volume 1, Mechanics and Thermodynamics. Addison-Wesley Publishing Company, 2nd edition; 1980.
2. Berkeley Physics Course, Mechanics, Volume 1, 2nd edition; 1977.
3. Ford K. Classical and modern Physics, Volume 3. John Wiley and sons, New York; 1974.
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B. Books Popularizing Physics

1. Einstein A. The theory of Relativity.
2. Epstein L. Relativity Visualized. Insight Press; 1985.
3. Feymann, R. Six not-so-easy Pieces. Addison-Wesley; 1995.
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