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Investigating the Principle of Relativity and the Principle of Equivalence in classical mechanics: A teaching learning sequence based on experiments and simulations

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Summary. — We present a teaching-learning sequence on relative motion that addresses some fundamental aspects such as the principle of relativity and the principle of equivalence in classical mechanics. To highlight key concepts and motivate students to explore the topic, experimental activities based on video analysis and some interactive simulations were used, which can be modified on the fly by the students. These tools are useful to stimulate autonomous investigation and to support the modelling of different physical situations.

1. – Introduction

Relativity of motion is a central concept in both Galilean relativity and the modern theory of relativity. Both theories, classical and modern, use the concept of the inertial reference frame to describe motion, and the two fundamental principles can be presented to students already in the study of Classical Mechanics: the principle of relativity (RP) and the principle of equivalence (PoE). RP will be the starting point of Special Relativity while PoE will be essential for General Relativity. Thus Classical relativity is a relevant and critical subject in teaching physics.

In this work we present a teaching-learning sequence (TLS) designed to address students' difficulties and to help them to acquire the fundamentals of an explanatory model for the complex concepts involved in relative motions in classical mechanics. The development of TLSs is an important line of research in science education. It focuses on the design and evaluation of curricular products that include sequences of activities that aim at improving specific topics [1].

The TLS on Relativity proceeds through a combination of real-world experiments and interactive computer simulations, designed to foster students' understanding. The design of the sequence was based on a careful analysis of the textbooks and on the results of the research on students' difficulties. A relevant factor in designing the TLS was related to the temporary closure of university laboratories due to the spread of coronavirus

(COVID-19) in the spring of 2020. So we were forced to redesign the sequence by transforming the traditional face-to-face lab course into an online course. Therefore, while adopting a distance teaching methodology, we tried to offer students an authentic and meaningful laboratory experience, capable of providing the rigor required in a physics laboratory. Most of the experiments in the sequence are demonstrations performed by teachers (quantitatively analyzed by students) or experiments performed by students alone, simply using everyday objects available at home, a kind of experimental activity that we could define as "kitchen physics".

2. – TLS Design

A) Educational context. The sequence of activities was designed for students in introductory physics courses and was tested with a group of 24 undergraduate students in an online lab course, in which some distance learning tools were also tried.

B) Didactic choices. We made some central decisions about the design of the TLS as follows: a) follow a Predict-Observe-Explain (POE) strategy, an interactive teaching strategy that we implemented during the sequence [2]; b) propose activities based on a combination of real experiments and interactive simulations; c) let students perform experimental and modelling activities even in absence of specific equipment; d) when it was not possible for the students to perform the experiments themselves at home, the experiments were replaced by some demonstration videos with experiments also performed with objects of common use at home by the teacher; e) let students perform data analysis, modelling activities and explanation phase individually, in small or large groups; f) involve students in the step-by-step process of building a qualitative model that they can use to predict and explain; g) encourage autonomous exploration of problems starting from motivating questions.

3. – Description of the sequence

We identified some central themes, focusing on the two principles of relativity. Schematically, the main aspects that we highlighted with the students were: a) Inertial Reference frame (RP); b) Non-Inertial Reference frame in accelerated motion with uniform acceleration; c) Einstein's elevator, in free fall (PoE).

Once we identified the main Learning Goals, we gave attention to students' difficulties and, by discussing them, compared the known results from the literature with the results of a pre-activity test proposed to students. Thus we designed a specific experimental activity aimed to address students' difficulties with specific concepts. In table I we summarize the Learning Goals and the experimental activities proposed during the TLS.

3·1. *Predict*. – In the predict phase students answered some questions for each of the main conceptual areas. The questionnaire was intended to focus on the fundamental concepts underlying our didactic sequence and had the function of stimulating students towards the investigation of each phenomenon by encouraging them to make predictions. The overall analysis of the questionnaire stressed the students' difficulties while approaching inertial, non-inertial and free-falling reference frames: they found it difficult to make predictions about motion but also to detect the initial condition of the problem from a different point of view.

- *Inertial Reference frame (RP).* Two questions from the Relativity Concept Inventory [3] and the answers confirmed students' difficulty in viewing the trajectory of objects in different RFs;

TABLE I. – *The concepts tested by the pre-test and a summary of the activities*

Conceptual area	Activity
Inertial reference frame	Video analysis of a motion seen by two different reference frames in uniform rectilinear motion with respect to each other.
Non-inertial reference frame	Video analysis of a motion seen by two different reference frames in straight motion uniformly accelerated relative to each other. Video analysis of the shape of the surface of a liquid in a vessel descending along an inclined plane. Simulation of the surface of a fluid in an accelerated vessel.
	Algodoo simulation of the oscillations of a pendulum in a car descending along an inclined plane.
Free fall reference frame	Video of a qualitative experiment with a perforated bottle in free fall. Simulation of horizontal motion in an elevator in free fall.
	Simulation of the behavior of a mass-spring system in a free-falling elevator.
	Video analysis and simulations of the motion of a pendulum in the elevator in an elevator in free fall.

– *Non-inertial reference frame in accelerated motion with uniform acceleration.* Students were not able to distinguish the case of the inertial RF from the non-inertial one; they also confused concepts about the trajectories of a body in two RFs. Students failed to predict the shape that the surface of liquid takes in an accelerated system and the center and the period of small amplitude oscillations for a simple pendulum placed in an accelerating RF;

– *Einstein elevator, in free fall.* Some learning difficulties that emerged concern the equality of inertial mass and gravitational mass, and the ideas of "weight" and "weightlessness". We asked students to point out what happens in a free fall RF with 4 questions describing physical situations that can be easily reproduced in homemade experiments or through simulations developed independently by the students.

3·2. *Observe.* – With the aim of challenging with these topics we proposed experimental activities which answer the questions in the test. When the university laboratory was available, we used specific equipment and demonstrations performed by teachers, while, during the pandemic, in the remote laboratory course some students tried to make videos by themselves simply using everyday objects available at home. Once the video of the experiment was shot with their phones, students quantitatively analyzed motion in the different RFs using Tracker Video Analysis [4-6]. Algodoo simulations designed and realized by students helped them to analyze some of the topics proposed in the test items. In fig. 1 we compare some items of the pre-test and some experiments realized at home by students.

4. – Results

The sequence was tested with a group of 24 university students in Physics and Mathematics in a course aimed at training future physics teachers. We analyzed the data

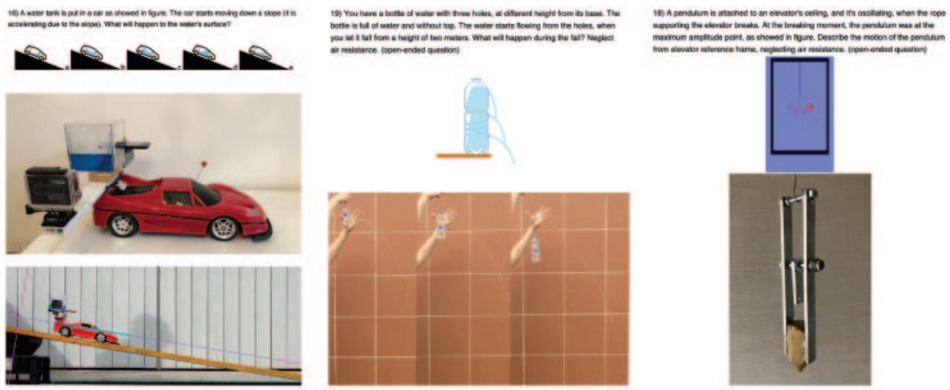

Fig. 1. – Items and corresponding experiments.

collected from asurvey provided before the activities (pre-test), some teaching/learning interviews and some questions for the evaluation of the course.

The problems proposed in the interviews mainly follow those of the pre-test and we found that, although most students were able to address the problems proposed by providing correct solutions, recourse to the principles of relativity and equivalence is very limited. As far as the principle of relativity is concerned, it is typically replaced by the usually adequate use of the principle of inertia and students rarely approach problems by resorting to Galileo's transformations.

Analogously, the principle of equivalence often is not mentioned spontaneously in dealing with the discussion of systems in free fall, where fictitious forces are widely used.

With the aim of comparing the different approaches to the lab, we first compare the evaluation of students on the various kinds of activities. We asked students to rate experiences in terms of 3 dimensions on a Likert scale from 1 to 5: i) Effectiveness in terms of understanding a phenomenon thanks to the proposed activities. ii) Enjoyment during each workshop activity. iii) Engagement and personal interest during the activities. All activities have been evaluated as very effective. The experiments performed by teachers have been considered more funny but less engaging, on the contrary, the cooking experiments designed and performed at home, although less funny, have been evaluated as more engaging. Algodoo simulations have been preferred to experiments on each of the different dimensions, although in the comments reported by the students, many of them have pointed out that simulations can in no way replace real experiments.

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