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Teaching special relativity in high school

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At present the problem of introducing topics of "modern" physics in Italian high school is the object of a wide debate among teachers and researchers in physics education. As regards special relativity, the debate is supported by projects and experimentation carried out since the seventies (Cortini G. 1977, Fabri E. 1989). It seems appropriate to introduce special relativity in high school for the following reasons: cultural value of this theory; possibility of dealing with its basic concepts without a sophisticated mathematic approach and of promoting a deep involvement of students; pedagogical value of experiencing the passage from one scientific theory to a new one, and importance of recognising how a physics theory can be, in particular aspects, in contrast with common sense and every day experience.

Our work is aimed at contributing to this debate with new elements gathered in a teaching experiment with high school students 17-18 years old. The idea of this attempt was suggested by the participation of a group of our physics students to a computer conference on special relativity held in 1990-91. The course, directed by R.C. Smith of West Florida University and supervised by E. Taylor of M.I.T. , was based on a preliminary version of the book "Spacetime - Physics" (Taylor and Wheeler 1992). It was diffused on bitnet and involved 50 students in different universities in USA and Europe. The students of the University of Pavia were particularly interested in the educational aspects of the experience because they were preparing themselves to become high school physics teachers. They had already studied special relativity in an introductory physics course, and at the end of the bitnet course they were convinced that the approach proposed in the mentioned text was attractive and effective in promoting a deep reflection on the topic. It was particularly appreciated that concepts are presented with a number of examples which help students to understand, and that a strong mathematical background is not required. The observation of our students during their work and the dialogue among the participants in the computer conference led us to conclude that the material used in the bitnet course could be a suitable base for introducing special relativity in Italian high school.

Basing on the hypothesis that young students could be very interested in a topic which can both convey new ideas and promote reflection on basic concepts of classical mechanics, we decided to organise the teaching experiment presented here .

METHOD

The students (23 in total) involved in our research are attending the Liceo Scientifico, a high school where physics is taught to all students in the last three years (age of students: 16-19 years). They were exposed to special relativity for two years through the phases listed in Table1, which shows the pattern of the teaching strategy we used.

Table 1

Phase 1. Classical Mechanics - kinematics - Newtonian dynamics - gravitation law **Phase 2. Introduction to relativistic kinematics** - the invariant spacetime interval - Lorentz reference frame - the principles of special relativity **Phase 3. Energy and thermal physics** - Work , kinetic energy and momentum - conservation of energy and of momentum; collisions - heat and temperature - kinetic theory of gases - thermodynamics **Phase 4. Going on with relativistic kinematics** - time stretching and length contraction - Lorentz transformation - spacetime maps; worldline and invariant hyperbola - working with computer simulations **Phase 5. Relativistic dynamics** - momentum, energy and mass - invariance and conservation - collisions **Phase 6. Waves and optics** - elastic waves and their propagation - reflection, refraction, interference and diffraction - Doppler effect - light :reflection, refraction, interference and Doppler effect

Our initial plan was to introduce special relativity at the end of classical dynamics and to carry out its analysis in three years, together with the study of traditional physics topics. But, at the beginning of the second year, due to the encouraging results obtained in the first year, the teacher proposed to complete special relativity in two years in order to devote the third one entirely to electromagnetism which traditionally is the main physics subject in the national examination at the end of high school in Italy. It seemed advantageous that students work on special relativity longer than one year in order to:

- allow them to gradually assimilate concepts very difficult to understand, by making room for clarification and testing procedures;
- favour a connection of special relativity with the other curricular subjects;
- analyse physics under a new perspective;
- present relativistic dynamics when the students have the proper mathematical background (differential calculus is generally introduced at the beginning of the final year of high school);
- substantially enrich the curriculum and provide the students with the opportunity to reconsider topics learned in the previous years.

In our teaching experiment the time devoted to special relativity in the classroom was 18 hours in the first year (22 sessions of 50 minutes each) and about 33 in the second year (40 sessions of 50 minutes each). The work in the classroom was carried out jointly by the teacher (M.T.Viola) and one of the authors (doing her thesis research in the first year and working as a graduate student in the second one).

MATERIAL

The material provided to the students has been prepared starting from the text by Taylor and Wheeler, taking into account the age of the students and their cultural background. A reorganisation of the initial material and a different style of exposition were necessary: for instance, the Lorentz transformation was anticipated and completed by means of software (Berman & Taylor 1988, Horwitz 1990, Bergomi et al. 1990), and the use of a conversational style was gradually reduced. Relativistic dynamics has been presented by taking advantage also of the approach suggested by E. Fabri of the University of Pisa - Italy (Fabri E. 1989). The material prepared for the students contains:

- a guide which presents special relativity;

- worksheets to be used in the classroom as a complement to the theory and as guide to problem solving;
- worksheets for homework;
- worksheet for the assessment;
- guidelines for the use of “Spacetime” software and suggestions on exercises to be done with the help of software.

THE STUDY

In the work carried out with students, special relativity is presented from the point of view of a contemporary physicist who can resort to experimental evidences and rely on this theory as an important tool for his/her research. This choice implies that, at the very beginning, the historical development of the theory will be neglected, but it offers the possibility of focusing immediately on the core of the problem, even with students who have not yet studied electromagnetism. The approach is grounded on spacetime interval and Lorentz geometry. The idea is to combine this approach to a wide use of experimental references. We tried to stress this aspect as our students showed interest in going deep on crucial points as, for example, measurement of time in frames of reference in relative motion, life time of radioactive particles, etc.

The first year of the teaching experiment

As Table 1 shows, the students were introduced to special relativity after the study of kinematics and part of dynamics. They immediately showed interest in the subject and deep involvement in taking part to a challenging learning experiment. The first impact with the "Parable of the surveyors", proposed in Taylor and Wheeler's book, greatly surprised our students: resorting to a story to present concepts is a definitely unusual approach for Italian physics textbooks. We think that this initial surprise was effective in introducing the topic and suggesting to students the need to enter a new environment. On the other hand we decided to limit this style at the initial phase of the work, gradually abandoning it in the written material we prepared. The students appeared comfortable (well over our expectations) with the invariant spacetime interval and the use of the same unit for time and space. On the contrary, at the very beginning of their work students met difficulties in visualising the motion of an object in different frames of reference and in understanding how observations made by different observers are related, as reported in the literature (Saltiel and Malgrange 1980, Whitaker 1983, Mac Dermott 1984, Borghi et al. 1991). To tackle this problem we provided students with different resources, as specific exercises (Horwitz 1992) and the PSSC film "Frames of reference" (narrated by Hume and Ivey of the University of Toronto). This material favoured discussions and led students to recognise that the preferential use of the Lab reference, common also to a number of textbooks, is unjustified. Students' knowledge of classical mechanics played an important role in enabling them to master the concept of free-float frame of reference and it was enhanced by reflections about systems in free fall motion together with discussions on the local character of free-float frames of reference. This last point made it necessary to refer to experimental situations, to consider the problem of the accuracy of measurements, and the number of figures in experimental data, and fostered in students a deepening of their knowledge on these important subjects. It seemed very effective to introduce a latticework of rods and clocks, to clarify how the clocks can be synchronised, and to distinguish between observer and system of reference: this distinction was essential to grasp the relativity of simultaneity. The relativity of simultaneity was introduced starting from Einstein's Train Paradox, which fostered a debate among students about its consequences, in particular the Lorentz contraction of length. Finally the invariance of spacetime interval was derived from the principle of relativity by analysing an example. The students have been involved in a highly autonomous work with a number of exercises, homework, and collective discussions in the classroom, where they often revealed intuition of ideas which we had planned to develop later. Their questions sometime modified our initial plans and suggested to consider new points of view.

Testing has been carried out in three phases: an initial test after 2 weeks of work, a second test after 3 weeks and a test at the end after 5 weeks; each test contained exercises and quizzes. Finally the students were invited to express their feelings about the course. This type of assessment for physics is unusual in Italian school where oral questioning, based on exposition of the theory, is preferred. The students reacted positively:

perhaps they were confirmed in the perception of a new learning experience. Fig. 1 shows the score obtained at the end of the first term, in which classical mechanics was studied, the score in each test on special relativity and the final score in physics. Maximum score is 9; marks under 6 express an insufficient result.

Test scores and final results in the first year					
Student	**IE**	**IT**	**IIT**	**IIIT**	**FE**
Guido A.	6	7	5	7.5	7
Ferdinando A.	5	5	5	5	6
Chiara B.	6	7.7	A	7.5	7
Claudia B.	5	6.7	5	6	6
Gianbattista C.	7	6.5	6	8.5	8
Alessandro C.	7	7.5	6.5	8	8
Francesca C.	6	5	5	7	7
Andrea D.	5	6,5	5	6.3	6
Paolo D. M.	6	6	6.3	7	7
Giacomo G.	7	A	7	9	9
Stefano L.	6	6.7	6	A	6
Valeria L.	6	7.3	A	8	7
Stefano L.	5	7.5	6	8	7
Federica P.	7	7.5	6	7	7
Luca R.	5	7.5	6.7	5	6
Benedetto S.	6	7.5	6.7	7	7
Federica S.	4	5	6.3	5	6
Ulisse S.	8	7.5	9	9	9
Luca T.	4	5	5	5	5
Cristina T.	6	6.5	5	7	7
Luca T.	5	5	5	A	6
Umberto Z.	4	5	6.3	5	5
Andrea Z.	4	5	A	6.5	6

Symbols:
IE= 1° term evaluation; FE= Final Evaluation; T=test; A=absent

Fig. 1

In order to show how the students appreciated special relativity it is enough to mention one of their responses to the final test. At the question concerning their interest in the course 77 % of them chose the first of the following answers: *A lot - Enough - A little - Not at all*.
The others chose the second one.

The second year of the teaching experiment

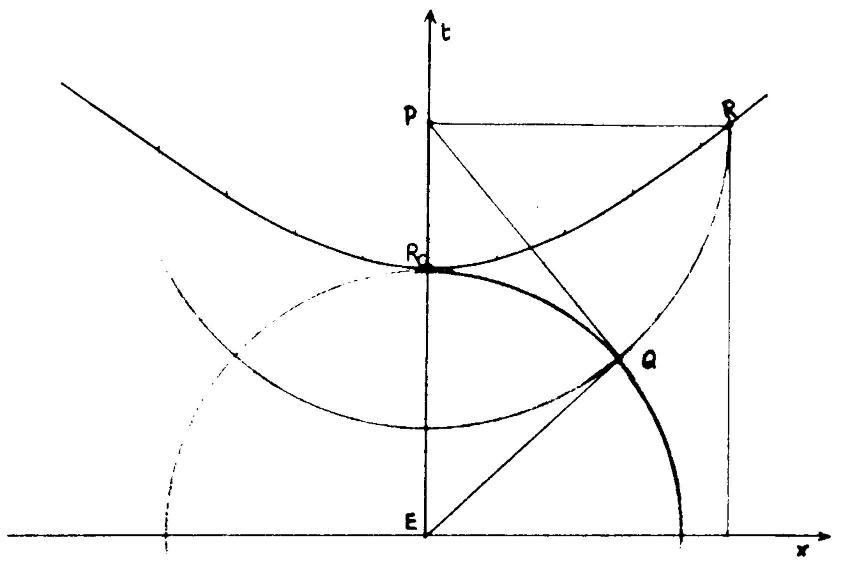
The work in the second year has been carried out in a similar way as in the first one. The interest of students for each experiment designed to confirm the special relativity theory was high as in the first year: for example, modern experiments with atomic clocks were considered in detail, starting from the suggestion of Taylor and resorting to papers by Hafele and Keating (Hafele and Keating 1972). Students' questions revealed, in different contexts, the need to reconsider the idea of relativity of simultaneity and to anchor this idea to experimental data, like the desyncronization of clocks in different frames of reference. In order to help students reflect on the relativity of simultaneity, we supplied them with a computer program on muon decay which contains a visualisation of the train paradox (Bergomi et al. 1990). The formal tool offered by the Lorentz Transformation did not seem to thoroughly satisfy their request of understanding. It was a surprise to us their limited interest in the Lorentz Transformation: they were, in fact, expected to be comfortable with this tool because of their familiarity with mathematics and formal descriptions. As in the first year, during the discussion of homework we noticed that they autonomously anticipated concepts and often forced us to deal with ideas we had not planned to consider: this is the case, for example, of the light cone and space-like interval. They appeared particularly interested in comparing intervals of a different kind. The students spontaneously inquired about the existence of an inertial frame of reference in which two space-like events, with a time separation Δt in the Lab reference, were simultaneus and they asked to find the velocity of this reference relative to the laboratory. The importance of graphical representation appeared evident in favouring the understanding of special relativity. Since the very beginning students tended to use in the new context skills acquired in the study of classical kinematics and some of them proposed to represent events in a diagram x,t much earlier than we had planned to do. This attitude paved the way to introducing the world line and favoured its use to reconsider situations and problems previously examined, as for example the twin paradox. A proof of the high involvement of our students is the fact that one of them (Giacomo Gorni) produced an original representation of the invariance of the spacetime interval, based on geometry. The student's work is represented in Figure 2.

The interest of our students for the relativistic dynamics appeared to be very high: perhaps it was stimulated also by their plan to visit the CERN at Geneve.

As already mentioned, we decided to present relativistic dynamics by referring also to the approach proposed by Fabri, i.e. to introduce momentum and energy without defining the momenergy 4-vector.

Two events E and R are considered: E is taken as reference event, i. e.as the origin of overlapping inertial frames of reference. We know that the spacetime interval between E and R is an invariant; This invariance can be graphically expressed.

In the reference frame where the events E and R have the same spatial coordinate the time separation is equal to proper time τ , i.e. $\Delta t = \tau = I$ (event R is called R_0 in this frame).



We can draw the invariant hyperbole for the event R and the circle γ (centre E, radius I) and γ' (centre P, radius PR); γ and γ' have an intersection at Q (because PR<PE).

We know that $PQ = PR = x_R$ and $PE = t_R$

Since R is on the hyperbole $t_R^2 - x_R^2 = I^2$ or $t_R^2 = I^2 + x_R^2$ which expresses the Pythagorean Theorem for the triangle PQE. This representation allows to visualise the invariant interval resorting to Euclidean geometry.

Fig.2

In order to present these quantities the teacher chose to modify the mathematics curriculum by anticipating basic elements of calculus, in particular limits and derivatives, which are normally introduced in the final year of Liceo. The students' reaction was positive and the connection between mathematics and physics seemed effective, with great satisfaction of the teacher.

It is worthwhile to mention here the difficulties we noticed in our students. A number of them had problems with abandoning the idea (present in textbooks and newspapers) that the mass of a particle varies with its velocity and distinguishing between the invariant mass and the energy depending on the frame of reference. They were also surprised to discover that, according to the relativistic definition of mass, energy and momentum, the relation between system mass and mass of parts is not additive. To clarify this point the students expressed the desire to consider additional examples of collisions and to insist with examples from relativistic dynamics: time constraints forced the teacher to limit the time devoted to this part to 7 hours.

Testing has been carried out in five phases: an initial test after 3 weeks of work, the second after 4 weeks, the third after 5 weeks, the fourth before starting relativistic dynamics, the fifth on relativistic dynamics. We decided to administrate students a test (the fourth one) on classic mechanics, resorting to questions culled from literature (Fusco et al. 1981) to see if the students involved in special relativity could reach good results in the other physics subjects of the curriculum. Results of this test seem to reveal that the long time devoted to special relativity did not prevent students to gain a good knowledge of other subjects (see column cmT in Fig. 2).

Fig. 3 shows the score obtained in each test on special relativity, and the final score in physics.

Test scores and final results in the second year						
Student	**IT**	**IIT**	**IIIT**	**cmT**	**VT**	**FE**
Guido A.	4.3	6.5	A	7.1	6	6
Ferdinando A.	4.1	5.8	4.3	6	5.8	6
Chiara B.	A	7	6.5	9.1	6.3	6
Claudia B.	4.7	A	5.8	9.5	5	6
Gianbattista C.	5	7.7	7.5	8.2	A	7
Alessandro C.	8	8.2	7.4	9.5	6.5	8
Francesca C.	6.2	4.6	4.8	8.4	6.5	6
Andrea D.	5.8	5.3	6.2	9.5	6	6
Paolo D. M.	7	7	6.2	6.3	5	6
Giacomo G.	6	8.3	7.6	7.9	A	8
Stefano Li.	6.3	6.6	4.9	10	5.7	6
Valeria L.	A	6.9	5.9	8.5	A	6
Stefano Lo.	A	6.6	7.1	8.8	6.3	6
Federica P.	6	8.3	7.4	6	7.9	7
Luca R.	5.7	6.2	6.9	9	6.5	6
Benedetto S.	5.8	A	7.8	8.5	7.5	8
Federica S.	5.2	6	4.4	5.2	5.6	6
Gavino S.	6	5.9	6.7	6	4	6
Ulisse S.	9	7.5	9	9.8	8	8
Cristina T.	6,5	7	5.8	9.8	6.7	7
Luca T.	7	7.7	5.6	8.5	6	6

Symbols:
A=absent;T=test; cmT=Test on classic mechanics; FE=Final Evaluation

Fig. 3

At the end of the work with special relativity we administrated the students a questionnaire, containing 18 items, to test their feelings, as we had done at the end of the first year of our teaching experiment. High interest in special relativity was again confirmed and the idea that this subject deeply influenced their vision of reality was expressed by the majority of students (75%). A percentage of 41% considered relativistic dynamics to be the most difficult part in the study of special relativity. At the question "If you were given the possibility to repeat this learning experience would you like to repeat it?" all the students answered positively.

CONCLUSIONS

The co-operation between the teacher and the researcher in presenting special relativity created a good environment, favoured an active participation of students, provided opportunity of useful suggestions, and greatly contributed to the success of the teaching experiment. The good results of our experiment seem to suggest that, by following Taylor and Wheeler's approach, it is possible to introduce special relativity in high school before starting the study of electromagnetism. A crucial problem is the training of teachers: in our case in fact the teacher was a very good one. She is an experienced teacher whose main interest, due to her background, had always been in mathematics. In this teaching experience she realised how essential it is for students to work in problem solving activities and to discuss their results and ideas in the classroom. She obtained a direct and deep involvement of the students despite the lack of a lab activity, which generally complements the study of other physics topics. She expressed the conviction that the experience with special relativity will substantially modify her way of teaching physics and the role she will assign to exercises.

REFERENCES

Bergomi N., Cantoni M., Vegni G. 1990, Scoperta e decadimento del muone - Relatività Ristretta. SIF, Bologna.
Berman E., Taylor E.F. 1988, Highway and Spacetime Diagram Programs, Spacetime Software, Belmont, MA 02178
Borghi L., DeAmbrosis A.,Gazzaniga G., Ironi L., Mascheretti P. and Massara C.I. 1991, Practical use of simulations to study relative motion. Computers Educ. vol. 16, n.2, 157 R

Cortini G. 1977, Vedute recenti sull'insegnamento della relatività ristretta. Quaderni del Giornale di Fisica, vol.II, n.4, 13
Fabri E. 1989, Per un insegnamento moderno della relatività, A.I.F., sezioni di Lucca e Pisa
Fusco C., Segrè G., Sperandeo R.M. and Tomasini N. 1981, I test di profitto costruiti per l'Iniziativa Relatività. Quaderni del Giornale di Fisica vol.4, 21
Hafele J.C. and Keating R.E. 1972 Around-the-World Atomic Clocks: Observed Relativistic Time Gains. Science, vol.177, 168
Hafele J.C. and Keating R.E. 1972, Around-the-World Atomic Clocks: Predicted Relativistic Time Gains. Science, vol.177, 166
Horwitz P. - Feurzeig W. 1992, RelLab, Bolt Beranek and Newman Inc., Cambridge, MA
McDermott L.C. 1984, Research on conceptual understanding in mechanics. Phys. Today 24
Saltiel E. and MelgrangeL. 1980, Spontaneous ways of reasoning in elementary kinematics. Eur. J. Phys. 1, 73
Taylor E.F.- Wheeler J.A. 1992, SPACETIME - Introduction to Special Relativity; second edition, Freeman & Co., New York.
Whitaker R.J. 1983, Aristotle is not dead: student understanding of trajectory motion. Am. J. Phys. 51, 352