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An online teaching learning sequence with home experiments and simulations on relativity of motion and the equivalence principle in classical mechanics

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Abstract. We designed a teaching-learning sequence on relative motion in classical mechanics, based on the fundamental design principle of highlighting those conceptual elements which could be valuable in the future learning of special and general relativity In order to highlight selected key concepts and motivate students in their exploration, we used a series of experiments based on video analysis and interactive simulations, which can be modified on the fly by the students. In this study, we introduce a pilot investigation focused on testing the instructional sequence, and we provide initial outcomes regarding students' understanding. The sequence of activities was tested with a group of 24 undergraduate students in an online laboratory course during the COVID-19 pandemic.

1. Introduction

Classical mechanics (CM) represents our best understanding of physical phenomena in the macroscopic world surrounding us and forms a conceptual paradigm which is the reference and comparison for all other possible ways of modelling and understanding Nature. Not surprisingly, CM contains within itself concepts and principles which can pave the way for better understanding of different theories or areas of science, and several different reconstructions and reorganizations of the content of CM are possible. For example, by emphasizing the role of the principle of least action, one may formulate classical physics in such a way as to highlight structural analogies with quantum mechanics [1]; reconstructions of CM centred on energy conservation, transformation and transfer may form the base for an integrated understanding of energy also in thermodynamics and chemistry [2]; and a focus on conservation principles (energy, momentum, angular momentum) is advocated for bringing students nearer to a modern perspective on physics, with immediate applications in particular to particle physics [3].

In this work, motivated also by the current research interest on an early introduction of general relativity [4] we propose a teaching-learning sequence (TLS) based on an educational reconstruction of relative motion in CM focused on those elements which may facilitate the adoption of a relativistic world view, in particular the principle of Galilean relativity (PGR) and the principle of equivalence (PoE).

The activity sequence was 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 favor students' understanding.

2. Theoretical and methodological framework

Our work is based on the Model of Educational Reconstruction (MER), and the German Didaktik tradition [5], which was one of the main sources for the original elaboration of MER. In fact, our choice of science content was heavily driven by instructional goals, which can be summarized in the general question: what is useful for teaching relative motion in CM in such a way to facilitate the future adoption of a relativistic world view by students? Such question oriented our analysis (historical and epistemological) of the science content of relative motion in CM and guided our review of existing textbooks and educational materials. Both these processes played a significant role in shaping the final design of our TLS.

Great attention was given also to the second “leg” of educational design according to the MER, namely the analysis of educational research literature on student difficulties and educational strategies. In this sense, a key choice was the regular adoption of the Predict-Observe-Explain (POE) approach [6,7] to probe and bring to the surface student difficulties, produce occasions of cognitive conflict, facilitate conceptual change.

2.1 Main elements of an analysis of science content

The Principle of Relativity (PoR) grants the same status to all frame references in uniform relative motion, with respect to the laws of mechanics. The PoR can be taken as a postulate of classical mechanics [8] but this is not usually done in textbooks, a more common approach is to present it because of the definition of inertial frames of reference, and the principle of inertia. Historically, the PoR was first formulated to explain why the motion of the Earth with respect to the stars, as postulated within the Copernican system, would not have been detectable through an experiment performed on Earth.

The Principle of Equivalence has played an indispensable heuristic role in the conceptual transition from special to general relativity. Notwithstanding a century of debate on whether the PoE really is at the foundations of general relativity[9], its educational value in the conceptual understanding of Einstein’s theory of gravitation is generally recognized [10].

The concept of frame of reference is identified as central for understanding the content of both principles. First the distinction between observer/container and frame of reference has to be clarified, then the evolution of the concept of frame of reference from classical mechanics to special relativity (latticework of synchronized clocks and measuring rods) can be introduced.

Moving on to discuss the formal curriculum, the PoR is mentioned in the Italian guidelines in the following statement regarding the beginning of the second cycle of high school (grade 11): “The laws of motion will be reconsidered, in parallel with the discussion of inertial and non-inertial frames of reference and of the principle of relativity of Galilei” Several Italian textbooks present the PoR using the passage of the “gran navilio” from Galileo’s “Dialogue Concerning the Two Chief World Systems”. This seems a good approach although the meaning of that passage in Galileo’s line of argumentation also should be highlighted, as it clarifies the actual content of the principle (impossibility to distinguish with an experiment carried out from within an inertial system whether it is still or in uniform motion).

The PoE is never mentioned in the Italian secondary school curriculum and many students never encounter it before university; however, some high school textbooks discuss it in “special” pages devoted to more in depth scrutiny of topics. Some textbooks, even at university level also neglect to discuss the PoE and the equivalence between inertial and gravitational masses before the chapter about relativity.

2.2 Main elements of an analysis from the point of view of the learner

Previous research has emphasized the need for a progressive construction of the concept of FoR [11] from the ingenuous model which includes an identification with the observer, and the idea of absolute rest, to the Newtonian and then the Einsteinian versions of the concept.

Some researchers [12] have found that some students tend to develop versions of the PoR in which invariance of physical laws is connected to ‘container-systems’ (trains, ships, planes) in which all objects have the same velocity, and thus would apply to non-inertial systems also. It was also highlighted that some students show what has been called “relativistic noise”, consisting in the belief that the PoR can be *violated* in the relativistic limit, for example believe that an observer can infer the state of motion of the FoR in which she id at rest, by observing relativistic effects. This, indeed, is the main point of several items in the RCI.

Research on student understanding of the PoE is scarce. However, Bandyopadhyay and Kumar [13] found that a) few students problematize the proportionality between inertial and gravitational mass; b) of those who do, many believe such proportionality must necessarily be an identity; c) few students can reconcile the idea of a free-falling system as inertial with the Newtonian perspective, and few can concretely apply the PoE to the solution of problems in mechanics.

2.3 Reconstruction of the content for instruction

With the aim of engaging students in the step-by-step process of constructing their knowledge, we propose activities based on a combination of real experiments (based on new technologies such as smartphones and free software, Tracker®, for video analysis[14]) and interactive simulations (within the freeware 2D simulation environment Algodoo [15,16]).

In general, experiments are designed with the goal of making the principles of relativity and equivalence relevant from students already at the level of classical mechanics. In fact, both the PoR and the PoE can be used as auxiliary reasoning tools in classical mechanics. For example, in the following problem an approach based on the PoR is an alternative to an approach based directly on the composition of initial velocities:

"*In the reference system of a cart moving horizontally at speed v with respect to the ground, a stone is thrown upwards with vertical speed w. Determine the distance at which it falls back to the floor in the frame of reference of the ground*."

Similarly, in the following problem an approach based on the PoE is an alternative to an approach based on inertial forces:

"A support with a simple pendulum mounted on it is sliding without friction on an inclined plane with inclination α. The pendulum is oscillating. What is the direction of the axis passing through the pendulum's pivot with respect to which the oscillation is symmetric? Is the duration of small oscillations longer or shorter with respect to the same pendulum oscillating on a fixed support in the laboratory?"

Since the test was carried out during the pandemic, a constraint to consider was related to the requirements of distance learning. Several experiments have been proposed in the literature to improve students' understanding of classical relativity and overcoming known misconceptions. Although many of these proposals are excellent, only a few are suitable for unskilled students and do not require a well-equipped physics lab. These experiments were mainly aimed at presentation of Einstein's lift[17,18,19] and on the physics of free fall, as the ones shown in ref.[20].

3. Description of the teaching-learning sequence

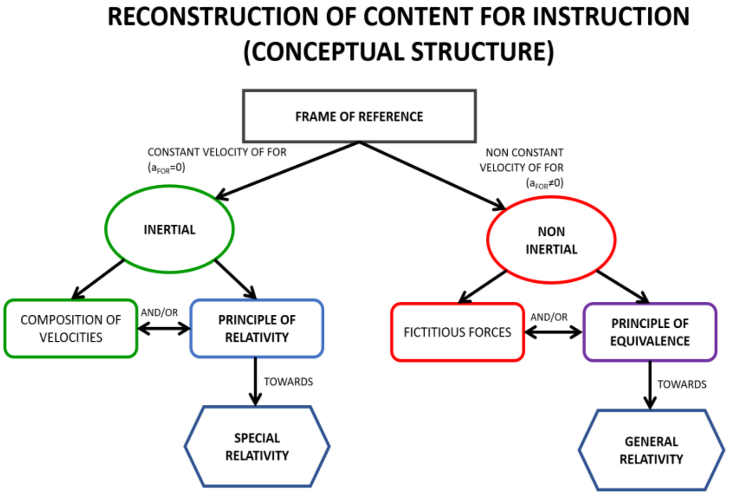


Figure 1 The structure of a TLS on relative motion (partial reconstruction of the content of classical mechanics) centered on the principles of relativity and equivalence.

The key concepts on which our TLS is based following the analysis process summarized above are a) The concept of Frames of Reference (FoR) and their classification into inertial and non-inertial; b) the Principle of Galilean Relativity (PGR) c) the Principle of Equivalence (PoE).

The sequence of activities is organized into 6 parts: (A) Introductory examples and experiments: trajectories in different inertial reference frames; (B) Non-inertial reference frame: trajectories in a linearly accelerated FoR; (C) Free surface of liquids in non-inertial linear accelerated FoR; (D) Pendulum in a non-inertial reference frame (cart rolling on an inclined plane): center and period of oscillations; (E) Bottle of water in free fall and demonstration of Einstein's elevator (interacting magnets and mass on the spring); (G) Pendulum in Einstein's elevator.

For each of the steps of the sequence, we use experiments, either performed at home by students or in some cases remotely by the teacher, and in some cases also Algodoo simulations.

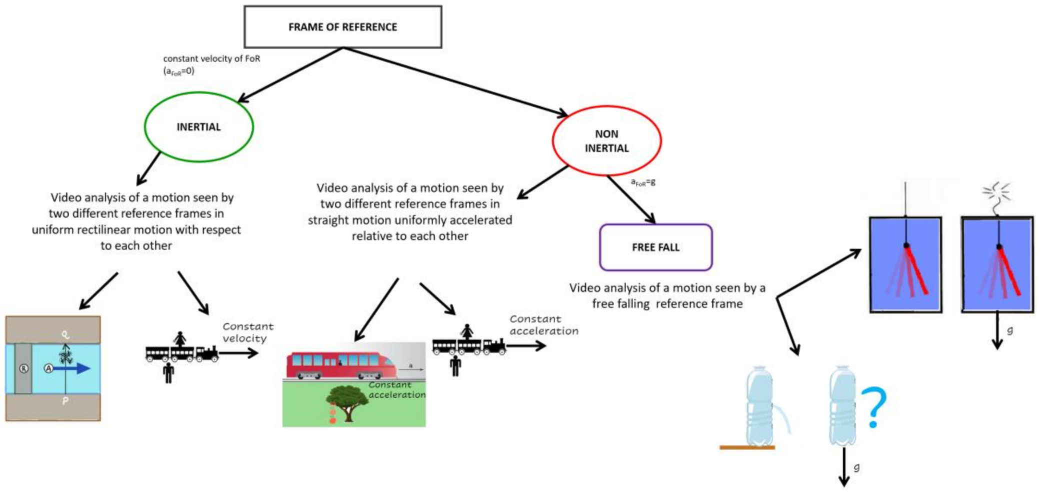
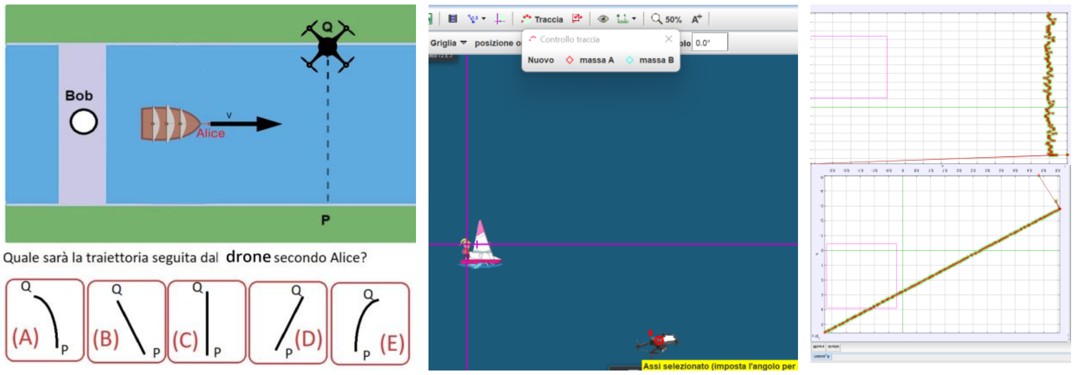


Figure 2 The structure of the TLS on relative motion and the typical examples involving inertial Frame of references, non-inertial FoR and free falling FoR.

3.1 Trajectories in different inertial reference frames

Introductory experiments are meant to clarify the meaning of Galilean transformations between inertial reference frames. Since Algodoo cannot natively produce graphs of quantities in different frames of reference, we adopt the practice of using Tracker video analysis on Algodoo simulations also.

Students were presented with three distinct questions. The initial inquiry, depicted in Figure 3, is as follows: "Bob is situated on a bridge spanning the river. Alice is positioned on a boat that is in motion along the river at a steady velocity. Meanwhile, a drone takes off from point Q and travels to point P at a constant speed."



Quale sarà la traiettoria seguita dal drone secondo Alice?

Figure 3. The question (left panel). In the middle panel a frame from the video of an Algodoo simulation designed by a student to reproduce the question. (right panel) The Tracker Analysis of the video shows the path of the drone for Bob(top) and for Alice (bottom).

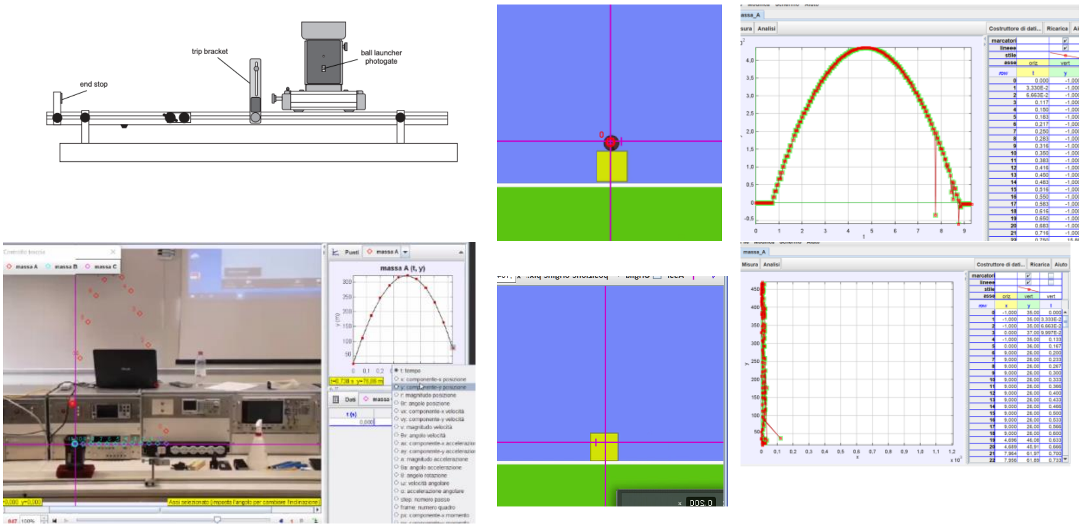


Figure 4 Video and Video analysis of the real experiment. (Midlle) Two frames of a simulation designed by a student (right) Video analysis of the simulated experiment.

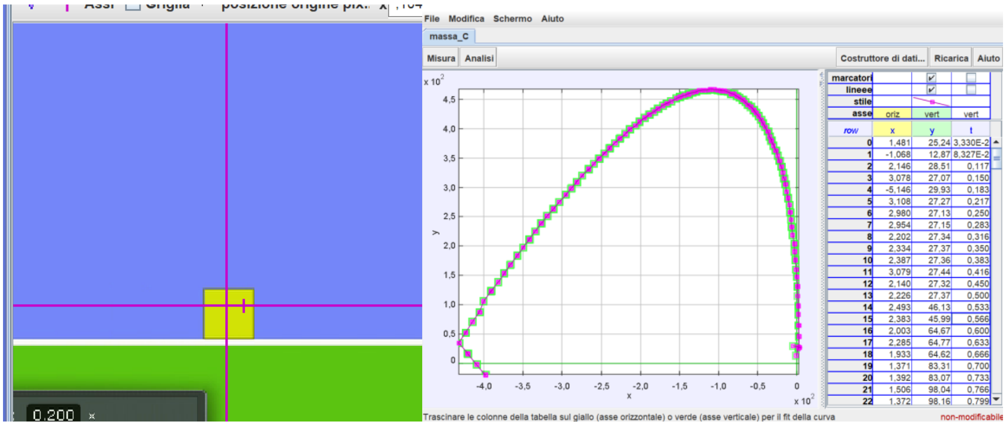
Subsequently, we introduced two questions derived from the Relativity Concept Inventory[21], and the provided responses reaffirmed the challenge students face in conceptualizing object trajectories within varying reference frames—an often encountered misconception. The original questions from the RCI were as follows: "Alice is standing in a train moving at velocity v from left to right relative to Bob, who is standing on a platform. As Alice passes Bob, she drops a bowling ball out of the train's window: Ignoring air resistance, which path of the ball would Bob observe, standing on the platform?" To recreate this phenomenon within a laboratory environment, we utilized the Ballistic Cart Accessory in conjunction with the Cart and track [22] to launch a plastic ball vertically from the moving cart. Given the cart's constant velocity, the ball would subsequently descend and return to the cart's catcher. Notably, the ball's release was initiated using a photogate, thus ensuring no impulse was imparted to the cart upon release. The experimental arrangement is illustrated in figure 4 where we also present an Algodoo simulation devised by a student to replicate the analogous phenomenon.

3.2 Trajectories in non-inertial reference frames

We introduce the experimental activity asking a question: *Alice is standing in a train from left to right relative to Bob, who is standing on a platform. As Alice passes Bob, a ball is thrown vertically upwards from the train while the train is accelerating. Ignoring air resistance, what path of the ball would Bob observe, standing on the platform?*

To discuss the case of a non-inertial FoR with the students in the face to face laboratory they employed the Ballistic Cart Accessory with the Cart and track, acquired a video and analyze it with Tracker. The video shows that if the ball is thrown vertically upwards from the cart while the cart is accelerating, the ball will not land in the cart. Since carrying out such an experiment at home is quite difficult, students designed a Algodoo simulation, then acquired a video and analyzed it with tracker.

Also in this case, it was therefore possible to analyze the motion both from the FR at rest, and from the one that moves by accelerated motion. In figure 4 we show the trajectories of the ball from the moving FoR.



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1	-1,068	12,87	8,327E-2
2	2,146	28,51	0,117
3	3,078	27,07	0,150
4	-5,146	29,93	0,183
5	3,108	27,27	0,217
6	2,980	27,13	0,250
7	2,954	27,15	0,283
8	2,202	27,34	0,316
9	2,334	27,37	0,350
10	2,387	27,36	0,383
11	3,079	27,44	0,416
12	2,140	27,32	0,450
13	2,226	27,37	0,500
14	2,493	46,13	0,533
15	2,383	45,99	0,566
16	2,003	64,67	0,600
17	2,285	64,77	0,633
18	1,933	64,62	0,666
19	1,371	83,31	0,700
20	1,392	83,07	0,733
21	1,506	98,04	0,766
22	1,372	98,16	0,799

Trascinare le colonne della tabella sul giallo (asse orizzontale) o verde (asse verticale) per il fit della curva

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Figure 5. (Left) A frame of the simulation designed by a student (right) Video analysis of the simulated experiment.

3.3 Free surface of liquids in accelerated frame of reference

In this experiment, students qualitatively analysed a video taken by one of the instructors focusing on the dependence on the inclination of the angle formed by the surface of the water. Using Tracker, students measured the inclination of the liquid surface and the acceleration of the. Furthermore, they also produced Algodoo simulations of the system, both on an inclined plane, and accelerating on a horizontal plane.

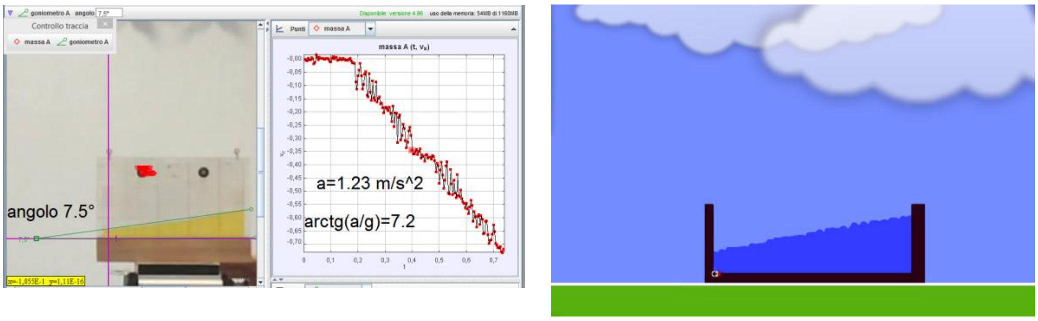

Figure 6. (Left) Measure of the angle of the liquid’s surface by analysing the video recorded in Lab by the teacher and (right) the analogous case in the Algodoo simulation produced by a student.

The focus for this experiment is to have students appreciate the relevance of the PoE already at the level of classical mechanics. In fact, the inclination of the liquid surface can be most easily understood by mentally constructing an ‘effective gravity’ incorporating both the real gravity and accelerations resulting from inertial forces.

3.4 Free falling reference frames and the Einstein elevator

3.4.1 The falling bottle. The physics exhibition of free-fall container[23,24,25] shows students that a water jet, flowing out from a stationary container through a hole, will stop if the container is permitted to fall freely and the water jet would stop flowing even in the freely rising bottle [26].

We introduce the experimental activity asking a question about what happens to a water jet flowing from a stationary bottle when the bottle starts falling in the gravitational field.

To discuss this experiment with the students they acquired a video and analyze it (see fig 7 right) and students designed a Algodoo simulation (see Fig 7 left).

Figure 7 For all free motions of a water-filled bottle in gravitational field (downward, upward, sideward), according to Einstein's equivalence principle, water in bottle-bound reference frame can be thought of as 'weightless' and, consequently, unable to flow out through a hole. On the left the Algodoo simulations for a Free-falling Container at rest, with downward velocity, and with upward velocity. On the right three frames from a video acquired by a student.

3.4.2 The falling pendulum. The physics exhibition physics exhibition of falling pendulum[18] shows students how a rigid pendulum behaves in absence of gravity. The experiments of ref[18] as the one reported in in Fig 6, right were reproduced by students thanks to Algodoo simulations.

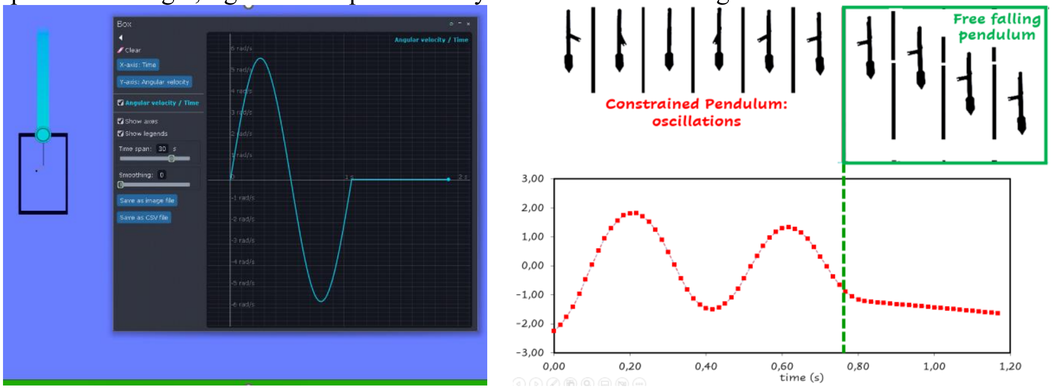

Figure 8 (Left) Students worked with the Algodoo simulation that exactly represents the situation of the pendulum in the elevator. (Right) The experiment, adapted from ref[18]. A sequence of photos of the free-falling model of Einstein's lift with a pendulum, where the angular velocity of the pendulum is approximately zero when it starts falling. The images were acquired with a time interval between consecutive frames 1/12 s. Thus, the angle versus time plot for the pendulum released in the maximum displacement position: data acquired by Tracker starting from the slow-motion video.

The simulation was useful for students, to explore a vast scenario of events by changing the initial conditions, that is, changing the moment when the rope supporting the elevator breaks.

4. Results and conclusions

The sequence was tested with a group of 24 university students of mathematics and physics who attended a course oriented to the training of future physics teachers. During their previous studies students had attended at least two university courses in mechanics. Our sources of data on students' progression and ideas include a questionnaire provided before the activities (pre-test), a delayed post-test given about one year after the end of the sequence, discussions recorded during and after the experiments, responses to some clinical interviews few days after the end of the course and some questions for course evaluation provided after the activities.

Here we condense the key findings drawn from the pre-test to provide an overarching understanding of the students' concepts prior to engaging in the activity sequence: (i) A substantial challenge emerged as students encountered difficulties in distinguishing between the trajectories of a projectile relative to two different inertial Frames of Reference (FoRs). Less than one quarter of students (24%) correctly identified the trajectory within the moving FoR, while half of the students successfully recognized the trajectory within the Lab's FoR. (ii) Only 36% of students accurately determined the actual path of the drone in Question 3 when observed by an individual situated on the riverbank, maintaining a constant speed relative to the moving FoR. Furthermore, only 50% of students correctly acknowledged the absence of fictitious forces acting on the drone in this reference frame. (iii) A vast majority of students (92%) provided imprecise predictions regarding the alteration in the shape of the free surface of a liquid contained within an accelerated motion apparatus. (iv) Few students (21%) were resolute in their belief that water within a bottle remains weightless and does not exert pressure through a side aperture during free fall.

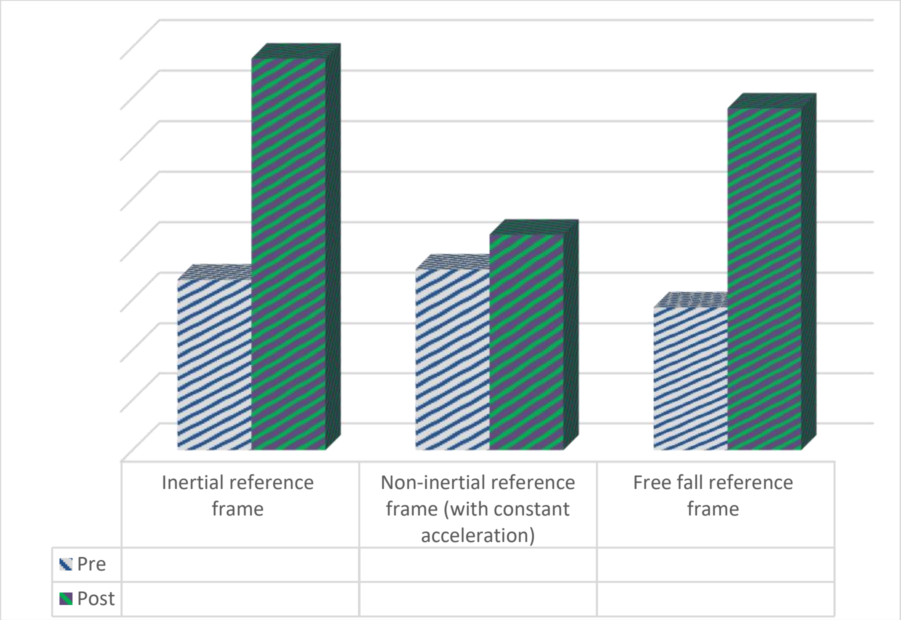

Figure 9 Comparison between pre and post test results analysing the questions of multi-choice test by concepts.

Examining the responses provided by students in the concluding examination revealed the effectiveness of the activity sequence, not only in comprehending specific concepts but also in fostering an alternative methodology for dissecting physical phenomena. Numerous students employed self-generated Algodoo simulations to elucidate the observed phenomena across diverse scenarios. All students proficiently tackled the presented challenges, showcasing a clear assimilation of the core principles.

The pre- and (delayed) post- test holds in our view particular significance as students registered large educational gains (standardized gain G=0.6-0.7) on items related to a) relative motion in inertial FoR and b) free falling FoR; however, students showed only little or no gain on items related to relative motion in non-inertial, not free falling FoR (such as carts sliding on an incline, with or without friction G=0.1) showing that, while they understood the basic meaning of the PoE (as highlighted by results on free falling FoR) they were still unable to use it as auxiliary tool for interpreting physical situations in mechanics, i.e. regularly translating from inertial to gravitational forces and vice versa; and were confused with the interpretation of such phenomena in terms of inertial forces only.

Investigating into more details, we can explore the post-test outcomes. These findings unveil diverse levels of effectiveness across distinct subjects within the sequence, and it becomes evident that the recall of experimental outcomes has a notable influence on responses to post-test queries, especially those pertaining to the compelling demonstration involving a descending bottle. Overall, during the post-test phase, the proportion of incorrect responses among our students was approximately 25%, signifying that the sequence engendered a productive learning environment, empowering students to grapple with most of their initial challenges. To delve further into the specifics: (i) Responses to the post-test substantiated an enhancement in students' grasp of how trajectories within an inertial frame can be transformed into trajectories within another by means of a straightforward transformation. (ii) After the sequence, a significant number of students still inaccurately predicted the alterations in the shape of the free surface of a liquid contained within an accelerated motion apparatus. (iii) Post-sequence, a large majority of students (90%) displayed the ability to discern that, during free fall, water within a bottle attains a state of weightlessness and does not exert pressure through a lateral aperture.

These insights collectively shed light on the multifaceted impact of the activity sequence on students' understanding and application of various physical concepts.

We conducted teaching and learning interviews with 11 students, focusing on problems related to the principles of equivalence and relativity. Our findings indicate that while most students were able to successfully solve the given problems, their utilization of the principles of relativity and equivalence was quite limited. (i) Concerning the principle of relativity, students frequently replaced it with the principle of inertia, which generally sufficed for their solutions. The use of Galilei transformations in problem-solving was rare, with only one student opting for a rigorous application of Galileo's transformations due to their reliability. Another student suggested that students' difficulties may stem from confusing physical scenarios with everyday situations. They tend to treat reference frames as tangible entities and draw comparisons to real-world conditions, for instance, considering external forces like air friction. (ii) Addressing "non-inertial" Frames of Reference, one student highlighted the challenge of identifying forces after a shift in FoR, specifically pointing out the counterintuitive nature of the Coriolis Force. He commented: "Fictitious forces create a problem because I see the effects of these forces, but I don’t see something acting." Despite demonstrating strong understanding of the Principle of Equivalence during the exam, students usually still referred to fictitious forces while explaining the dynamics of a free-falling elevator. Some students admitted to previously considering inertial and gravitational mass as the same concept without any problematization of the issue, and some expressed a disregard for the Principle of Equivalence, asserting that they already habitually equate inertial and gravitational masses, and that to treat inertial forces as equivalent to gravitational ones did not appear to them a great insight.

In summary, our interviews with students revealed that while they could effectively solve problems, their application of the principles of relativity and equivalence was limited. Students often replaced the principle of inertia for relativity and grappled with understanding fictitious forces, particularly in non-inertial reference frames. This sheds light on the complexities students face when interpreting and applying these fundamental principles.

5. Conclusions

This work aimed to propose a new educational method for teaching classical relativity to high school and university physics students. The researchers identified key concepts of classical relativity and examined students' difficulties through textbook analysis. They developed an instructional plan based on these findings and tested it with university students, focusing on the Principles of Relativity and Equivalence in classical mechanics. The preliminary results of our pilot study showed that this approach improved students' understanding. The study used video analysis and interactive simulations to enhance the learning experience. However, the limitations included a small and diverse sample of students, and future research will involve a larger trial with a more representative group.

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