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Integration of information and communication technologies in special relativity teaching

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Abstract

Integration of information and communication technologies (ICTs) in special relativity teaching may bring multiple and complementary methods for introducing either difficult or abstract counterintuitive concepts. This paper describes multimedia content developed at Lyon University to enhance the learning process of undergraduate students. Two categories of animated scenarios have been identified: real experiments and thought experiments. Both typical examples of these scenarios and their impacts on the teaching process are discussed.

1. Introduction

For most undergraduate students in science, special relativity is a fascinating theory of Nature. In this theory, one can no longer rely on common knowledge of the classical world with intuition based on the human experience of dynamics. This underscores why an introductory lecture on special relativity has to carefully emphasize the interaction between experiment and intuition in generating the physical theory [1]. One possible approach is the use of new tools such as information and communication technologies (ICTs). At Lyon University, new physics teaching methods have been developed that address the above issues. These approaches were also designed to attract students who do not intend to continue in science. In our opinion, introducing ICTs in physics teaching gives us a powerful new tool that is complementary to classical lectures. In addition, for some students it could be the right means to understanding complex phenomena.

After two years of developing ICTs, we began implementing these new advances in our lecture on special relativity. The audience is composed of undergraduate students in both physics and chemistry. About 100 students will have participated in this new lecture format by the end of the academic year at the University of Lyon. Our lecture, of which 66% is computer based, is composed of

- lessons (six chapters),
- exercises and evaluations,
- illustrations or experiment scenarios (most of them are interactive) based on ICTs.

These different learning tools are developed within the e-learning framework proposed by the Lyon University ICTs staff, called 'SPIRAL' [2]. We use this framework to define the weekly agenda followed by students. The agenda is composed of lessons, exercises and ICT scenarios. The undergraduate student standing alone in a computer session can go through the proposed agenda at his own pace. The teacher, present in the classroom, answers specific questions or addresses issues collectively when it seems necessary. The agenda on SPIRAL is available to students during the entire period and can be used to assist with homework assignments. Each connection is tracked and individual progress and statistical group results are calculated to monitor the learning process. There is also an open forum based on the lecture where students can pose questions and add comments. This can provide insight about whether the lecture needs to be improved or enhanced. Nevertheless, the students are strongly encouraged to interact with teachers during the on-line lessons.

This paper is organized as follows. Section 2 is devoted to revisiting the learning process of the special relativity theory with the new ICT tools. In section 3, ICT developments will be presented. Two categories of scenarios will be defined. Examples will be described and their use by students will be discussed.

2. Motivation for introducing ICTs in special relativity lectures

The first question when it comes to integrating ICTs in a learning process is: what for? The main idea here is that an introductory lecture on special relativity has to carefully emphasize the interaction of experiment and intuition in generating the physical theory. Indeed, many undergraduate students consider special relativity theory to be a breakthrough in modern physics. Beyond the new mathematical formalism, the discovery of the theory means understanding or revisiting concepts not necessarily based on intuitive human experience. Such concepts are: space invariance properties, invariance of the physical laws, measurement of length and duration, and relating physical quantities to new mathematical objects. Invariance principles appear intimately related to spacetime and light properties:

- invariance of the Euclidean norm under rotation and space isotropy,
- invariance under translation and space homogeneity,
- invariance of pseudo-norm and causality,
- invariance of physics laws and inertial frame,
- invariance of the speed of light and relativity of simultaneity.

They all have the same basic properties. Indeed, the use of invariance concepts needs to give a representation of the transformation law and a description (or measure) of the 'state' before and after the transformation. ICT tools are good candidates to perform this task through animated and interactive scenarios called illustration scenarios and thought experiment scenarios. Furthermore, the construction of the theory has to be emphasized via an efficient description of real experiments prior and posterior to the theory. We will call them real experiment scenarios.

Table 1. List of the Macromedia Flash scenarios included in our package. The categories I correspond to real experiment scenarios and II to thought experiment scenarios. The number in parenthesis indicates the number of scenarios.

Category 1	Category 2
Römer observation	Minkowski diagram
Michelson experiment	Measurement theory (3)
Speed of light measurements	Lorentz transformation demonstration (6)
Compton diffusion	Lorentz contraction (2)
Cosmic muons	Mass–energy equivalence
Doppler effect	Relativity of simultaneity
	Moving clock
	Light aberration
	Paradox of the ruler and the hole
	Kinematics (10)

3. ICT developments

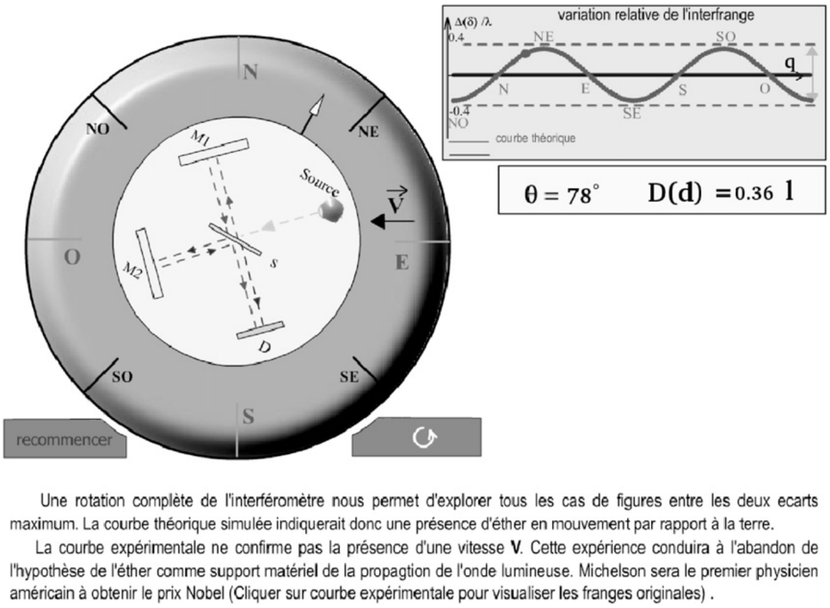
All animations later described have been performed using the Macromedia Flash language. A list of the scenarios is given in table 1, where the real experiment and thought experiment scenarios have been distinguished. These scenarios are either self-consistent or embedded in a demonstration.

3.1. Real experiment scenarios

One can find many examples in the history of physics of how a new theory emerges when the current one cannot explain a set of experimental results. In the case of special relativity, at the end of the 19th century, experiments on the influence of the motion of a medium on the speed of light [3] were strong motivations to modify space and time properties. Precise presentation of these historical experiments is usually the starting point of a lecture on special relativity. In a classical framework of teaching the difficulty lies in presenting the experimental set-up and results. Therefore, the lesson is limited to the presentation of the important facts. We have chosen to develop historical experiment scenarios to give students a real opportunity to precisely describe all steps of these experiments and discuss the expected and obtained results.

We 'wrote' three scenarios based on different aspects of the velocity of light: its measure and its universality. The first one explains how Römer, in the 16th century, showed by observing the periodicity of an Io eclipse that the velocity of light is finite. The second (figure 1) presents the well-known Michelson–Morley experiment on the influence of motion of the medium on the velocity of light. In this scenario, the student can rotate the experimental set-up and visualize at the same time the expected fringe behaviour as well as the original result obtained by Michelson and Morley [3]. The third shows the evolution of the velocity of light measurement starting from Römer and ending with the 'Conférence Générale des Poids et Mesures' in 1983 where the velocity had been fixed to $c = 299\,792\,458$ m s^{-1}. This animated synoptic also presents the experimental uncertainties and the experimental devices used.

In the category of real experiment scenarios, one can see another interesting contribution of ICTs. Indeed, special relativity experiments involve high technology materials that are not available for teaching purposes. We produced a few scenarios based on well-known experiments, such as the Doppler effect or the Compton effect. In the first, we stress the difference between classical and special relativity effects. In the second, real detector spectra are shown and we focus on different parameters such as the observation angle. The animated



Une rotation complète de l'interféromètre nous permet d'explorer tous les cas de figures entre les deux ecarts maximum. La courbe théorique simulée indiquerait donc une présence d'éther en mouvement par rapport à la terre.

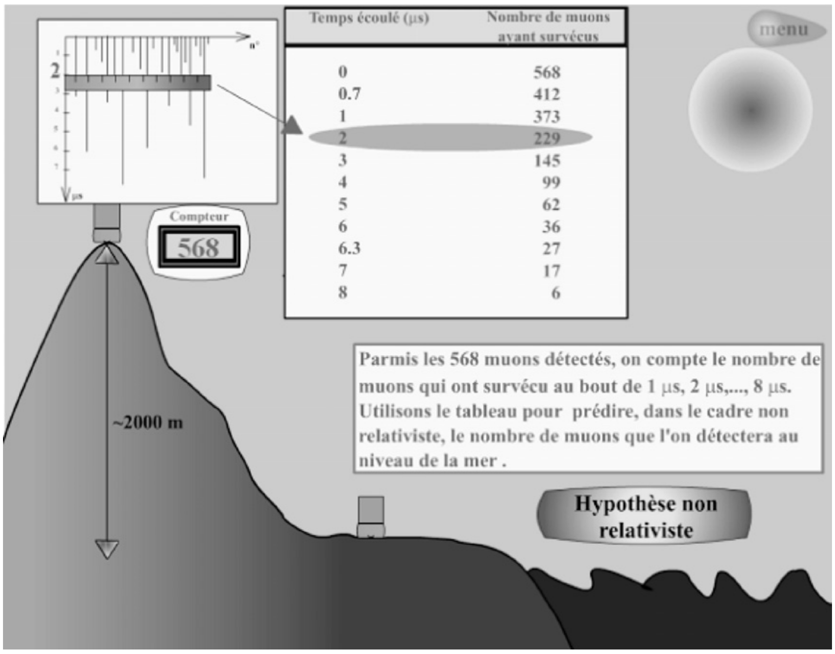
La courbe expérimentale ne confirme pas la présence d'une vitesse **V**. Cette expérience conduira à l'abandon de l'hypothèse de l'éther comme support matériel de la propagtion de l'onde lumineuse. Michelson sera le premier physicien américain à obtenir le prix Nobel (Cliquer sur courbe expérimentale pour visualiser les franges originales) .

Figure 1. The Michelson–Morley experiment scenario. This scenario builds step by step the experimental set-up and shows how to detect the variation of the fringes. The student can rotate the experimental set-up and has access to the expected results and the results obtained by Michelson and Morlay [3]. Accompanying text: a complete rotation of the interferometer allows us to explore all possibilities between the two maxima. The simulated theoretical curve should show the presence of an ether moving relatively to the earth. The experimental curve does not confirm the existence of a speed v. This experiment led to the abandonment of ether as a medium for light propagation. Michelson was the first American physicist to obtain the Nobel prize (click to obtain the original fringes).

scenario treating the light aberration from a moving star is another example of the versatility of ICTs. Note that this tool is perfectly suited to describe astronomical experiments. With the ICT scenario, one can imagine complex experiments and simulate recent results obtained in this field. Real experiments such as the Frisch and Smith experiment [4] on the measurement of the relativistic time dilatation using mu-mesons can be simulated very well step by step. In this scenario (figure 2), we show how atmospheric muons are detected and how their lifetime is obtained for two different altitudes. We explain interactively how the results are compatible with time dilatation between the muon rest frame and the earth frame. To complete the learning process, the non-relativistic case hypothesis with the expected number of detected muons is presented. In scenarios that are based on real experiments, one can easily split a scenario into different parts accessible through a menu allowing the student to choose, for example, the detector physics, measurement method, result treatment or any related information. This kind of organization allows the student to get a greater background on the subject and is not restricted to special relativity. Thus, one can see that such a tool is of interest for presenting up-to-date physics results with various reading levels.

3.2. Thought experiment scenarios

This section deals with the scenarios devoted to the intuitive illustration of concepts and to thought experiments.



Temps écoulé (µs)	Nombre de muons ayant survécus
0	568
0.7	412
1	373
2	229
3	145
4	99
5	62
6	36
6.3	27
7	17
8	6

Parmis les 568 muons détectés, on compte le nombre de muons qui ont survécu au bout de 1 µs, 2 µs,..., 8 µs. Utilisons le tableau pour prédire, dans le cadre non relativiste, le nombre de muons que l'on détectera au niveau de la mer .

Figure 2. Cosmic muons experiment. Accompanying text: among 568 detected muons, one can count the number of muons which survived after 1 μs, 2 μs, 8 μs. The table can be used to predict, within the non-relativistic framework, the number of muons one can detect at sea level.

First we start our report by presenting intuitive illustration scenarios for three distinct concepts:

- the invariance principles used in the demonstration of Lorentz transformation [5],
- the precise definition of the measurement of length and duration,
- the presentation of Minkowski diagrams.

We used systematically animated geometrical illustrations that are not intended to be standalone but embedded into a ‘classical’ explanation (demonstration). They represent a step-by-step geometrical visualization of mentioned concepts. Let us concentrate on the Lorentz transformation demonstration.

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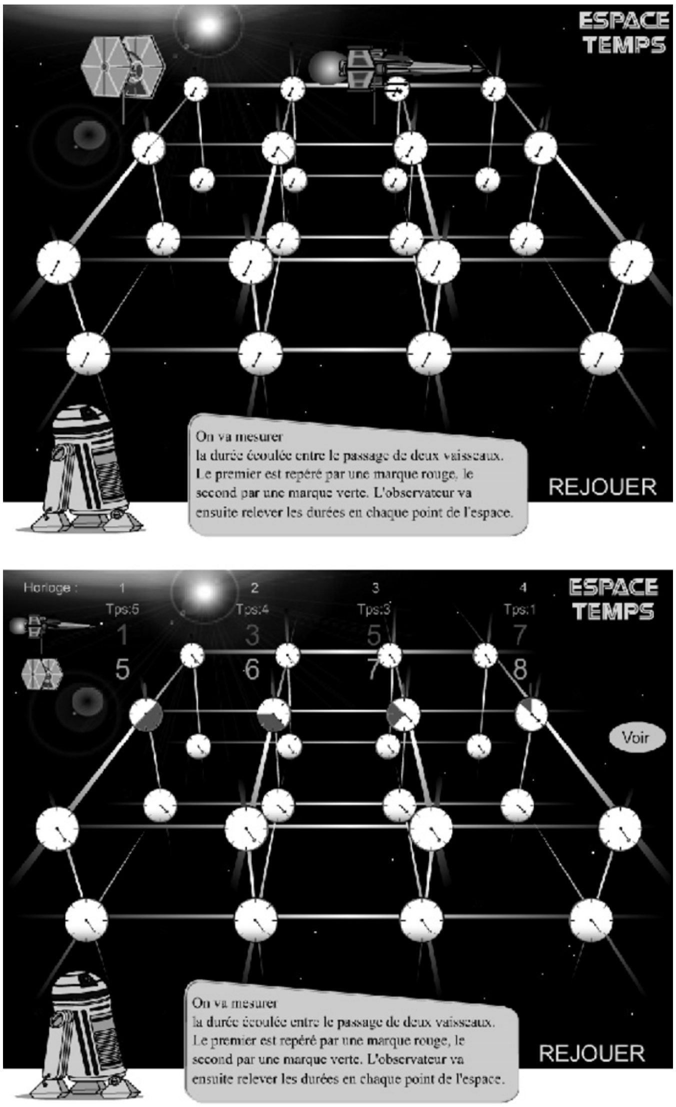
At the beginning of a lecture on special relativity, the student is confronted by a choice of spacetime properties. Thus, the properties of isotropy and homogeneity of space could be considered as abstract concepts by the student. He is surprised when he goes through the full demonstration of the Lorentz transformations based solely on these basic axioms and on the two postulates given by Einstein [6]. During the lesson, when the student has to jump from abstract definitions or axioms to a mathematical expression, we introduce animated inertial frames and animated coordinates to illustrate the consequences of invariance principles. Therefore, each step of the demonstration starts with an intuitive illustration and corresponds to a computation of an unknown parameter in the linear transformations. They are listed as follows:

- derivation of the coordinates of one event with two inertial frames,
- illustration of invariance due to space isotropy and space homogeneity and their consequences in the choice of the origin and the direction of inertial frames,



On va mesurer
la durée écoulée entre le passage de deux vaisseaux.
Le premier est repéré par une marque rouge, le
second par une marque verte. L'observateur va
ensuite relever les durées en chaque point de l'espace.

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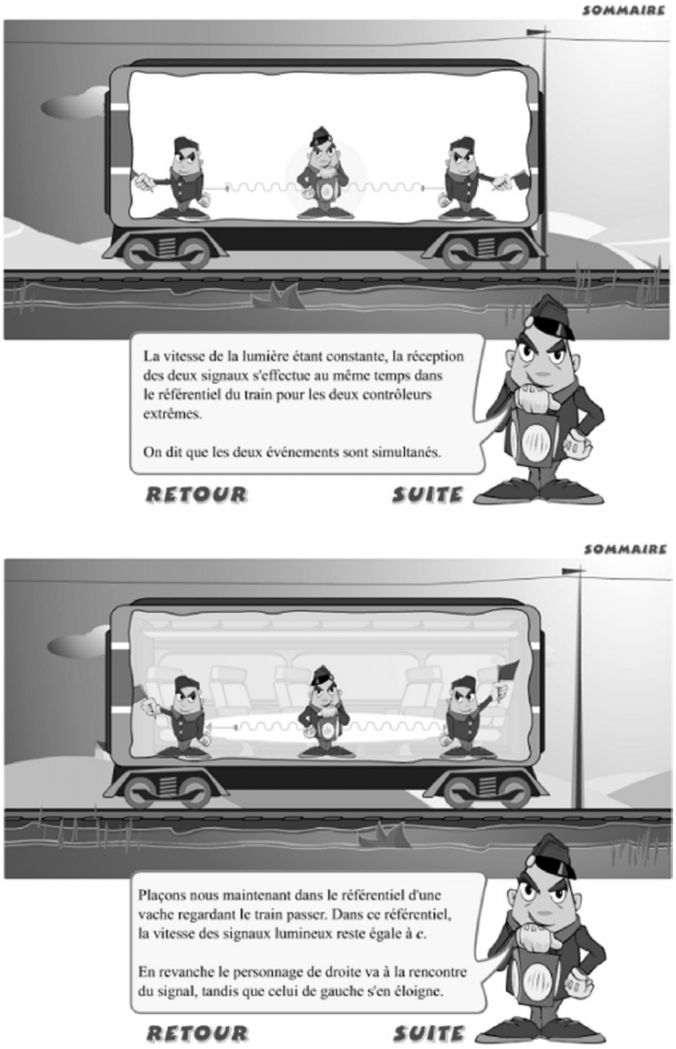
Figure 3. Illustration of the length and duration measurement and spacetime properties. Accompanying text: one can measure the duration between two passages of the ship (the first one being identified with a red line and the second with a green line). The observer then measures the duration at each point of space.

- space coordinate of one point moving in the proper frame and in the laboratory frame,
- equivalence between space-parity transformation and velocity sign change,
- relativity of the motion for different inertial frames,
- velocity of light is c in all inertial frames.

The measurement theory explains the meaning of distance or duration that students usually consider as easy to grasp. However, our experience indicates that they do not really understand that the distance measurement implies space coordinates at the same time of this frame, and that duration measurement implies times in each of the space positions. In our scenarios, the discrete spacetime is represented by a 3D grid, a clock being placed in each of its nodes. All



La vitesse de la lumière étant constante, la réception des deux signaux s'effectue au même temps dans le référentiel du train pour les deux contrôleurs extrêmes.

On dit que les deux événements sont simultanés.

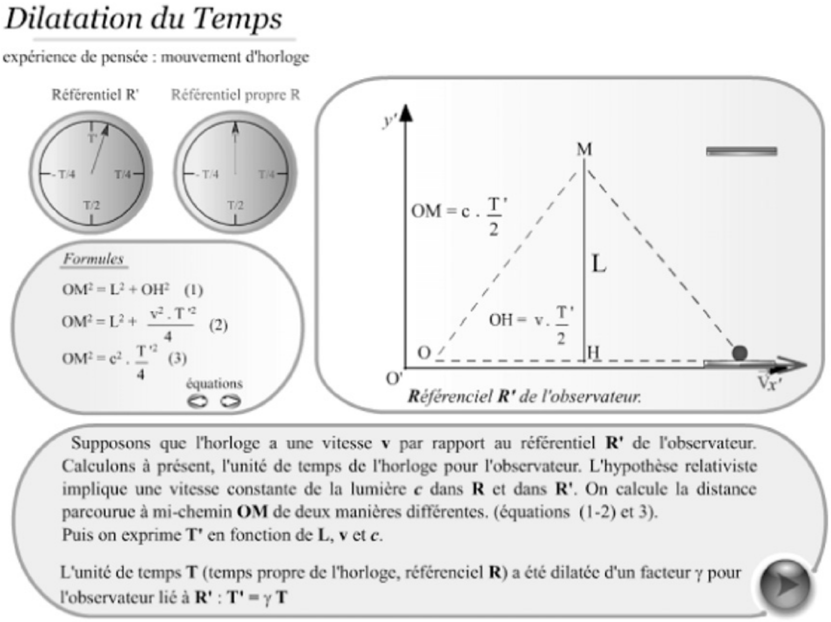
Plaçons nous maintenant dans le référentiel d'une vache regardant le train passer. Dans ce référentiel, la vitesse des signaux lumineux reste égale à *c*.

En revanche le personnage de droite va à la rencontre du signal, tandis que celui de gauche s'en éloigne.

Figure 4. Relativity of simultaneity in the frame linked to the train, where the photons arrive simultaneously (top), and in the frame linked to an outsider (bottom). Accompanying text (top): the speed of light being constant, receptions of the two signals happen at the same time in the train's frame; (bottom): let us consider the frame of a cow looking at the train passing by. In this frame the signal speed is still c. Nevertheless the man on the right is getting closer to the signal, and the one on the left is moving away from it.

clocks have been synchronized. A spaceship can travel in this space, and each passage of the spaceship on a lattice node triggers a clock memory. The reconstitution of the spaceship's universe line is made by a robot traversing the space and noting the clock's memories. The scenario considers three cases:

- illustration of the spacetime in its discrete version,
- measurement of duration between two spaceships moving with different velocities (figure 3),
- measurement of the size of a big spaceship.


Dilatation du Temps

expérience de pensée : mouvement d'horloge

Formules

$OM^2 = L^2 + OH^2$ (1)

$OM^2 = L^2 + \frac{v^2 . T'^2}{4}$ (2)

$OM^2 = c^2 . \frac{T'^2}{4}$ (3)

Supposons que l'horloge a une vitesse **v** par rapport au référentiel **R'** de l'observateur. Calculons à présent, l'unité de temps de l'horloge pour l'observateur. L'hypothèse relativiste implique une vitesse constante de la lumière ***c*** dans **R** et dans **R'**. On calcule la distance parcourue à mi-chemin **OM** de deux manières différentes. (équations (1-2) et 3).
Puis on exprime **T'** en fonction de **L**, **v** et ***c***.

L'unité de temps **T** (temps propre de l'horloge, référenciel **R**) a été dilatée d'un facteur γ pour l'observateur lié à **R'** : **T' = γ T**

Figure 5. Time dilation shown with light reflection on moving mirrors. Accompanying text: let us assume that the clock has a speed c in the observer's frame R′. One can now calculate the clock time unit for the observer. The relativistic hypothesis leads to a constant speed c for light in both frames R and R′. One calculates the half path OM in two different ways (equations (1)–(2) and (3)), from which T' can be expressed as a function of L, v and c. The time unit T (clock proper time, R frame) has been dilated by a gamma factor for the observer linked to R′.

Despite its particular look and *a priori* simplicity, this scenario really helps in the understanding of the spacetime notion by the students. Finally, the last scenario on intuitive illustration of concepts is devoted to Minkowski diagrams. These diagrams are 2D geometrical representations of inertial frames and event coordinates. They allow spacetime properties to be geometrically derived. For example, timelike or spacelike intervals are cleanly obtained, hyperbole calibrations are used to illustrate the length contraction or time dilatation. In these animated scenarios, geometrical constructions allow students to generate and intuitively understand special relativity effects.

The second type of scenario refers to what Einstein called a 'Gedankenexperiment'. Thought experiments were used a lot in the early years of special relativity's construction. To summarize, one can say that those thought experiments were supposed to 'test' the new born concepts by experiments impossible to perform in a real world. Often, these experiments were trying to manipulate everyday life object such as trains at relativistic velocity. Such experiments often led to an apparent paradox since they were dealing with macroscopic objects whose common behaviours are well known in classical mechanics. The main goal of the thought experiments is to focus on the special relativity effects that contradict common perception.

Following that historical point of view, we tried to illustrate with ICT scenarios some interesting consequences of special relativity (length contraction or loss of absolute simultaneity). Moreover, ICT scenarios allow the instructor to focus dynamically on different points of view of the same problem and to present the resolution of fake paradoxes. Among the scenarios falling in that category, we can distinguish two main themes. The first theme is devoted to the relativistic effect of length contraction. For example, one of the animations presents the length contraction of a pole held by a gladiator, Hercules, entering into a barn smaller than the proper length of his pole.

A similar but more detailed animation involves cows looking at a very fast train (i.e. relativistic). In that animation, the paradox comes from the fact that the cow who measures the train at rest is able to see the train disappear in a tunnel smaller than the proper length of the train. The last animation dealing with the length contraction is a complete study of the famous ruler and hole paradox [7]. ICT scenarios are very interesting tools to treat this type of problem. The student can switch from one frame to another and see the computation of the coordinates.

The second theme of thought experiments deals with the time concept and how simultaneity can be lost when changing frame. For example, the scenario in figure 4 shows three people in a relativistic train who compare the simultaneity (arrival time) of two events (each passenger receives a photon) in the frame linked to the inside or to the outside of the train. Time dilation is also presented in a scenario where moving clocks show different durations according to their motion. The moving clock is composed of one oscillating photon between two mirrors (see figure 5). The two cases, with translation motion or at rest, are simulated and the duration of one photon oscillation is computed with the postulate of constant velocity of light. In this case, the gamma factor is obtained by comparing the two durations.

3.3. Conclusion

In this paper, we concentrated on the animated scenarios built to carefully emphasize the contribution of experiment and intuition to generate the physical theory of special relativity. We categorized our developments into two types of ICT scenarios: real experiments and thought experiments. The first has the advantage of giving a complete view of a real experiment and its interaction with the theory. The second is well adapted to pushing the student to a deeper understanding of an abstract notion or difficult concept of special relativity. This is clearly the counterpart of a strict application of the mathematical formalism.

The fact that each student can work at his own pace, and can come back when necessary to any of these scenarios, has a net advantage compared to classical teaching. It is clear for us that this learning method enhances the participation of the students throughout the learning process and demands their focus. In some sense, ICT scenarios provide the student with a powerful tool to test his understanding of the different relationships between the components of the theory. In exchange, we observe that the teaching rhythm is slower than would be obtained in a classical lecture on a blackboard. This is why some break points (classical exercises and lessons) have to be scheduled to perform a status report and to set the remaining objectives. Based on our experience with these new developments, we believe that the student has to establish a dialogue between ‘classical’ teaching on one hand and ICTs on the other. The students benefit from these two parts of the learning process and will be able to achieve real practice of a modern physics theory.

It is too early for us to have a final estimation of the impact of information and communication technology resources in the teaching of special relativity. A serious evaluation would need to build the right tools in collaboration with specialists of didactics for instance. This evaluation should clearly be done on a short- and on a long-term basis. Some questions to address are whether on average students have a better understanding of basic concepts and if they keep benefitting from this type of teaching after a few years. Our objectives include, with didactitian collaborators, the development of tools to properly evaluate our products.

The animated scenarios mentioned can be downloaded at http://spiral.univ-lyon1.fr/00-perso/itc4relativity/index.htm.

Acknowledgments

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