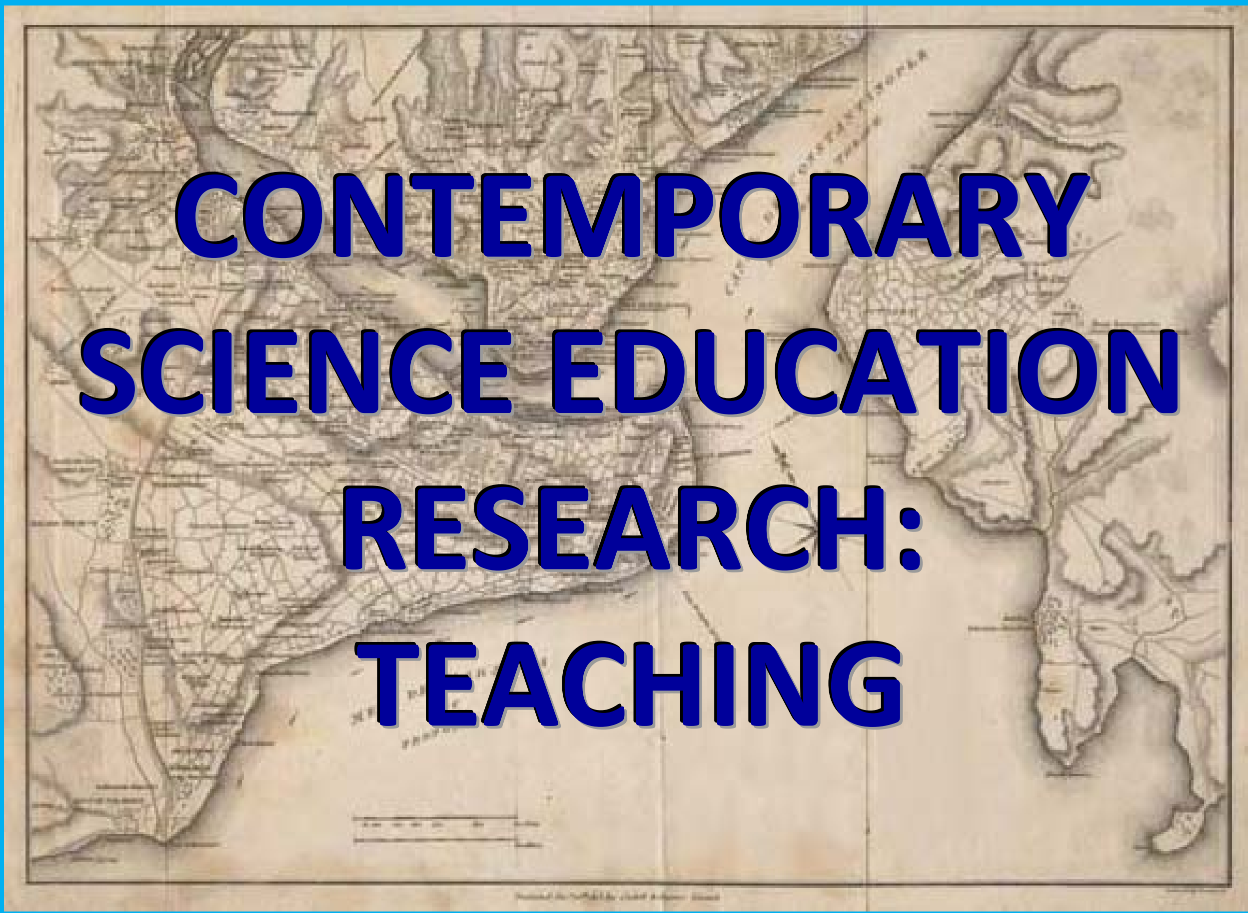

CONTEMPORARY SCIENCE EDUCATION RESEARCH: TEACHING

A collection of papers presented at ESERA 2009 Conference

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A DIDACTIC PROPOSAL FOR THE VISUAL TEACHING OF THE THEORY OF RELATIVITY IN HIGH SCHOOL FIRST COURSE

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Abstract

This paper presents an innovative approach to enlighten students attending first year High School Physics and Chemistry courses (16 years old) on the qualitative aspects of Einstein's Theory of Relativity. This is being done in the scope of setting the foundations for a later comprehension of the quantitative contents of the Theory, within the curricula of the second year. This new approach is founded on Minkowski's geometrical formulation of the Theory of Relativity. We have added to this instructive display a visual inference of the Lorentz transformation, as well as a representation of the mass-energy equivalence by showing a comparison of the graphs resulting from a non-elastic collision. Following the description of the operational model, some examples are presented, as well as the consequences of its implementation in the classroom.

Introduction

The experimental design of the investigation is sketched in Table 1. Its type can be described as pretest-postest-postest without a control group. Reasoning and action schemes that students are able to activate during the deployment of the programmed activities were elaborated and analysed throughout the different phases of the investigation (Domínguez *et al*, 2003; Rumelhart and Ortony, 1982). The proposal itself became the independent variable along the investigation.

Table 1. Experimental design of the investigation

Phase 1	Phase 2	Phase 3	Phase 4
The sample is adjusted to the new methodology	Initial characterisation of the sample	Implementation of the didactic proposal in the classroom	Final characterisation of the sample

In Phase 1 a didactic proposal on Galileo's Relativity was presented to the classroom with the aim to acquaint students and teacher with the new methodology. In phase 2 the sample was initially presented (18 students of High School First course) in order to measure their level of knowledge prior to the implementation of the instruction proposal. In Phase 3 the didactic proposal *Einstein's Theory of the Special Relativity* was developed. In Phase 4 the final mastery of the students was assessed and contrasted with their previous notions. Finally, a statistical analysis was fulfilled to audit the significance of the knowledge improvements obtained through the learning protocol.

An analytical method was used to probe the experimental data. It was based on a qualitative diagnosis about the activity and reasoning schemes that were activated by the students for the description, explanation and prediction of the proposed facts, phenomena and situations.

Rationale

The usual mathematical demonstration of the Theory of Relativity involves too many difficulties at the academic level of a High School student.

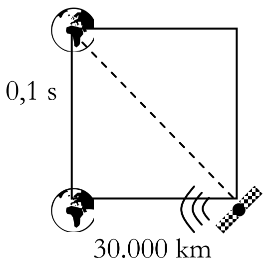

Figure 3

Minkowski (Sazánov, 1990; Mermin, 1997) proved that all the physical outcomes of the Theory were of a geometrical nature, and as such could be formulated in a four dimensions spacetime. In this proposal, we have extended the field of applications of Minkowski's diagrams in two senses:

- In order to build the Theory itself in a visual way starting from the same principles that were used by Einstein: relativity and the conservation of the speed of light.
- As a way to envision the mass-energy equivalence by the use of an analogy: the graphic analysis of a non-elastic collision.

This also allowed us to introduce the Theory in a qualitative and visual way in early courses:

- To direct a larger number of students towards the comprehension of the Theory of Relativity. Even for those that will not follow higher degrees in education,
- To provide students with a larger base for the later study of the quantitative aspects.

The teaching methodology employed is based on the ability that the spacetime diagrams have, which allows the qualitative explanation of many concepts of the Relativity Theory while retaining all its quantitative power, due to the fact of being geometrical figures.

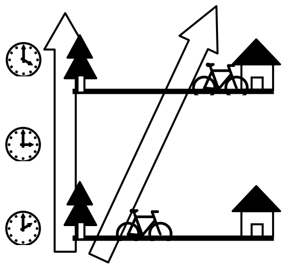

Figure 1

We can put together the time and space axis in the same figure, thus obtaining a "spacetime diagram" (figure 1). In these diagrams some physical magnitudes can be observed and measured, like (obviously) space and time or speed (shown like arrows in the figure). It must be kept on mind that the left, vertical arrow doesn't represent any movement. It would suggest the time elapsed (clock) without displacement of the object (tree). This is a definition of the State of Rest.

The figure also shows that the slope or angle of the arrow (or line) represents the displacement of an object (bicycle) as time passes by. That way, a sloped arrow (or line) means movement, and the tilt of the line would be an indication of the speed rate of an object. .

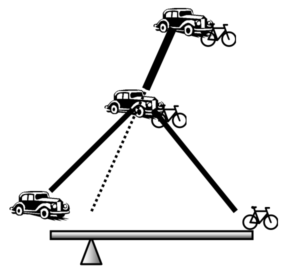

Figure 2

The space-time diagrams can be used to measure an unknown mass. In that purpose we incite an inelastic collision against another known mass in such a way that they both move against each other at the same speed. If both were of equal mass, the set won't move after the collision (a vertical line in the space-time diagram).

In figure 2 the masses of the car and the bicycle are different, and after the collision, the car will drag the bicycle towards the right. If we extend backwards in time the line of the set after the collision, the centre of mass will be shown shifted towards the car, an indication that its mass is bigger than the bicycle one.

Once shown how to physically understand the spacetime diagrams, we have to set up its main symbolic unit: the *cell unit*.

Given that the Theory of Relativity considers the speed of light in a particular way, we will choose the units for the space and time, where the light speed (c) is one. Given that light travels 300.000 km in one second, we can choose as unit a tenth of a second for time, which means that the space through which lights travels will be of 30.000 km. In this case we will have a cell unit suitable for the analysis of the signals broadcasted from the satellites that beam the GPS *Galileo* system, located at an orbit around earth with a radius of similar value (figure 3). The diagonal dotted line indicates a signal send to earth from the satellite at light speed. Spacetime is covered by an infinite number of these unit-cells, the same way as tiles over a wall.

In figure 4 we apply the Galileo transformation (that is an inclination of the time axis while the space axis is kept unaltered in a horizontal position) from the Earth reference system (grey squares) to the figure that explains the functioning of the GPS. As this system is based in signals sent from satellites positioned on an orbit circling the Earth, unmistakably above the atmosphere, these signals will travel through the space vacuum, which means that its speed should be affected by the Galileo transformation.

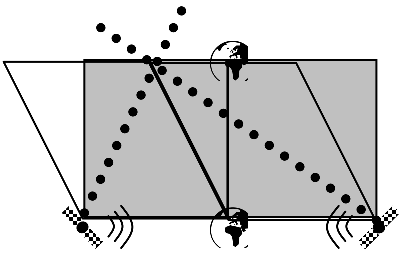

Figure 4

As a consequence, due to the different speeds of the signals, now they will not join in the same point as before. There will be a space displacement equal to the space along which Earth has moved during the time spent by the signals to arrive, which is of 0,1s. But we know that the earth, during that same time, travels 3 km orbiting around the Sun. If the Earth would move always in the same direction there shouldn't be any problem, since it would be enough to adjust the figures resulting from the calculation of such a displacement, uniform at any time. But the earth revolves around the Sun along the year, which means that after six months it will be moving in the opposite direction, signifying that the location is continuously changing within a 3km radius along the year and it would be impossible to obtain a better accuracy than 3km with a GPS device.

The fact that the GPS accuracy is of a few meters and that no corrections or adjustments due to the Earth movement are needed, corroborates the null result obtained by Michelson in his well-known experiment.

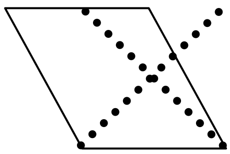

Figure 5

If Earth would not move through the space as is stated by the Geocentric Model this would be in accordance with the expected results. But by the time when Michelson made his test, this Ptolemaic system was no longer valid.

Resulting from the above, we can see in figure 5 that there is an unresolved disagreement between the Galileo transformation (a horizontally based parallelogram) and the light pathway (dotted line).

When we consider that the Galileo transformation is at the base of all the Newtonian mechanics, and that the speed of light (and all the electromagnetic waves) makes the core of the electromagnetic theory, we find that these results put both theories, the richest of Classical Mechanics, in an overt opposition against each other.

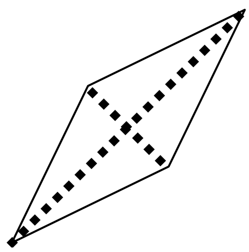

Figure 6

This was the situation at the dawn of the Twentieth Century.

After several attempts to find an explanation to Michelson's outcome, it was finally Lorenz who put forward an innovative approach to the spacetime transformation where the speed of light was kept unchanged. This new approach is shown in figure 6 as a 45º slope rhomb.

As in the Galileo transformation the surface of the rhomb is the same of the original square. In order to achieve that, one of the diagonals is lengthened while the other is shortened in an equal amount. Given that the surface of the rhomb is half the product of its diagonals, the result is the same.

Three elements in this figure must be highlighted:

- Although one of the diagonals is lengthened more than the other, the light speed is the same in both. It must be remembered that the speed is shown by the slope and that both diagonals have the same 45º slope.

- The main difference with Galileo's transformation is that, -in this case-, the base is no longer horizontal but slopes in the same sense as the side of the square. It is precisely in this fact that the un-intuitive elements of the Special Theory of Relativity are based.

- In the Galileo's transformation there was an invariable line: the horizontal. As a consequence time was absolute, the same for the whole Universe. The Lorentz transformation shows a different invariable: all diagonals. That way a new absolute shows in the Universe: the speed of light.

Once the geometric form of the Lorenz transformation is established, we will find out which are its outcomes when dealing with the same physical magnitudes as above.

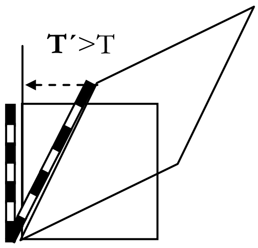

Figure 7

Now, as shown in figure 7, the measure of time is not the same in the original frame of reference as it is in the transformed one. Time in a moving FR is slower, a phenomenon called *time dilation*, which is the first of the four relativistic effects that we are trying to exemplify. It is interesting to emphasize that the figures not only show a qualitative image of this effect (and the later), but they can also be used in the founding of numerical values. In this case, comparing both scales we can see that 6 units of time in the new FR are equivalent to 7 in the original FR, that is to say: time has expanded in 7/6. This value coincides with the outcome that would result from a mathematical handling.

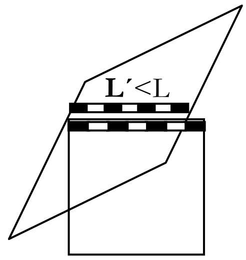

Figure 8

By applying similar considerations to figure 8 we can examine the experience of *space contraction* by which the lengths of a moving system are smaller than in a state of rest. It's important to emphasize that, in this case, the longitude of a ruler means the measure of the horizontal distance between its both ends, which would generally result in two lines with the same slope. In this case, they will be coincident to the lateral limits of the unit cell, both in the case of the square as in the rhomb (Lorentz transformation).

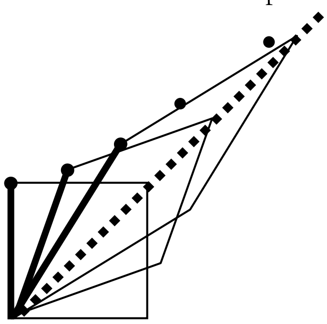

Figure 9

In the following diagram (figure 9) we can observe the relativistic effect of the limiting speed. Many people know somehow that the speed of light cannot be exceeded, but only a few would know why. Sometimes it is thought that it's only a current limit due to our nowadays' technical restraints, similar to what it used to be, a few decades ago, with the sound barrier, and that further technological progress will allow us to go beyond the known limit. It is also thought that science doesn't have the specific instrument that could allow the measure of speeds beyond 300.000 km/s and so it is taken as an immeasurable speed in its own. In the figure we can grasp the reality and characteristics of such a limit.

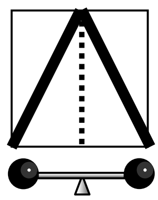

Figure 10

While the reference system increases its speed, the left side increases its slope. Due to the shape of the Lorentz transformation, the base of the figure also slopes upwards in an equal proportion. As a result, both lines will merge towards the dotted diagonal (speed of light). But we also know that the rhomb limiting both lines has to keep a constant surface, so that no matter how much is the rhomb stretched, it will never totally close or collapse. As a result, it is impossible for any frame of reference to reach the speed of light relative to others.

In order to appraise the effect of Lorenz transformation upon a mass, we look at figure 10, representing an inelastic symmetric collision. It shows that the speed attained by both masses is represented by the vertical dotted line, indicating a state of rest (which responds to the fact that the situation is completely symmetric).

Let's now have a look to the same event, but in a frame of reference that moves together with the right hand mass, that is to say, half the speed of light to the left (figure 11). To solve it we apply the Lorentz transformation to the square at the start and draw the lines between the due points (lower vertexes and midpoints at the sides). At a first look we confirm that the line of the right hand mass is now vertical, meaning that from the new frame of reference, this one doesn't move, which is exactly what we expected. We also notice that the centre of mass, -which in the previous example was steady-, is now moving to the right at half the speed of light, as was also expected.

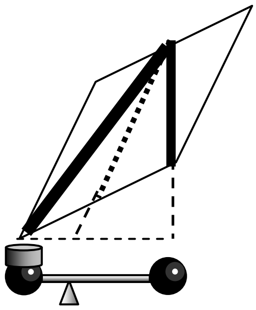

Figure 11

The most important feature results by applying a horizontal line in the lower part of figure 11. Now we can see that the centre of mass is no longer located at the middle point between the two masses, which is an indication that "something" pushes the centre of mass left wise.

The present situation is no longer symmetric, since the mass on the right side doesn't move any longer, which means it hasn't got any kinetic energy, while the left one moves faster than before, that is to say it's got kinetic energy. It can be graphically shown that the amount of kinetic energy of the left mass is equal to an additional mass that would shift the centre of mass to the point where it is presently located. This is the relativistic phenomenon known as the *mass-energy equivalence*, that can be shortened by stating that energy has the same inertial characters as mass or that mass and energy are two forms of the same physical property. We can express this result by the following equation that seems to be almost trivial: E= m.

If we consider that to be able to change the mass and energy units we must multiply by the square of a speed, and that in the diagrams we used the speed of light is the unit (c = 1) we can rewrite the equation this way: $E = m\ 1^2$. Finally, for a light speed different to the unit, the equation becomes: $E = m\ c^2$ which is the well known Einstein equation, considered to be one of the most mysterious and hard to understand in Physics, and that we can now figure out as a geometric outcome of the Lorenz transformation.

Methods

The model established by Domínguez *et al.* (2007) was used as a basis for the design, planning and development of the educational proposal. That model comprises the following assignments:

Assessment of the academic content; valuation of learning problems' burden; selection, formulation and progression of objectives; choice of teaching strategies and design and sequence of activities, and appraisal of evaluation strategies.

The first stage allowed us to sort out, systematize and settle on a sequence the topics to be learnt, founded on the analysis of the current Galician curricula (XUGA, 2008) and their epistemic appraisal. This enabled us to elaborate the action and reasoning schemes that are considered as *schemes of reference*, moreover as the suitable level of knowledge from the school sciences point of view.

Considering the level desired for Sciences students, we designed a scheme of thought named "Einstein" and shown in figure 12.

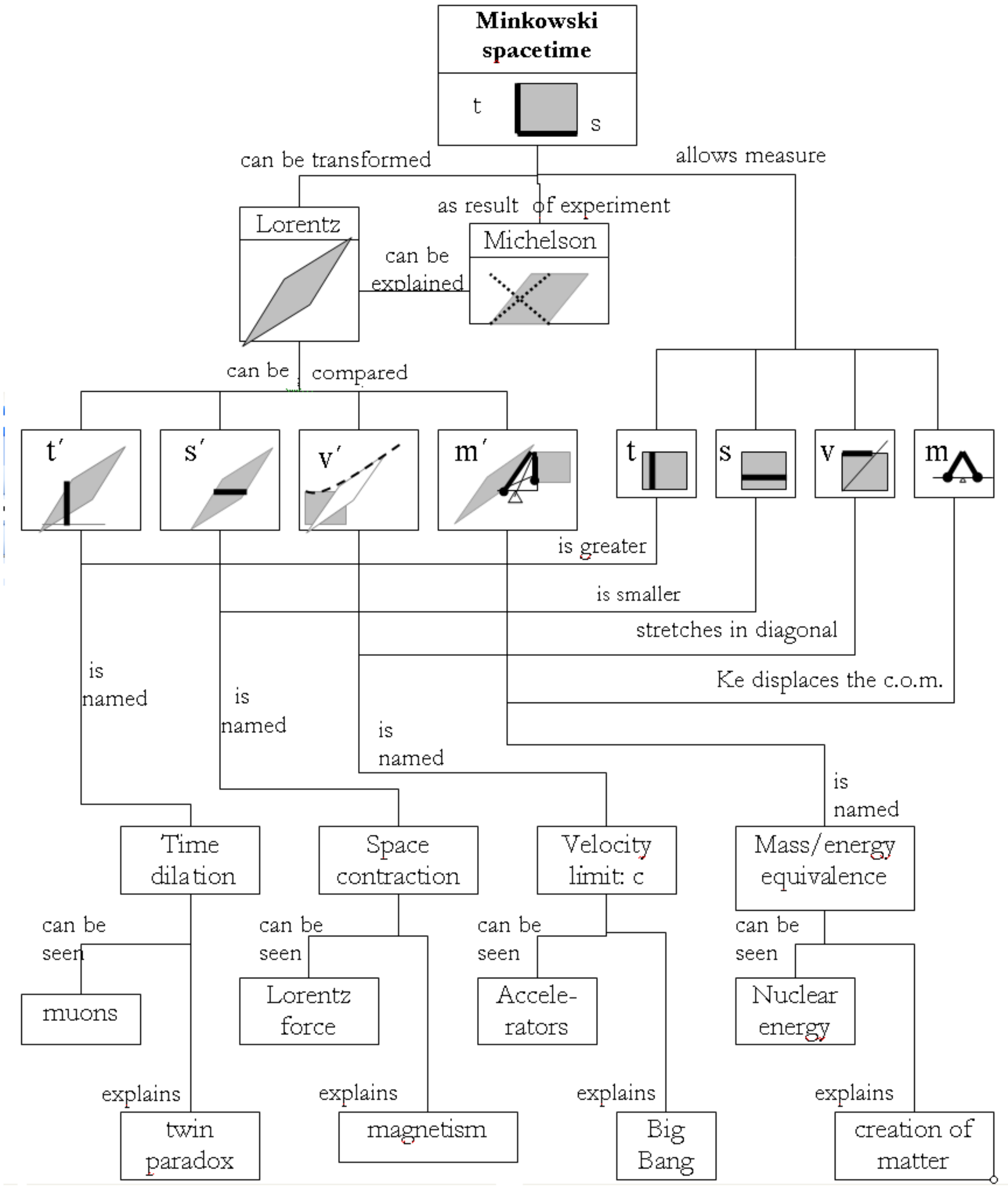

Figure 12: "Einstein" scheme of thought

In this referential scheme we can distinguish a main sub-scheme (Minkowski's space-time), two previous sub-schemes (Michelson and Lorentz) which have their own structure and that are not expressed in the referential, and four sub-schemes (time, space, speed and mass) where each of them have also their own structure, revealed in this case only in part for each of them by means of relations of image, of comparison, of denomination, of verification and of explanation, that will be exemplified for the case of the "speed" sub-scheme:

Image relations: as is shown in the figure, a proper mental picture of speed in the space-time requires the measurement of the horizontal displacement during the time unit.

Comparison relations: while representing the speed in the Lorenz transformation we find that the velocities don't add-up horizontally like in the Galilean case, but they evolve towards the diagonal line (dotted line) in an asymptotic way (never reaching it).

Denomination relations: the fact that even with a succession of speed boosts it would be impossible to attain the speed of light is called "finite speed of light" which is one of the relativistic concepts that we seek to present in a qualitative way by means of this task.

Verification relations: the impossibility to attain the speed of light is constantly confirmed in particle accelerators.

Explanation relations: the fact that no material entity is capable of moving at a speed greater than the speed of light makes it possible to understand why the Universe, -according to the Big Bang theory-, has a limited size, given that no galaxy can be parting away from us at a speed faster than the speed of light.

Regarding the second task, we thoroughly went through the available bibliography, a move that enabled us to foresee the learning difficulties in connection to the Theory of Special Relativity (Table 2).

Concept	Students ideas	Bibliography
System of reference	Rest is considered an "undeniable" state in itself. It was shown that the visual explanation helped in elucidating the issue.	Hewson, P.W., 1982.
Spacetime	Resistance to consent that time or length measures are tied to the system of reference. An "immutable" nature is assigned to measuring values obtained within a system of reference in relation to the observer.	Villani and Pacca, 1987.
Speed of light	The impossibility to surpass or even to reach the speed of light is taken as the result of present day technical limitations that prevent us going beyond. Galileo's sum of velocities is given credit.	Villani and Arruda, 1998

Table 2: Some learning difficulties to be expected

The third task concerns the integration of the analyses of the academic content with the learning difficulties. This provides the selection and formulation of possible learning objectives.

The implementation of the fourth task allowed us to select the teaching strategies and to model a sequence of nine learning activities. Table 2 shows two examples of such activities.

Activities	Concise description
Activity nº 4. Lorentz transformation	The analysis is done in an entirely visual way, using the same spacetime graphs and the visual display of the Physics' concepts that allowed us to establish the form of Galileo's transformation in activity nº 2. However, now, instead of the common sense, we applied the notion of the speed of light conservation.
Activity nº 5. Consequences of Lorentz transformation	This activity analyses in a systematized way the physical implications of Lorentz transformation. This is done without overlooking the qualitative vision that defines these activities.

Table 3. Educational activities

The activities are put forward as pragmatic problems (Jiménez 1998; García *et al.,* 2000) in the scope of promoting discussion and interchange. They are arranged in small teams of students, seeking to reproduce the social nature of science (Reigosa and Jiménez 2000). This contributed in building a classroom ambience suitable for the debate and discussion of ideas.

Finally, in the fifth task, evaluation strategies were chosen that were subsequently integrated to the actual learning process. They result from the analysis of educational activities and imply the current evaluation standards of the official curricula (XUGA, 2008).

Results

Throughout the execution of the proposal, it was found that the students' arguments converge towards proper interpretations in accordance with the relativity theory. Spacetime diagrams make up an efficient didactic tool for the understanding of the relativity theory concepts. In the explanatory process, the students put into effect new reasoning skills, including the relationship between relativity theory concepts and the implications learnt from the visual application, thus filling them with full significance. The students schemes were graded by levels (i: initial, f: final, r: retention after a year, g: general).

Table 1 shows the way by which the thinking schemes of tested students were structured for the three different phases (i, f, r). Each capital letter represents a student in the group. In the initial characterization (i) almost the whole group of students is placed at the lowest level, which corresponds to expectations, given that the Theory of Relativity was not explained to them in previous courses. In the final characterization, after four weeks of training, a conspicuous increase of levels is perceived, emphasizing the fact that almost a quarter of the sample attained f5 level, corresponding to what would be expected for school sciences. In the retention phase the students show a downgrading of levels, due to the loss of information retained in the short term memory and as such, of little significance. Considering that the retention test was done after a year without any additional instruction on the Theory of Relativity, the downgrading is considered adequate.

Table 4. Students levels at the assessment stages

Levels g	Levels i	Students N=24	Levels f	Students N=24	Levels r	Students N=23
g5			f5	**B,D,F,K,L,R,Y**	r5	**L**
g4			f4b, f4a	**A,G,H,M,S,T,V,X**	r4	**D,F**
g3			f3b, f3a	**I,N,O,P,U,W, Z**	r3b, r3a	**A,B,C,G,H,O,R,X**
g2	i2b, i2a	**F , U**	f2	**C**	r2b, r2a	**E,I,K,T,U,W,Y**
g1	i1b, i1a	**A,B,C,D,E,G,H,I ,K,L,M,N,O,P,R, S,T,V,W,X,YZ**	f1	**E**	r1b, r1a	**N,P,S,V,Z**

The class exhibited a lofty degree of satisfaction all along the activities. The reason being the enhancement of the students' ability to ponder over concepts generally admitted as difficult to understand.

Conclusions and Implications

The visual methodology could be used with larger efficiency if incorporated at earlier courses of sciences and mathematics by the adjustment of the current curricula contents (spacetime graphics, changes of origin, geometric transformations).

A systematic use of Minkowski spacetime graphs as a visual didactic tool would allow the inclusion of General Relativity subjects also in a qualitative form in High School courses.

A leap forward is requested to secure quantitative results, and it doesn't seem to be loaded with excessive difficulties. It is hoped that the methodological approach being submitted in this paper would help in its introduction in the second course of High School.

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