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A teaching-learning sequence to present the relativity principle and the principle of equivalence in classical Mechanics to pre-service physics teachers

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Abstract We designed a teaching-learning sequence on the relativity principle and the principle of equivalence in classical Mechanics, rooted in previous research about students and teachers' conceptions. A series of experiments based on video analysis is used to highlight selected key concepts and to motivate students in their exploration of the topic and interactive simulations, which can be modified on the fly by student teachers, are used to stimulate autonomous investigation. The sequence was designed for teacher education at University level and was tested with a group of 20 pre-service physics teachers.

1. Introduction

The relativity of motion is a central concept in both Galilean and special relativity. Both theories use inertial reference frames to describe motion and two fundamental general principles can be shown to students in Classical Mechanics: the relativity principle (RP) and the principle of equivalence (PoE). The RP will be the starting point of Special Relativity while the PoE will be essential for General Relativity.

The RP of Galilean relativity grants equal status to all inertial frames of reference in uniform relative motion, with respect to the laws of mechanics while the PoE restricted to the realm of mechanics states that all the *laws of motion for freely falling particles are the same as in an unaccelerated reference frame*.

Student difficulties with inertial reference frames and relative motion have been documented in some papers in the past [1-2] while more recently students' understanding of the PoE and RP was also investigated [4-5]. According to some authors, learning effectiveness can be improved when students are allowed to see a movement in different frames of reference and perform the experiments independently while carrying out quantitative estimates.

Over the last years numerous experiments have been developed to help students to understand physics concepts regarding RP and PoE. Although there are some "good" educational experiments, few are available for inexpert students while most require that students and teachers have advanced experimental skills. Many experiments were focused on demonstration of Einstein's lift [5,6] and on the physics of free fall, as the ones illustrated in ref [7] where the author reported a collection of experiments by employing techniques that can be implemented by unskilled students. These experiments integrate new technologies such as smartphones and free software (Tracker®) for video analysis. [8]

In this paper we present an activity sequence, aimed at pre-service physics teacher's audience, designed to address students' difficulties as well as to help students acquire the elements of an explanatory model for the complex concepts involved in classical relative motions. The sequence proceeds through a combination of real experiments and interactive computer simulations, designed to favour students' understanding.

2. Methodology

We made a few fundamental decisions regarding the design of the teaching sequence which can be summarized as follows:

a) Propose activities based on a combination of real experiments (based on Video Analysis) and interactive simulations (within the freeware 2D simulation environment Algodoo)
b) Follow a *Predict-Observe-Explain* (POE) strategy, an interactive teaching strategy which we implemented during the sequence [9-10]
c) Let students perform the data analysis, the modelling activities and the explain phase individually, in small or large groups, guided by the instructors who stimulated a discussion about the outcomes of the experiment.
d) Engage students in the step-by-step process of constructing a qualitative model that they can use to predict and explain and encourage autonomous exploration of problems starting from motivating questions.

3. The sequence

We identified some central themes, focusing on the two relativity principles. Schematically, the main aspects we highlighted with students were:

- Inertial Frame of Reference (RP)
- Non Inertial Frame of Reference
- Non-Inertial (Free-Falling) Frame of Reference (PoE)

Table 1. The concepts tested by the pre-test and a summary of the activities. Although some questions are linked to more than one concept, we have assigned each question to just one concept.

Concept	Description of the task	Questions
Inertial reference frame	a) Video analysis of a motion seen from two different reference systems in uniform straight motion with respect to each other	1, 2
Non-inertial reference frame (with constant acceleration on the horizontal plane)	b) Video analysis of a motion seen from two different reference systems in straight motion uniformly accelerated with respect to each other	3
Non-inertial reference frame (inclined plane)	c) Video analysis and simulations of the surface shape of a liquid in a container descending along an inclined plane	4,5
	d) Algodoo simulation of pendulum swings in a cart descending along an inclined plane	6,7
Free-falling reference frame	e) Video of a qualitative experiment with a perforated free-falling bottle filled with water	8
	f) Simulation of horizontal motion in a free-falling lift	9
	g) Simulation of the behavior of a mass-spring system in a free-falling lift	10
	h) Video analysis and simulation of the motion of a pendulum in the lift in a free-falling lift	11 (open)

The sequence of activities is organized into six parts: (A) Introductory examples and experiments: the different trajectories in different Inertial reference frames; (B) Linearly Accelerating Non Inertial reference frame: the different trajectories; (C) Liquids' Surface Shape in Accelerated Non Inertial reference frame (incline); (D) Pendulum in Non Inertial reference frame (incline): center and period of oscillations; (E) Free-falling bottle filled with water; (F) horizontal motion in a freefall lift (G) Demonstration of Einstein's lift (spring mass) ; (H) The pendulum in the Einstein lift.

In the following we describe the main features of the sequence, paying special attention to experiments and simulations involved. We also focus on students' difficulties, and in discussing them we compare known results from the literature to our findings from student teachers' pre-activity tests.

3.1 Inertial reference frame

We proposed two questions taken by *Relativity concept inventory [11]* and we found out the difficulty of students to visualize the trajectory of objects from different reference frames, which is a common misconception [106]. In the remote lab Course, to observe the trajectory of objects in uniformly relative motion, a student realized a video by himself. He was standing on a car which was moving at constant speed, when he launched a ball vertically from his perspective, as shown in Figure 1.

By looking at the entire video it becomes clear that the ball falls in his hand again, i.e., there is no relative motion along the horizontal axis between the ball and the guy standing on the car.

By using Tracker, it is possible to set the reference frame on moving object. In this case, it was therefore possible to analyse the motion from both the reference frame at rest, and the one moving by uniform motion with the car.

By looking at the trajectory from the car's reference frame, the ball and the hand of the student always share the same x-coordinate. The x-component of the velocity of the ball was zero.

The Galilean transformation can be quantitatively obtained by measuring the velocities and by fitting the trajectories.

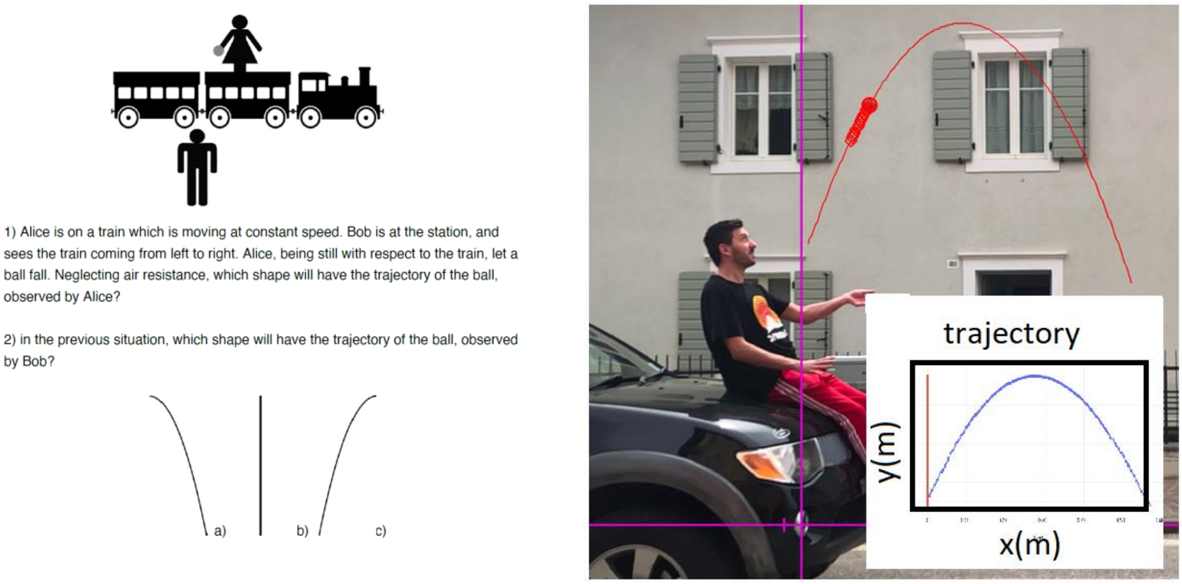


Figure 1 Questions 1 and 2. Some students made a video on their own. A student was sitting on the bonnet of a car moving at constant speed when he threw a ball vertically from his point of view and the ball fell back into the student's hand, Thanks to Tracker students can view the trajectories in the two different reference systems starting from the same video.
The video is available here: https://www.youtube.com/watch?v=hlxLNPzViGg&feature=youtu.be

3.2 Non-inertial reference frame (with constant acceleration on the horizontal plane)

Students in introductory physics courses have great difficulty distinguishing the case of inertial and non inertial reference frame. Thus, ideas about the trajectories of a body were confused also in this case, even though someone predicted correctly that, when the ball is shot vertically upward from the train while the train is accelerating, the ball will not land in the hand of Alice.

Thus, differently from the inertial case, from the accelerating reference frame, the ball would have moved away along the horizontal axis. With the aim of overcoming the students' difficulties we propose a demonstration which shows this phenomenon. Since realizing such a kind of experiment at home is quite difficult (or hazardous using the same apparatus of the previous one), we decided to analyse a video recorded in physics lab, before quarantine started, and based on the PASCO equipment [12].

3.3 Non-inertial reference frame (inclined plane)

The surface shape of a liquid in an accelerated system is a typical topic faced in introductory physics courses and is useful to understand and visualize a complex and non-intuitive concept and improve the understanding of the fictitious forces. When we ask the students to predict the shape of a liquid in a box climbing down along an incline without friction, ideas are confused and just one over five students answered appropriately.

We asked students to realize a video with commonly used objects available at home, in order to reproduce the behaviour of a liquid tank climbing down along an incline and also, we showed a video demonstration made by one of the instructors with day life things.

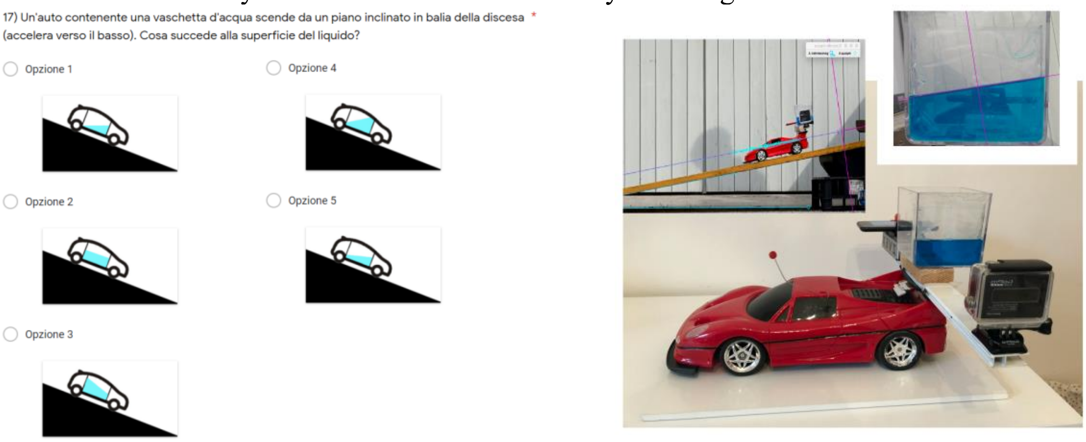


Figure 2 Question 4. Setup of the experiment. Measure of the angle of the liquid's surface by analysing the video recorded by the action camera, jointed to the car. The car at restin the inset the car accelerating down the slope and the inclined surface of the liquid. The x-axis of the Cartesian plane here shown corresponds to the horizontal plane.

To investigate this situation, students also worked with virtual simulations performed by using Algodoo. Students worked with Algodoo simulations reproducing the system of the pendulum in the cart descending along the incline. By running the simulation, it becomes clear that the equilibrium point, which corresponds to the centre of the oscillating harmonic motion moved away from the vertical and the period of the pendulum becomes larger.

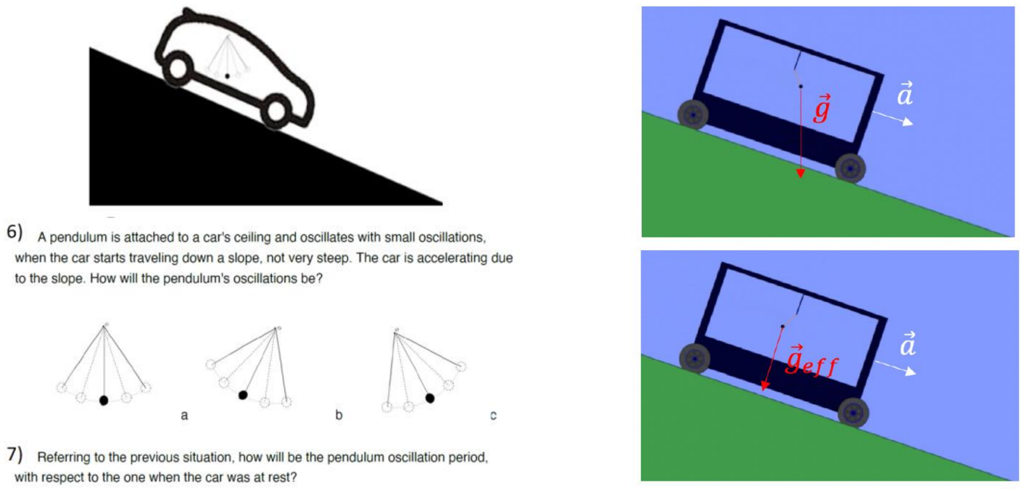


Figure 3. Left: Questions 6 and 7. Right: The Algodoo simulation

3.4 Freefall reference frame

We focussed on what happens in a free-falling reference frame with 4 questions, describing physical situations easily reproducible in home-made experiments or simulations.

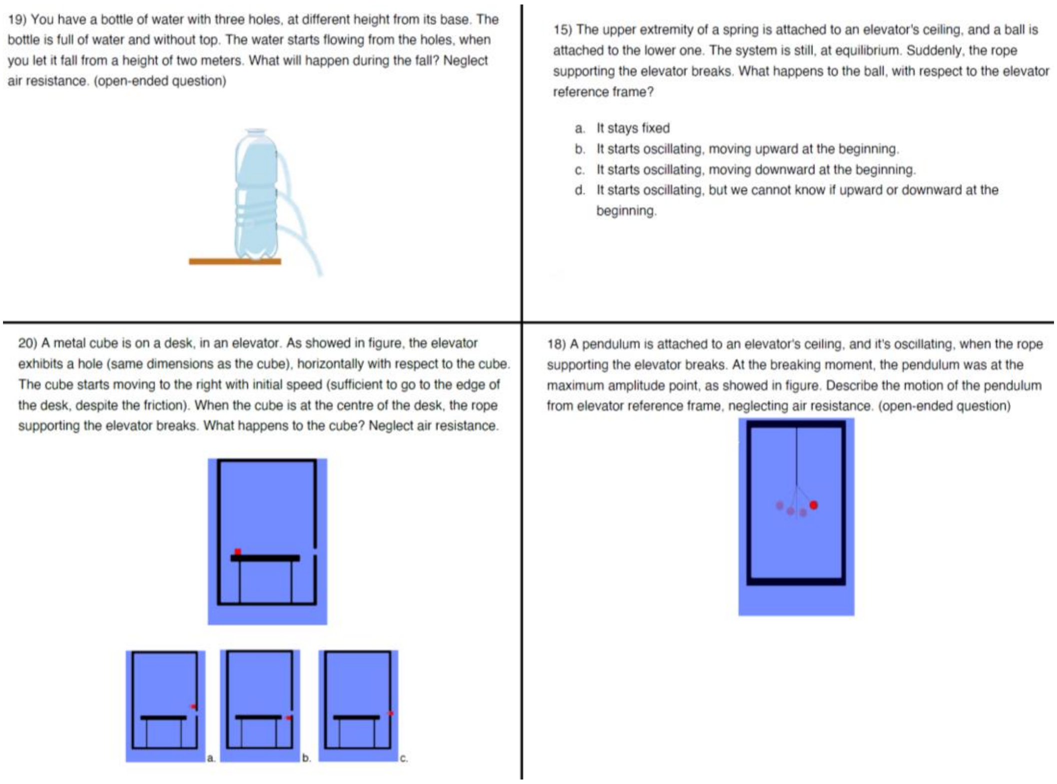


Figure 4 Questions 8,9,10, and 11 about the free falling system

The first question concerns the free-falling bottle: just one student over five is sure that during the free-fall, the water is no more sloshing out. In the second question we present an object moving along the horizontal direction in a lift, initially at rest. We ask students to predict the motion when the lift starts to fall. Here most of the students answered that the cube will move also upward with respect to the lift. The next question concerns a spring in the Einstein lift, and we can notice that many students answered correctly about the motion of the spring mass system in free fall, also if a relevant part thinks that the ball would stay at rest with respect to the lift reference frame.

The last question is an open-ended question which concerns the motion of a simple pendulum in the free falling "Einstein" lift. In this case there were many kinds of answers.

It is very useful for students to reproduce the physical situations proposed in the questions, performing the experiments independently and making quantitative estimates whenever possible.

The first experiment is a simple qualitative activity, and we asked the students to carry out the experiment of the free fall bottle at home and analyze the video, just qualitatively and observe that when the bottle begins to fall, suddenly no more water comes out.

For the next question, about an object moving along the horizontal direction in a freefall lift, the students worked with a virtual Algodoo simulation.

The spring mass system and the oscillating pendulum were proposed through some videos acquired by one of the instructors, analyzed by the students with Tracker and accompanied by some Algodoo simulations made by the students. In Figure 6 we show some images of the proposed models of Einstein's lift.

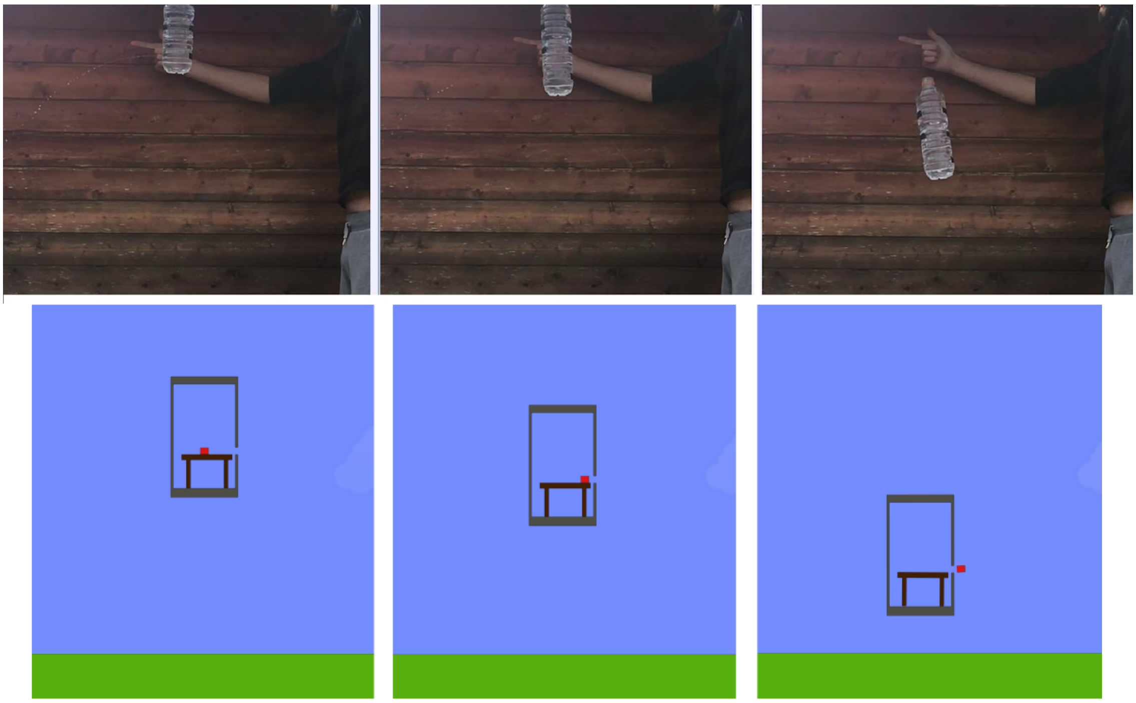
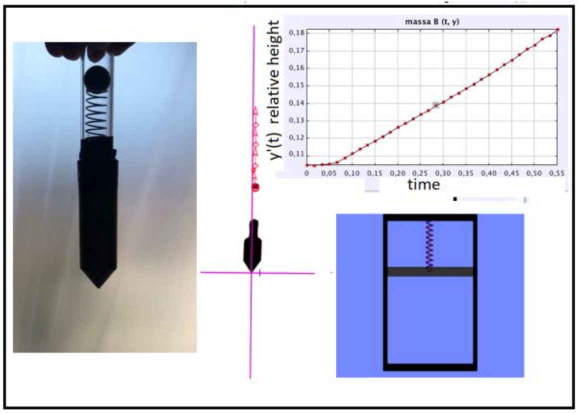


Figure 5 Experiment about question 8 and simulation about question 9 performed autonomously by students

The students first observed the lift at rest, when the two forces acting on the steel sphere, the gravitational and the elastic, are balanced. After release, the lift freely falls down while the spring deformation disappears due to weightlessness in the falling lift. So, the spring pushes the ball upwards and, after the very short time the spring stretches, the ball moves with constant speed in the lift reference system. Thanks to the use of Tracker students were able to build the graphs related to the motion of the lift and the ball in the two different reference systems, both the ball and the lift have an accelerated motion in the laboratory system while the ball has a uniform motion in the lift reference system. Students in this way understand that a body that falls freely in the gravitational field has no weight, even if the force of gravity acts on the body.



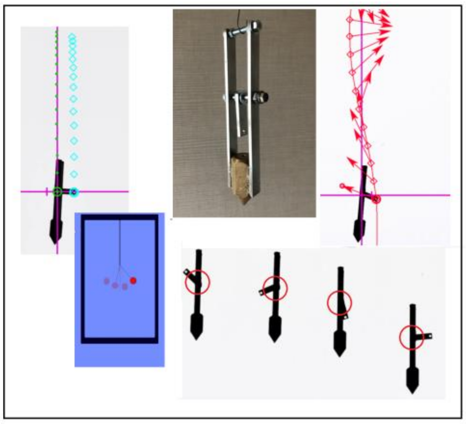


Figure 6 Experiments and simulations about questions 10 and 11. The two videos are available at:
https://www.youtube.com/watch?v=c9jtOKSis28&feature=youtu.be
https://www.youtube.com/watch?v=06cep5VCdrI&feature=youtu.be
https://www.youtube.com/watch?v=F_Ta53LuuGw&feature=youtu.be
https://www.youtube.com/watch?v=oh-HRTN83tc&feature=youtu.be

For the quantitative investigation of the falling pendulum, the students analyzed two videos with Tracker in both the reference frames.

At the end of the video work, the students worked with the Algodoo simulations which exactly represented the physics in the free-falling lift. The simulations were really useful for students, in order to explore a vast scenario of events by changing the initial conditions, that is, changing the moment when the rope supporting the lift breaks. For example, using simulations, it becomes clear that, in case the pendulum was inverting the point of movement at the time of release, it would be absolutely at rest compared to the lift.

4. Results

The sequence was designed for teacher education at University level and was tested with a group of 20 pre-service physics and mathematics teachers who, during their path, attended two mechanics courses (the first about Newtonian mechanics, and the second about Lagrangian and Hamiltonian mechanics at University of Trento. The programs of these courses included reference frames and classical relative motion.

We analyzed data from:

- A pre-test questionnaire
- Some final examinations
- Some teaching-learning interviews
- Some questions to assess the course

We are now going to summarize our quantitative and qualitative results.

The focus of the pre-test questionnaire was on the main concept of the teaching-learning sequence (Table I) with the double function of enlighten student's difficulties and misconceptions, and trigger their attention to the topic, asking them to make previsions. The overall analysis of the pre-test confirms the problematicness of the topic, and the student's difficulty in predicting the behavior of simple mechanical systems in relative motion between each other.

The analysis of the student's answers during the final examination showed us that the sequence revealed to be effective not only in understanding some difficult concepts, but also in developing a different approach to analyze physical phenomena.

To explain a particular phenomenon, many students used to build an Algodoo simulation, and then analyze it in different situation. Each student was able to deal with the problems and the questions in a proper way, showing a deep understanding of the fundamental concepts.

Then, we performed the teaching-learning interview with some students on different problems correlated with the Galilean relativity principle and the Einstein's equivalence principle. The problems were something similar to the pre-test situations (Alice on the train, the free-falling bottle filled with water, the free-falling pendulum, the pendulum going down an inclined plane) but often the discussion brought us to talk about the orbiting space station, as a free-falling system or a system in which the fictitious forces balance the gravitational force.

What it emerges is that, even if the majority of the students was able to deal with these kinds of problem in an effective way, reaching the right solutions, the use of the relativity/equivalence principle was absolutely limited.

4.1 Student's evaluation of the teaching-learning sequence

To compare the different activities, we asked students to give an evaluation their personal experience in three dimensions in a Likert scale from 1 to 5:

- Effectiveness in terms of comprehension of a phenomenon thanks to the proposed activities
- Enjoy and fun during each laboratory activity
- Engagement and personal interest during the activities

The results are in the following table.

Table 2. Students' evaluations of the different activities performed during the teaching-learning sequence.

Activity	*Effectiveness*	*Enjoyment*	*Engagement*
Experiments realized by students at home	4,1	3,5	3,8
Experiments realized at home by the teacher	4	3,7	3,5
The use of Algodoo to create virtual simulations	4,3	3,9	3,8

Each activity revealed to be really effective. The experiments carried by the teacher scored a higher Enjoy value, but a lower Engagement value. On the contrary, kitchen experiments, designed and performed at home by students resulted to be more engaging. Students liked more Algodoo simulation on both these two dimensions but, many students underlined that real hands-on experiments can never be replaced by virtual simulations.

We also asked to students what they think about the POE strategy, the performing hands-on experiments and virtual simulations. Student A said that '*real experiments work really good because they surprise the student*' because '*often what you see is surprisingly different from what you expected*', and a similar effect can be attributed to virtual simulations. Student B said, '*If I see a phenomenon with my eyes, it remains impressed and I'll never forget it'* and also reaffirm '*the importance of touching objects*' i.e., having the hands on the experimental apparatus. Talking about the POE approach, student B said that its main function is to '*make you think and activate interest and curiosity*' while for student A the main goal of POE consists in '*creating a cognitive conflict when predictions and observations don't* converge'.

5. Conclusions

A teaching-learning sequence for classical relative motion was designed for teacher education at University level and was tested with a group of 20 pre-service physics and mathematics teachers at University of Trento. During the entire sequence, our main goals were to provide a better understanding of the Galilean relativity principle and the Einstein's equivalence principle.

By analyzing and comparing the pre-tests and the final examination outcomes we can affirm that the sequence let students obtain a much better, deeper, and more precise understanding of the topic.

The activities based on video-analysis were used to enlighten experimental situations, and virtual simulations were essential to explore a vast scenario of different situations (for example changing the initial condition of the problem), providing an ideal environment for an inquiry activity.

The main limits of our analysis are the relatively small number of students on which we tested the teaching-learning sequence, and the fact that we did not performed a written final post-test. Anyway, we are planning a wider experimentation with a larger amount of university students, to evaluate if the sequence is proper for general physics courses. When doing this, we will add a delayed post-test, something like six months after the sequence, to verify the hypothesis that our approach could bring students to a deeper and durable conceptual comprehension of the main topics of classical relative motion.

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