# COMPARATIVE TEACHING STRATEGIES IN SPECIAL RELATIVITY

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ABSTRACT
The introduction of modern physics topics in secondary schools is one of the highest challenges in physics education. In this regard, a specific exercise has been carried out in the context of a dedicated Summer School involving both teachers with a Master in Education and secondary school students previously acquainted with these teachers. In the case of enlightening and overcoming conceptual and learning problems – with a deep insight to concepts and terms in contrast with common sense and everyday experience – a dedicated analysis of two different curricular proposals is outlined, showing possible weaknesses and strengths in both teaching frameworks and approaches.

KEY WORDS
conceptual knots, learning problems, modern physics, common sense, physics teachers, physics students, curricular proposals, secondary school

## INTRODUCTION

*The only thing that interferes with my learning is my education*
A. Einstein

The problem of introducing topics of modern physics in secondary schools is one of the highest challenges in science education. As regards special relativity, debate among teachers and researches is supported by projects and experimentation carried out for many years (Bergia, 1990, 1995, 2005; Borghi, 1993; Cortini, 1977; Fabri, 1989). Many reasons combine to make special relativity an appropriate subject to be addressed in high school: the cultural relevance of the theory; the pedagogical value of experiencing the assimilation of new concepts and relations and generalization of their use, the focus on the contrast between physics theories and common sense, the intense involvement and curiosity of students.

However, while holding a certain fascination for many people, the theory of relativity is often regarded as difficult to understand because of its high degree of abstraction and the contradiction of relativistic effects with everyday experience. Specifically, a large body of findings shows that prior knowledge remarkably influences the science learning processes, despite educators' best efforts to deliver ideas accurately (Hewson, 1982; Roschelle, 1995; Scherr, 2006). Well-documented studies show that students interpret certain concepts and results more successfully by following a spontaneous frame of thinking, rather than through accepting paradigms of the theory of relativity (Hewson, 1982): for instance, distance contraction and time dilation are interpreted as apparent effects resulting from perception, and light-speed value is more commonly related to the property of insuperability than of invariance.

In the realm of constructivism, learning processes can be divided into two phases (Orquiza and Villani, 1994): assimilation of new concepts and relations and generalization of their use (Villani and Arruda, 1998). According to this picture, the learning process does not simply occur by knowledge accumulation, but through the substitution of old ideas with new ones (similar to the transition from common sense experience to Newtonian physics), or with the subsumption of conceptual schemes within more extended frameworks (such as the conceptual change between classical and modern physics) (Berenguer, 2000; Hewson, 1981, 1982; Posner and al., 1982).

Indeed, all of these factors contribute to make the understanding and assimilation of concepts of the theory of relativity troublesome. In particular:

- students are reluctant to abandon their own spontaneous common sense conceptions in favour of those involved in physics' special relativity (Hewson, 1982, Villani and Arruda, 1998);
- they have difficulty considering new ideas as more general conceptual schemes, comprising the old picture as a particular situation (Berenguer, 2000; Hewson, 1981, 1982; Posner and al., 1982);
- they are not aware of the 4-dimentional texture of space-time (Berenguer, 2000);
- they do not distinguish between acceptance of an ultimate speed and the invariable speed of light (Villani and Arruda, 1998);
- different interpretations of the same quantity properties (i.e. invariance) or physical phenomena (i.e. simultaneity or causality) in the two frameworks – classical and relativistic – are not properly linked with the postulates of special relativity (Berenguer, 2000).

Many investigational efforts have been directed toward singling out proper curricular patterns to address the task of overcoming these conceptual difficulties or boundaries. Some authors concentrate on the content of educational proposals (De Ambrosis and Levrini, 2007; Levrini and di Sessa, 2008), while other studies address the problem of developing the best teaching strategy. Furthermore, many people claim that the historical process of acceptance of a new theory can provide a number of considerations and hints about how best to teach the theory, as well as how to interpret its learning (Matthews, 1989, 1994; Piaget and Garcia, 1982; Saltiel and Viennot, 1984; Villani and Arruda, 1998).

The present work is aimed at characterizing strengths or weaknesses in different educational methods in special relativity, in the light of the learning problems outlined above. Our main research question is the role of strategy in developing specific competences during a teaching/learning path experimentation: how and which specific strategies are able to improve reasoning on topical situations and to influence students' way of thinking to be more coherent with physics' interpretative models? We may reasonably expect that specific strategies will serve better than others with regard to particular aspects, and that a comprehensive and successful approach to the question may be achieved through the implementation of diverse and complementary material sets and procedures.

## CONTEXT

This research is based on a joint project involving both teachers trained in a Master in Modern Physics Education and secondary school students previously acquainted with these teachers, who took part in a dedicated Summer School.

### The IDIFO Master (Innovation in Didactic of Physics and Orientation)

In the framework of a national project aimed at promoting academic scientific studies (Scientific Degree Project – "Progetto Lauree Scientifiche", or PLS), Physics Education Research Groups of Italian Universities worked together to design and implement a Master in Didactic Innovation in Physics and Orientation (IDIFO). The course, a two year-project presented by the University of Udine, comprised 600 hours of didactic activity from March 2006 to June 2008, both on campus and via a dedicated e-learning platform (http://www.fisica.uniud.it/URDF/laurea/index.htm and http://idifo.fisica.uniud.it). The main target was teacher training in themes of modern physics – quantum mechanics, relativity, statistical and solid state physics – in the light of international research in physics education carried out by the 9 research units involved in the project and supported by 6 other universities. Particular attention was given to the improvement of teachers' competence in planning paths and curricular materials in the light of physics education research, and the implementation of their products in real classes, looking at learning processes in an action research perspective. Care was taken to provide operative learning contexts, discussions of professional aspects and to create intervention competences – for example concerning experiments in crucial problems of twentieth century physics, research data analysis techniques, computer modelling and simulations – as well as to perfect training proposals based on problem-solving for orientation (PSO) and individual group discussions of teaching/learning proposals.

**The Secondary Summer School in Modern Physics**

In the framework of IDIFO Master, in July 2007 the Department of Physics of Udine University organized a Summer School in Modern Physics attended by 40 secondary school students in their final two years of study who had the best marks at a national level; 15 places were reserved for the students of teachers participating in the formative Master.

Two very different strategies planned by teachers participating in the IDIFO Master, with the same content concerning special relativity, were selected and offered to students participating in the Summer School in Modern Physics by the teachers involved. For this task, the teaching/learning processes of these two experimentations were monitored, analysed and compared. The two teachers – selected from the highly cultured and professionally skilled participants in the IDIFO Master – were trained in the same way by the same researchers in physics education and relativity (S. Bergia, A. De Ambrosis, O. Levrini). Both used PEC (Prevision-Explore-Comparison) teaching strategies, within the framework of a constructivist theoretical approach. They proposed very different curricular patterns which addressed the same learning problems. In particular, one of the two focused on mathematical aspects, creating a formal and structured path and providing an analytical description of phenomena, while the other followed a more empirical approach to the problem, proposing different practical and experimental activities also based upon peer-teaching active strategies, and emphasizing the role of historical mistakes in the progress of scientific knowledge (*learning by conceptual change,* Villani and Arruda, 1998).

The main contents, purposes and strategies of the two curricular proposals are outlined in Table 1.

## RESEARCH QUESTIONS AND METHODS

In order to characterize the two curricular approaches by means of effectiveness of content and strategy choices concerning relativity understanding and learning, we prepared a set of questions focused on the main conceptual knots listed above. Students of both classes at the end of the Summer School were asked to answer a questionnaire with intermediate characteristics between a cognitive exploration and a conceptual elaboration. Questions cover the most relevant aspects of the theory, require both analytical reasoning and empirical deduction by means of mental experiments, and take into consideration the potentiality of a learning approach based on historical instances (Table 2). In particular, we considered questions involving elements belonging to both *situation* and *synthesis* contexts. The subjects were 40 secondary school students in their final two years of study, divided into classes of 21 and 19 – respectively.

## DATA ANALYSIS

In order to understand how the two different strategies and the curricular paths summarized in Table 1 influenced student reasoning and learning, we analyzed students' questionnaire responses considering answer structure in terms of correctness, completeness and coherence of internal elements – whether the right picture was associated with the right concepts and ideas, and in terms of correlations between the disciplinary elements involved.

**Methods**

Data analysis has been carried out on the following two levels:

- *Analysis of single concepts and their mutual correlations.* Focusing on the main learning problems of students (conditioning by previous conceptions, turning points between classical and modern theories, special relativity postulates – see above), we singled out concepts relevant to an understanding of special relativity (light-speed: *c* as an ultimate velocity, constancy of *c*, invariance of *c*; *space-time:* space and time as a unique quantity, 4-dimensional texture of space-time, concept of event; *frame system transformations:* crossing from Galileo to Lorentz transformations, inertial frame system; *common sense and paradoxes;* comparison between classical and modern theories regarding concepts of *simultaneity* and *causality*) and we estimated the evocative power associated with each question. Moreover, for those concepts common to more than one question, we calculated correlation factors between responses of students to each pair of answers, giving an indication of out-of-context understanding.

- *Analysis of answer elements.* We compared students' answers with correct and complete ones, and built exclusive categories by combining single blocks composing any answer into exclusive categories (we considered all possible combinations). On this basis, we provided evidence of a measure of the learning process as belonging to specific answer categories, i.e. either poor of content or exhaustive.

Table 1. Curricular proposals of the two teachers involved in the Summer School in Modern Physics at Udine University (2007).

| **Characteristic of the experimented paths** | **teacher 1** | **teacher 2** |
|---|---|---|
| | *SPACE-TIME EVENTS AND REFERENCE FRAME TRANSFORMATIONS* | *A PATTERN ON RELATIVITY BASED ON SIMPLE EXPERIMENTS* |
| *subject contents* | *a)* mathematical formulation and graphical representation of basic concepts and laws of special relativity;<br>*b)* inductive method;<br>*c)* resort to formulas and analytical inference to discuss main effects of Lorentz transformations;<br>*d)* graphical illustration of the difference between Galileo and Lorentz transformations;<br>*e)* discussion of paradoxes by means of dynamical representation in a space-time diagram;<br>*f)* numerical simulations of ideal experiments. | *a)* historical picture;<br>*b)* intuition of concepts and laws by empirical approach;<br>*c)* logical deduction;<br>*d)* analytical concepts by illustration;<br>*e)* electromagnetic waves;<br>*f)* geometrical maps on interval representation;<br>*g)* experiments (1 – measurement of the speed of an electromagnetic signal in a coaxial cave, 2 – Michelson-Morley interferometer experiment by means of microwaves, 3 – relationship between time and distance in observation of sky, 4 – conventional versus mass units). |

| | | |
|---|---|---|
| *goals and purposes* | *a)* understanding key concepts by reciprocal comparison (i.e., difference between space-time events and phenomena, coordinate and frame systems, constancy and invariance of a physical quantity);<br>*b)* deriving main relativistic effects by direct resort and elaboration of key concepts;<br>*c)* pointing out elements of reciprocity in descriptions of two frame systems in relative motion. | *a)* understanding of meaning and implications of terms and definitions, in the context of epistemological value of Einstein's reasoning. |
| *conceptual knots* | *a)* difference among concepts of 'constant', 'invariant' and 'conserved';<br>*b)* frame transformations in space-time;<br>*c)* role of maximum light-speed in the framework of special relativity;<br>*d)* reciprocity of observations in two systems in relative motion;<br>*e)* link between classical and relativistic kinematics. | *a)* light-speed properties: maximum value, constancy, finiteness, isotropy, role of conversion factor between measure units;<br>*b)* light-speed as the speed propagating information;<br>*c)* link between classical and relativistic kinematics. |
| *educational strategy* | *a)* income and outcome tests;<br>*b)* frontal and dialogic lessons;<br>*c)* student cards;<br>*d)* computer simulations;<br>*e)* working groups;<br>*f)* focus on students' motivation. | *a)* income and outcome tests;<br>*b)* dialogical discussion;<br>*c)* laboratory experiments;<br>*d)* focus on students' motivation. |
| *Prerequisites* | *a)* analytical geometry;<br>*b)* axis transformations;<br>*c)* classical kinematics. | – |

Table 2. End-of-course questionnaire presented to Summer School students.

**QUESTIONS**

*$Q_1$* The theory of special relativity has been formulated to solve the conflict between Newton and Maxwell's pictures. Precisely, Newtonian mechanics attempted to explain body movements at ordinary speed, while Maxwell looked at phenomena at the highest known velocities. This situation is well described by Einstein's words: "...a paradox impressed me already when I was sixteen. If I could run after a light-ray moving at the light-speed in the vacuum *c*, I should observe the light as an electromagnetic field oscillating in space – but at rest in time, i.e. not propagating. But nothing of the sort seems to exist, on the grounds of experience or according to Maxwell's equations." Where does the conflict arise?

*$Q_2$* (a) In which way does the principle of relativity, reformulated by Einstein's theory, reconsider the concept of physical law? (b) What does it mean when we say "a physical quantity is an invariant"? (c) What does it mean when we say "a physical law is covariant"?

*$Q_3$* Consider the motion of a ball inside a train, moving as regards a still observer. Repeat this conceptual experiment looking no more at a ball, but at a photon. The framework looks completely different. What implications are involved regarding the concepts of space and time?

*$Q_4$* Consider the physical relationship of wave propagation: $v = \lambda\nu$, (where v is a speed, $\lambda$ is a wavelength and $\nu$ is a frequency) and apply it to these two different situations: $v << c$ and $v \lesssim c$. (a) Which quantities may be considered constant in the respective cases? (b) What consequences are produced upon space and time by constancy of light-speed?

*$Q_5$* Is it possible that physical phenomena occurring at a speed comparable with light-speed in a vacuum may cause some paradox inside inertial frames?

*$Q_6$* Lorentz and Galileo transformations seem to be physical laws that are completely different from one another. Is it true? Make comments in your answer.

*$Q_7$* What are the differences between concepts of events' simultaneity in classical and relativistic frameworks?

*$Q_8$* The interval between two events is defined as:
$ds^2 = (c\,dt)^2 - dx^2 - dy^2 - dz^2$,
where $t$ is time, $(x,y,z)$ are spatial coordinates and $c$ is light-speed in a vacuum.
(a) What does it mean when we say "two events are causally connected"? Link your answer with concepts of "*time* interval ($ds^2 > 0$)", "*space* interval ($ds^2 < 0$)", "*light* interval ($ds^2 = 0$)".
(b) How does light-speed ground discourses on causality?
*Hint:* in order to establish a causal relationship between subsequent events, information about the first must somehow be communicated to the other.

*$Q_9$* How can you explain the sensation of being plunged into a 4-dimensional space-time with your ordinary experience of a 3-dimensional world?
*Hint:* Formulate the same question to an ant, lying on a 2-dimensional sphere surface, and extend expected answer to your own situation.

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## RESULTS AND DISCUSSION

Average performance with respect to single questions within the two classes is reported in Table 3. Values in the fourth and fifth columns respectively account for the total amount of single concepts for any question in each class (percentages are calculated counting the elements present in each report, with respect to all concepts singled out as relevant to understanding special relativity, as listed above). As we can easily see, the more rigorous and formal teaching style provides a richer picture for almost all questions. For instance, representative answers to question $Q_3$ were respectively in the two classes: "*In the classical case of the ball moving inside the train, the motion relative to the observer-at-rest can be deduced by the law of composition of velocities, that is grounded on absoluteness of space and time in the two reference systems of the train and the station respectively. The invariance of the speed of light leads to new consequences when describing a photon's motion: as its speed is the same in the two reference systems in relative motion, this necessarily implies a difference between the spatial and temporal distances in the two frames. Space and time therefore become relative to the reference frame*" (class 1) versus "*Space and time are no more absolute and independent things, but entities connected together in the "space-time". They are relative to the reference frame*" (class 2). Similarly, for question $Q_7$: "*Events that, in the same point of space, are simultaneous for a given observer, are simultaneous also for any other observer moving uniformly with respect to him. Events that, in different points of space, are simultaneous for a given observer, are not generally simultaneous for other observers in uniform motion with respect to him*" versus "*Two simultaneous classical events are always* *simultaneous, while two simultaneous relativistic events are not always simultaneous because their simultaneity depends on the reference frame*".

However variances are always of the order of mean values, i.e. completeness is not accompanied by corresponding uniformity among pupils' distribution; whereas average performance with respect to single questions does not serve as a valid measure of learning, we observe that this is only one way we can infer this kind of information. Table 3 provides a picture of the evocative power associated with each question. It appears that answer context quality (i.e. *situation* versus *synthesis* context) does not influence the number of mentioned concepts. Nevertheless, *a certain high coherence results if we recognize the most evocative answers as those required to overcome conceptual boundaries between classical and relativistic descriptions, meaning that a turning point between different pictures would produce a wider use of concepts and elements.*

The manner in which key-concepts linked to main conceptual knots and boundaries are tackled in different questions is shown in Figure 1. Self-standing concepts such as *light-speed 'invariance'* or *space-time connection* are generally better solved when associated with *situation* questions and appear to be more congenial to students of class 1, where the teaching strategy was focused more on detailed definitions of particular elements than on the general picture, such as that emerging through an empirical approach. Nevertheless, when dealing with more general concepts – where difficulty arose in determining results through extrapolation from the context – we find that both *synthesis* questions are more evocative, and that an empirical-global teaching style is more effective. This is shown, for instance, in the lower panels of Figure 1, which reports results relative to reference frame transformations.

Table 3. Average performance success with respect to single questions.

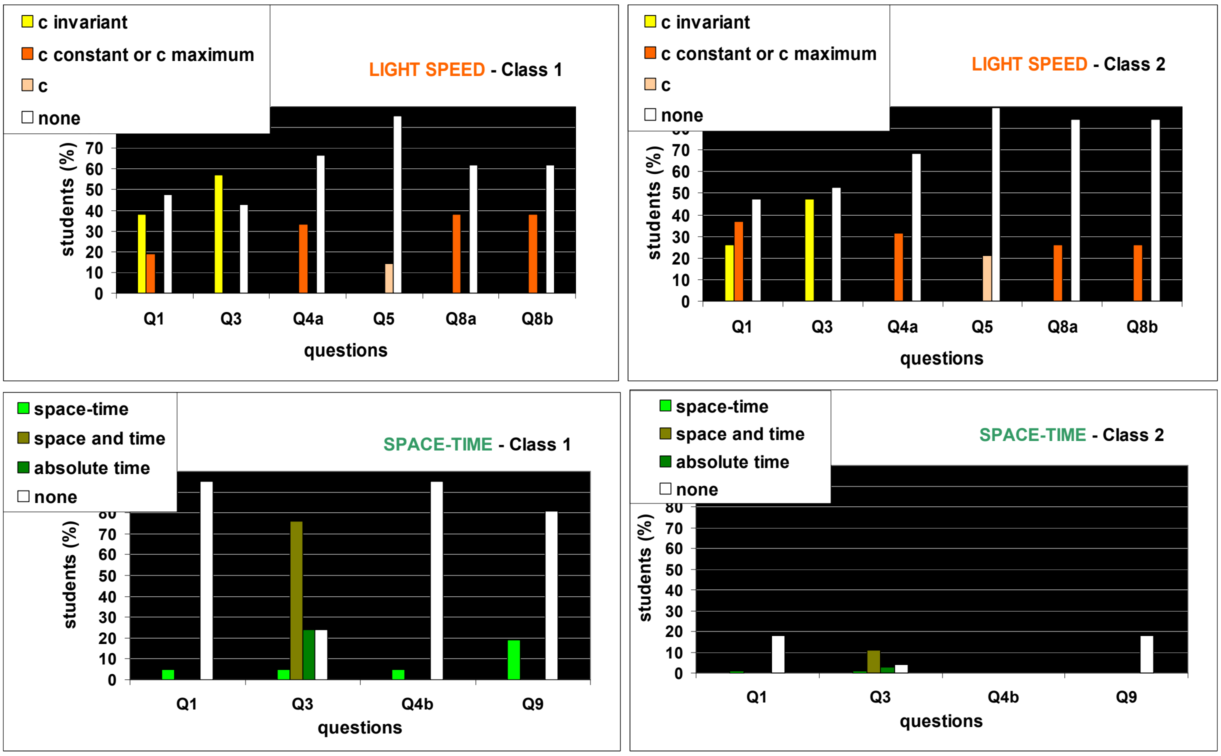
| *Questions* | *context quality* | *classical ÷ relativistic turning* | **Teacher 1** | **Teacher 2** |
|---|---|---|---|---|
| | | | *Average* | *Average* |
| $Q_1$ | synthesis | | *17,3%* | *13,1 %* |
| $Q_2a$ | synthesis | | *9,5 %* | *18 %* |
| $Q_2b$ | synthesis | | – | – |
| $Q_2c$ | synthesis | | – | – |
| $Q_3$ | situation | X | *33,3 %* | *28,8 %* |
| $Q_4a$ | situation | X | *33 %* | *31 %* |
| $Q_4b$ | synthesis | | *23,5 %* | *26 %* |
| $Q_5$ | synthesis | | *21 %* | *19,4 %* |
| $Q_6$ | situation | | – | – |
| $Q_7$ | synthesis | X | *45,4 %* | *37,2 %* |
| $Q_8a$ | situation | | *29,3 %* | *11,3 %* |
| $Q_8b$ | synthesis | | *35,5 %* | *15,5 %* |
| $Q_9$ | synthesis | X | *32,5 %* | *26,1 %* |

Table 4 reports a correlation in results between pairs of questions of different kinds, for those concepts better solved in the questionnaire. *A high degree of correlation for a large number of question pairs is indicative of out-of-context understanding, a result reinforced by separate distributions for each class.*

Table 4. Correlation probability between pairs of questions.

| | correlation probability |
|---|---|
| *invariance of c* | |
| $Q_1 - Q_3$ | > 90 % |
| *space-time* | |
| $Q_1 - Q_3$ | > 95 % |
| $Q_1 - Q_4b$ | > 95 % |
| *Lorentz transformations* | |
| $Q_3 - Q_4b$ | > 90 % |
| $Q_4b - Q_7$ | > 99 % |

*If analysis of concepts and their mutual correlations provides detailed information on single element understanding, to test the level of re-elaboration and developing of ideas into a global picture, we need to look at the degree of completeness and coherence in terms of the different parts that comprise a correct answer.* A selection of results is shown in Figure 2. We find that there is a certain tendency for students of class 1 to give better answers when dealing with *situation* questions (such as $Q_3$ and $Q_6$), while students belonging to class 2 are more skilled regarding *synthesis* situations ($Q_1$, $Q_4$b and $Q_9$ in the figure).



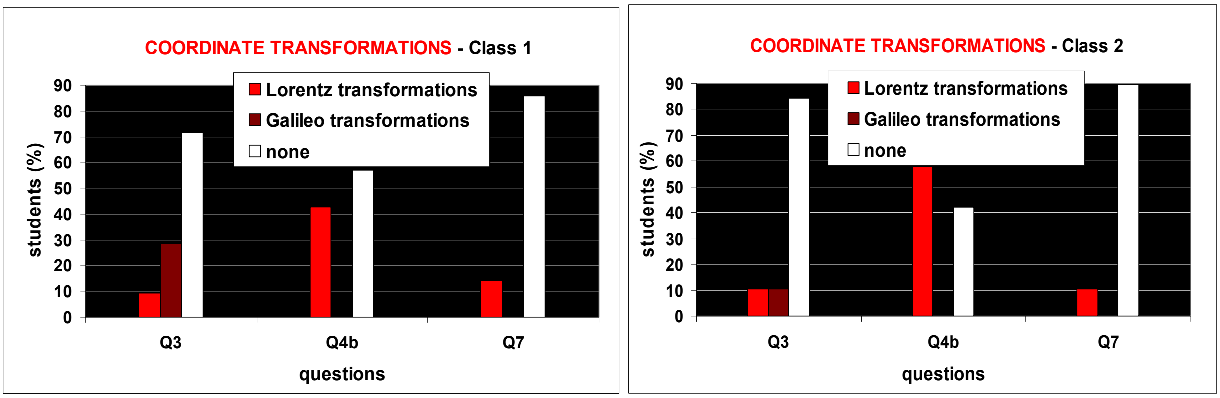
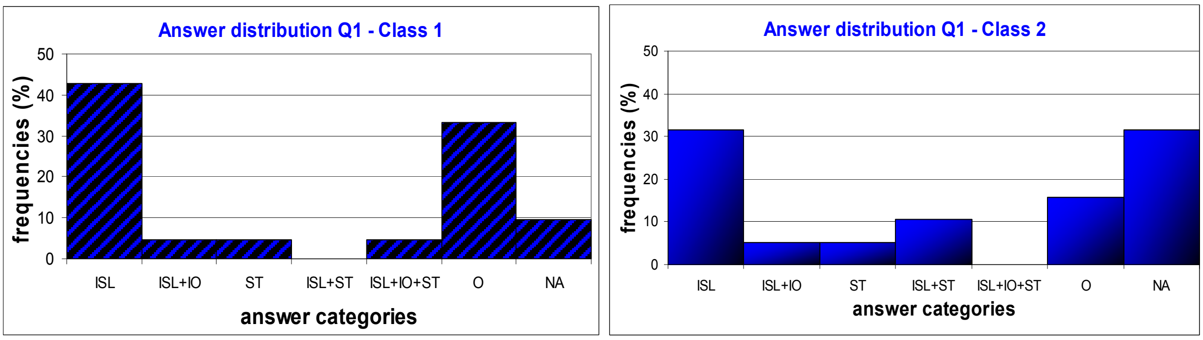
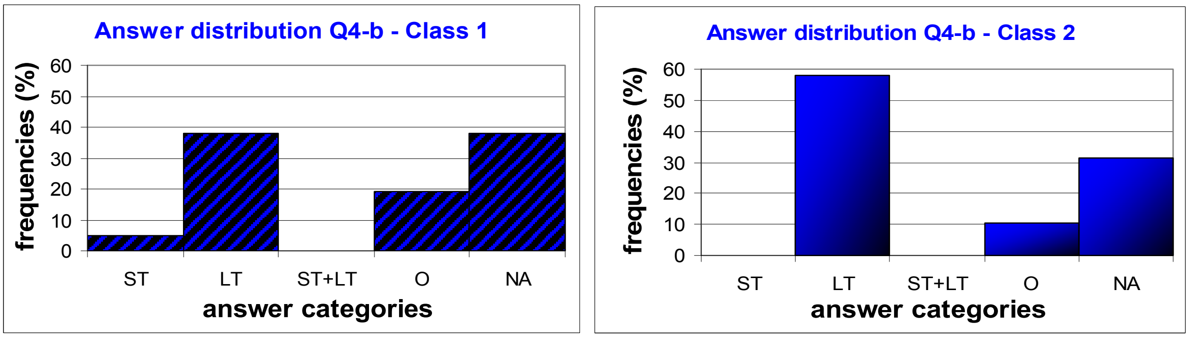



Figure 1. Distribution of key-concepts (listed inside white panels) according to questions.
*Left column:* results for class 1. *Right column:* results for class 2.

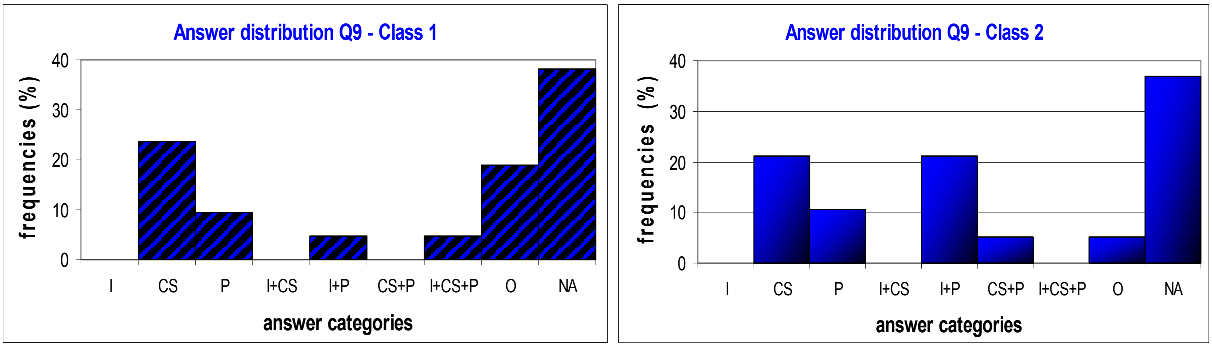
When looking at different answer elements within the same question, we see that students of the first class more readily give a right answer (see category ISL in $Q_1$ or ST in $Q_4$b), but they are less comprehensive and coherent in combining several concepts – in order to attain the right picture involving all of the required elements (categories LT in $Q_4$b and I+P in $Q_9$). Read, for instance, the following contrasting answers to question $Q_4$b: "*Space and time can no more be considered as absolute and separate entities, but they form a unique and unitary concept (space-time), whose four components in two inertial reference frames are connected by means of Lorentz transformations (with the term sqrt* $(1-v^2/c^2)$" – which represents a typical answer for students of class 1, and is notably more precise and correct than "*Space contracts, while time dilates and therefore space and time appear as different*" – which is a fairly standard answer from a student of the other class. For question $Q_9$, "*To represent a n-dimensional space, our mind needs to immerse it in an Euclidean (n+1)-dimensional space. This operation is for us so intuitive, that we execute it without boring about. Unfortunately our mind, moulded by experience and perception in a not-relativistic world, refuses to represent a 4-dimensional space*" (class 2) clearly indicates a more complete understanding of the context and its correlates than *"The ant experiences a two-dimensional world, while in reality they are three; similarly, we experience a three-dimensional world, while in reality they are four*" (class 1). *Situation* questions work in the opposite way: whereas students of class 2 may easily apply correct solutions relative to any single element, re-elaboration of concepts that resort to analytical and mathematical instruments to logically infer connections and laws is better achieved by the other group (see for instance $Q_8$a: *"$\Delta s^2 = c^2\Delta t^2 - \Delta x^2 = c^2\Delta t'^2 - \Delta x'^2$, where t is the proper time of the phenomenon. First case: $\Delta s^2 > 0$ implies $c^2\Delta t^2 > \Delta x^2$ so that c > v (causality); Second case: $\Delta s^2 = 0$ implies $c^2\Delta t^2 = \Delta x^2$ so that c = v (causality); Third case: $\Delta s^2 < 0$ implies $c^2\Delta t^2 < \Delta x^2$ so that c < v (no causality)*" (class 1) vs "*$\Delta s^2 = 0$: contemporaneous events; $\Delta s^2 < 0$: not correlated events; $\Delta s^2 > 0$: possible correlation*" (class 2).



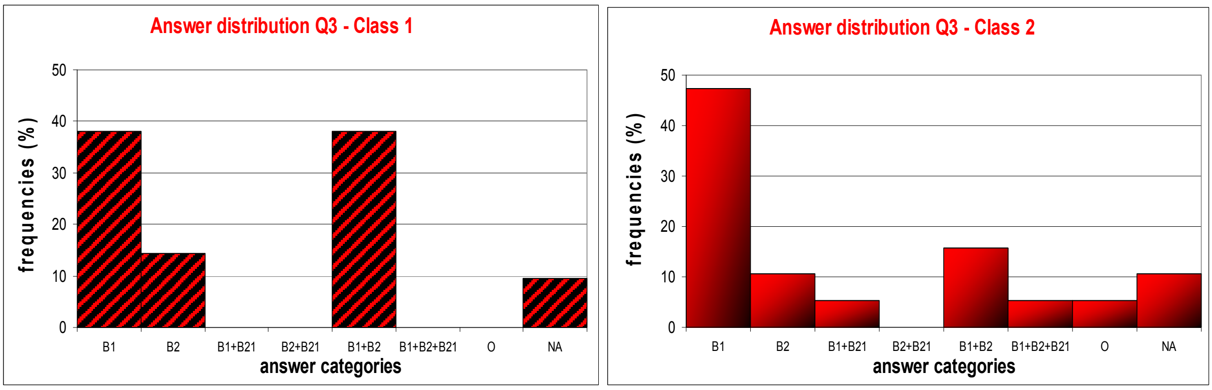

**Q1:** **ISL:** invariance of *c*
**IO:** inertial observators
**ST:** space-time varies according with observers' velocity
**O:** other
**NA:** no answer



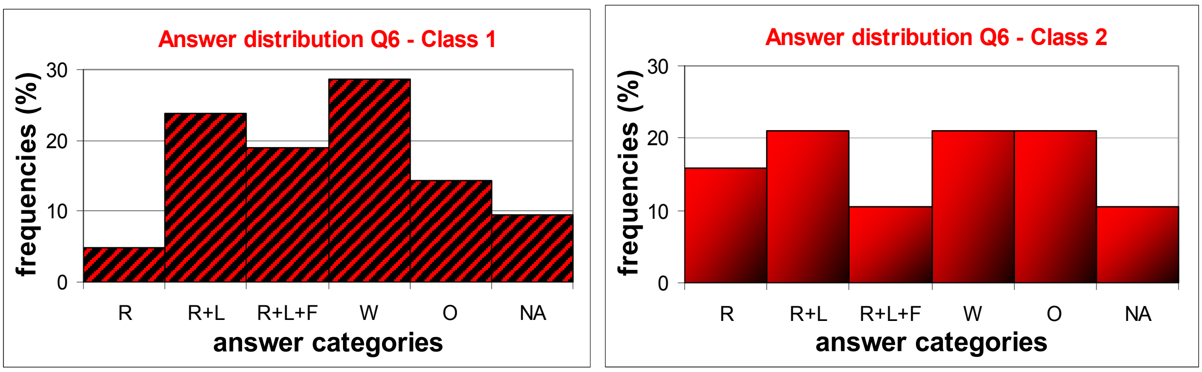

**Q4b:** **ST:** space-time as a unique entity
**LT:** space and time related by Lorentz tranformations
**O:** other
**NA:** no answer




**Q9:** **I:** space immersion
**CS:** resort to common sense
**P:** parallelism between ants' and men' world
**O:** other
**NA:** no answer




**Q3:** **$B_1$:** c invariance ⇒ Lorentz space- time transformations
**$B_2$:** *ball:* Galileo transformatons (GT), *photon:* Lorentz transformations (LT)
**$B_{21}$:** if $v \ll c$, LT ⊇ GT
**O:** other
**NA:** no answer




**Q6:** **R:** right
**L:** Lorentz ⊇ Galileo
**F:** formulas
**W:** wrong
**O:** other
**NA:** no answer

Figure 2. Answer category distributions for some proposed questions, for class 1 *(left)* and 2 *(right)*. *Blue panels:* examples of *synthesis* questions. *Red panels:* some *situation* questions. The meaning of different categories for each question is illustrated in the box below respective pairs of figures.

## CONCLUSIONS AND IMPLICATIONS

We analysed performances in special relativity of secondary school students who attended a Summer School in Modern Physics at Udine University. *Teachers acquainted in a Master in Didactic Innovation in Physics and Orientation (IDIFO) belonging to the same project presented notably different educational styles: the first one was more analytical, formal and rigorous in introducing concepts and pointing out relationships and laws, while the second was better oriented toward an empirical approach to ideas and effects of the theory. Students of the first group show a greater skill in using concepts in situations, i.e. they are able to re-elaborate single elements to achieve the right interpretation of phenomena; conversely, the pupils of the other group are less precise and comprehensive regarding single learning elements, however, perhaps as a consequence of a teaching strategy that also included active peer-teaching modules, they are more flexible in synthesising categories and inferring general pictures.*

In the realm of the increasing interest in planning curricular proposals on topics of modern physics in secondary schools, our work provides an indication of the role played by complementary analytical-intuitive and empirical-formal approaches to topics far removed from common sense, relating to studies aimed at understanding attitude with regard to the reusing of single concepts inside a general context – one of the most important investigation fields in physics education. The experimental paths studied represent emblematic examples of alternative choices for scholastic activities on special relativity, to be pursued according to the main tasks determined by the didactical operative context: providing a general and mainly cultural preparation and/or disciplinary instruments. The modular structure of the paths is also suitable for addressing partial and specific targets in an integrated fashion. In this sense collected data plays the role of choice indicators.

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