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A diagnostic multiple-choice questionnaire on student misconceptions about relativity in classical mechanics

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Keywords: course design and evaluation, research in physics education, concept inventory, physics knowledge, theory of testing and techniques

Abstract

A central objective of research in physics education is the identification and analysis of conceptual difficulties encountered by students in learning. This study explores the understanding of fundamental concepts of classical relativity, namely Reference Frames, the Principle of Relativity, and the Principle of Equivalence, by university students. To this end, a multiple-choice questionnaire consisting of 21 questions was designed and administered to a sample of approximately 260 physics undergraduate students. The study used various statistical techniques—including classical test analysis and the Rasch model—to evaluate the reliability of the instrument and its effectiveness in detecting possible alternative conceptions. The results highlight recurring difficulties in processing various concepts, offering useful insights for improving teaching strategies in classical mechanics instruction.

1. Introduction

One of the primary aims of physics education research (PER) is to pinpoint the reasons why quite often students struggle when learning physics [1]. Following this identification, the goal is to develop and evaluate innovative teaching methods and curricula that can overcome these difficulties. Investigating the specific conceptual areas where students encounter problems is essential for designing effective instructional strategies to reduce or eliminate these issues. While previous studies have documented difficulties and alternative conceptions in introductory and advanced physics courses [2], only a limited number have specifically explored students' understanding of relativity in classical mechanics, which is not just a description of macroscopic phenomena, but a true conceptual paradigm that paves the way for more advanced theories. Concepts such as the Galilean Principle of Relativity (PR) and the Principle of Equivalence (PE), when appropriately emphasized, facilitate the adoption of a relativistic worldview. This approach allows students to develop a solid understanding, which is essential for successfully tackling the complexities of special and general relativity. Several studies in PER consistently reveal that students encounter significant and persistent conceptual difficulties with fundamental concepts dealing with inertial and non-inertial reference frames. For example, several studies highlight students' struggles to distinguish between different types of reference frames and to apply Newton's laws accurately in accelerated systems [3, 4]. Specific prior conceptions are prevalent regarding the nature of 'centrifugal force', often perceived as a real force rather than an inertial one [5]. These studies underscore that students frequently fail to correctly predict or explain motion in non-inertial contexts, even after instruction [6, 7]. Students also exhibit deep-seated issues with the classical PR, struggling to grasp its implications for the invariance of physical laws across inertial frames [8, 9]. Similarly, the PE presents considerable conceptual hurdles, with students often misunderstanding the relationship between gravity, acceleration and, correspondingly, between gravitational and inertial mass [10]. This pervasive nature of alternative conceptions, as broadly discussed in PER literature [11], emphasizes the critical need for robust and systematic methods to analyze and

categorize these difficulties. Identifying the precise nature of these core misunderstandings is essential for designing effective pedagogical interventions and diagnostic tools that can lead to deeper and more accurate conceptual understanding in classical mechanics.

This study fits into this research area, aiming to analyze in detail the conceptual difficulties encountered by university students in understanding the concepts of Frame of Reference (FR), PR and PE within the context of classical mechanics. To achieve this, a 21-question multiple-choice questionnaire was developed and administered to a sample of 267 first-year physics students enrolled in an introductory mechanics course. The entire test can be viewed in appendix B; the correct answers are explicitly stated in section 4. The investigation employed various statistical techniques—including classical test theory and the Rasch model—to evaluate the instrument's reliability and its effectiveness in detecting alternative conceptions. Analyzing multiple-choice test data is crucial for assessing student learning in physics education. These quantitative methods are essential for a critical examination of student understanding and for informing effective pedagogical strategies in PER [12–14]. The results aim to provide new insights into the recurrent difficulties in processing these concepts, offering useful indications for improving teaching strategies. In section 2, we discuss the development of the inventory. Sections 3 and 4, respectively, cover the test statistics and the main alternative conceptions identified. Section 5 is dedicated to a discussion regarding the observations derived from the test results, while the conclusions are presented in section 6.

2. Development of the inventory

We developed the Classical Relativity Concept Inventory (CRCI) to assess the evolution of students' understanding of classical relativity. Its creation was necessary because no specific and comprehensive conceptual inventory for classical relative motion has been found in recent literature, even though some issues related to classical relativity have been discussed in the past in various contexts [4, 12, 13, 15]. The CRCI functions as a flexible tool, ideal for use as both a pre-test and post-test to track learning progress. Beyond measuring understanding, it is also valuable for uncovering student initial ideas. To ensure its reliability, the CRCI underwent rigorous validation, including expert feedback, in-depth analysis of student responses, and comprehensive statistical analysis [16, 17]. Our development process was significantly influenced by analyzing existing materials, such as the Force Concept Inventory [18], to pinpoint common difficulties related to forces and motion—concepts crucial to classical relative motion. We also consulted numerous scientific articles on classical relative motion, non-inertial FRs, fictitious forces, kinematics and forces, weightlessness, and gravity [3–10]. The selection of scientific content was primarily guided by our instructional objectives, specifically our aim to determine how teaching relative motion in classical mechanics could best prepare students to adopt a relativistic worldview. This guiding question shaped our historical and epistemological analysis of relevant scientific content within classical mechanics.

The inventory's development began with a cognitive analysis of the underlying concepts, supplemented by a thorough review of relevant research literature. After mapping out the content, we crafted a preliminary set of questions, emphasizing instances requiring conceptual 'interpretation'. The fact that most physical phenomena can be reproduced in the lab played a significant role in question selection. Consequently, many questions were taken from experiments such as those designed in [19, 20]. This initial draft was then rigorously tested through interactions with different groups, including pre-university to doctoral students, teachers, and subject matter experts. These engagements, conducted individually and in small groups, involved mathematics and physics university students thinking aloud as they responded, while teachers provided feedback on common difficulties and experts offered critical insights and validated content. This systematic feedback loop, combined with ongoing pilot studies, allowed the test developer to continually refine and modify the questions. The foundational step was formulating a comprehensive list of concepts aligned with the learning objectives of introductory classical relativity, presented in table 1. These concepts guided the creation of 21 multiple-choice questions for the CRCI, with some concepts leading to up to four questions.

2.1. The interviews

The development phase of the CRCI significantly benefited from a rigorous methodological approach, which included the conduction of in-depth interviews. Although the final test was administered to a sample of 267 first-year university students, preliminary interviews were conducted separately with a smaller group of 11 mathematics and physics master students [20]. These students, who were participants in a training course for future educators, had the opportunity to engage with a didactic sequence based on experiments and simulations that mirrored some of the contexts later presented in the questionnaire.

The primary objective of these preliminary interviews was the identification and detailed analysis of recurrent conceptual difficulties encountered by students in learning the principles of classical relativity. The results

Table 1. The concepts tested by the CRCI. The questionnaire is reported in the appendix. In the questions column are the question numbers we classified as associated with each concept. While some questions clearly relate to multiple concepts, we assigned each question to the conceptual area it primarily addresses.

Conceptual areas	Key concept	Description	Questions
Frame of Reference (FR)	FR in the general case	Acceleration and forces in the transition between different FRs	Q1–Q5
Principle of Relativity (PR) and Galilean transformations	Inertial FR	Trajectory in the transition between inertial FRs	Q2–Q3–Q7–Q8
	Galilean composition of velocities	Determining velocity in different inertial FRs.	Q4
Concept of FR and classification as inertial and non-inertial	Non-inertial FR (with constant acceleration in the horizontal plane)	Effective acceleration	Q6
	Non-inertial FR (inclined plane)	Pendulum motion downhill on an inclined plane	Q10–Q11
		Position of a moving fluid on an inclined plane	Q15–Q16
The (weak) PE: the equivalence of gravitational and inertial mass	Horizontal motion	Horizontal motion with constant acceleration	Q9
		Simple harmonic motion of a free-falling spring	Q12–Q13–Q14
		Motion of a pendulum in free fall	Q17–Q18
		Water flowing out of a bottle in free fall	Q19
		Motion on a horizontal plane	Q20–Q9
		Orbital motion	Q21
	Free fall FR		

of these interviews, consistent with findings in other studies, highlighted common and persistent difficulties. For instance, students demonstrated problems in distinguishing between different types of FRs and in accurately applying Newton's laws in accelerated systems. Specific alternative conceptions included the nature of 'centrifugal force,' often perceived as a real force rather than an inertial one, and the inability to correctly predict or explain motion in a non-inertial context.

The interviews confirmed that one of the major difficulties for many students lies in describing the same situation in different FRs [2]. Students expressed problems in 'mentally visualizing the trajectory by placing themselves in different FRs' and in 'identifying the implicit initial conditions (position but especially the velocity vector) of the problem in the different frames.'

Another aspect that emerged was the students' tendency to substitute the PR with the Principle of Inertia, considering it sufficient to reason about the laws of motion. This reflects a lack of operational understanding of the PR, whose conceptual scope is broader than that of the Principle of Inertia: the former implies the invariance of all physical laws under transformations between inertial frames, while the latter is limited to the persistence of uniform motion in the absence of net forces. Confusing these two principles risks obscuring the deeper meaning of relativity and its role in connecting different inertial observers. This illustrates a reliance on conceptual statements without fully grasping their operational and transformational implications.

Furthermore, the interviews highlighted difficulties in identifying the forces at play when changing FRs, particularly regarding the elusive nature of fictitious forces, whose effects are visible but whose 'action' is not attributed to a 'real' cause. Some students described the 'apparent force' as a 'theoretical trick,' reflecting a form of instrumentalism that, while pragmatically useful for performing calculations, risks limiting a more comprehensive conceptual understanding of classical mechanics. In fact, fictitious forces in non-inertial frames are not physical interactions but are introduced to preserve the applicability of Newton's laws in frames where the Principle of Inertia does not hold. It is important to explicitly distinguish this pragmatic use from a deeper understanding of the geometrical and dynamical structure of classical mechanics, in which inertial frames retain a privileged role, and apparent forces serve as computational tools rather than representing genuine physical interactions.

These conceptual limitations regarding both the role of FR transformations and the nature of fictitious forces suggest that students may approach non-inertial contexts and relative motion scenarios with an incomplete or inconsistent framework. This is further reflected in the response patterns observed in the multiple-choice questionnaire, which we analyze in the following sections.

The results of these preliminary interviews were crucial for the calibration and formulation of the 21 multiple-choice questions in the CRCI. Understanding the areas of greatest difficulty and the most common

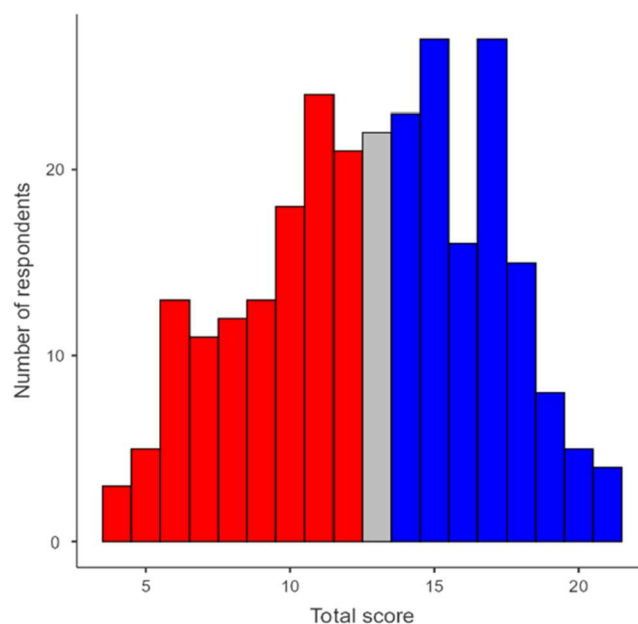


Figure 1. Distribution of total score. In grey the average score.

Table 2. Test analysis statistical values. Desired ranges are suggested by Ding *et al* (2009) [17].

Statistic value	Test's values	Desired ranges
Difficulty index	0.61	[0.30, 0.90]
Discrimination index	0.43	≥ 0.30
Point biserial coefficient	0.42	≥ 0.20
KR20 reliability	0.78	≥ 0.70
Ferguson's delta	0.97	≥ 0.90

Table 3. Summary of total score.

N	Min	Max	Mean	Median	SD
267	4	21	12.9	13.0	4.0

alternative conceptions allowed the developers of the test to specifically design questions that targeted these critical points, making the CRCI an effective diagnostic tool for detecting student initial ideas in classical mechanics. The interviews provided invaluable qualitative insights that informed the questionnaire design, ensuring that the questions were relevant and capable of probing students' genuine conceptual difficulties, moving beyond a mere assessment of superficial knowledge.

3. Administration of the inventory and test analysis

The questionnaire was administered to 267 students at the end of the General Physics I course in the first year of the Physics degree program in Italy. All students had covered the topic of relative motion when treating kinematics subjects during the course lessons.

3.1. Test analysis

The purpose of these analyzes is to examine if a test is reliable (giving similar results over time, if conditions remain the same) and discriminating (clearly distinguishing between participants who have a solid knowledge and those who do not of the tested materials). In this regard, several statistical indices that characterize the test were determined (see table 2) in addition to the overall results shown in figure 1 and table 3. Specifically, the

difficulty index, the discrimination index, the point-biserial coefficient, the Kuder–Richardson reliability index and the Ferguson’s delta were calculated.

The difficulty index is a measure of the easiness of an item and is defined as the proportion of correct responses, $P = \frac{N_C}{N}$, where N_C is the number of correct responses and N is the total number of students taking the test. Practically, item difficulty values ranging from 0.30 to 0.90 are acceptable. From this perspective, the questionnaire appears well-constructed, with an average difficulty coefficient of 0.61. Only one item is an exception, with a difficulty index of 0.21. On a total score of 21, the average is around 12.9, equal to 61.4%, with a standard deviation of 4.0.

The discrimination index measures the test’s ability to distinguish students in relation to their level of competence. In this case, for the calculation of the discrimination index (ULI—Upper–Lower Index), the top tercile and the bottom tercile were considered, so the discrimination index is defined as the difference in percentages of correct response to an item between the high-achieving students and the low-achieving students:

$$D = \frac{N_T - N_B}{N/3}. \quad (1)$$

Here N_T and N_B are the numbers of correct responses in the top tercile and bottom tercile, respectively, and N is the total number of students. The mean discrimination index is the mean of the discrimination indices for all questions. According to what was suggested in table 2. A commonly adopted standard for a satisfactory item discriminatory index is $D \geq 0.3$. The average discrimination index is 0.433. Several items within the assessment exhibit a discrimination index that falls below the minimum threshold recommended, as shown in appendix. This indicates that these particular items are not effectively differentiating between students of varying overall abilities. For some items, a low discrimination index is observed even when a significant percentage of students choose a specific distractor; in such cases, the item’s ability to discriminate is compromised because the correctness of student responses on that specific item does not align with their overall performance on the test. For instance, a majority of high-achieving students might answer correctly, but a notable portion of middle-achieving students answer incorrectly, while low-achieving students show a higher correct response rate than the middle group. This inconsistent pattern can suggest ambiguity in the question’s wording, leading to confusion among test-takers. In other items the responses are distributed nearly uniformly across all options. This lack of a clear pattern suggests that students may not have adequately understood the question, or the item itself is not effectively measuring the intended knowledge or skill. Conversely, some items demonstrate a low discrimination index due to their extreme simplicity. In these cases, nearly all students, including those with lower overall test scores, answer correctly. While this indicates a high level of accessibility, it also means the item provides little information about the relative abilities of the students. Despite some items, taken individually, having a discrimination index below the minimum recommended limit, we decided to keep them both in order to have a more complete and balanced test, covering basic (or advanced) topics as well, and to have a tool for sample calibration. In this sense, having items for which a well-defined result is expected, even if they are not very discriminatory among students, allows for an overview that helps classify the sample and determine whether the administration of the test can be effective.

The point biserial coefficient is a measure of individual item reliability and is defined as the correlation between the item scores and total scores:

$$r_{\text{pbi}} = \frac{\langle X_1 \rangle - \langle X_0 \rangle}{\sigma_X} \sqrt{P(1 - P)}. \quad (2)$$

Here, $\langle X_1 \rangle$ is the average total score for those who correctly answer an item, $\langle X_0 \rangle$ is the average total score for those who incorrectly answer the item, σ_X is the standard deviation of total scores, and P is the difficulty index for this item. A satisfactory point biserial coefficient is $r_{\text{pbi}} \geq 0.2$. In this case, the PBC shows an average value of 0.42.

Kuder–Richardson reliability (KR-20) measures the internal consistency of a test. For a multiple choice test where each item is scored as ‘correct’ or ‘wrong,’ the reliability index is calculated as follows:

$$r_{\text{test}} = \frac{K}{K - 1} \left(1 - \frac{\sum_i P_i (1 - P_i)}{\sigma_x^2} \right). \quad (3)$$

Here, K is the number of the test items, P_i is the difficulty level for the i th item, and σ_x is the standard deviation of total score. A widely accepted criterion is that a test of reliability higher than 0.70 is considered reliable for group measurement. The KR20 returns a value of 0.78, demonstrating good internal consistency of the test. Although removing one or two items would slightly increase the reliability index, this improvement would be minimal and not enough to justify their removal, especially when considering the goal of having a more comprehensive test in terms of content.

The Ferguson’s delta measures the discriminatory power of an entire test. Specifically, it investigates how broadly students’ total scores are distributed over the possible range. The calculation of Ferguson’s delta is

given as follows:

$$\delta = \frac{N^2 - \sum_i f_{k,i}}{N^2 - \frac{N^2}{K+1}}. \quad (4)$$

Here, N is the total number of students taking the test, K is the number of test items, and f_k is the number of students whose total score is k . Generally, if a test has Ferguson's delta greater than 0.90, it is considered to provide good discrimination among students. The calculated Ferguson's delta for the questionnaire was 0.97.

3.2. Item response theory: rasch analysis

Item Response Theory (IRT) can be used to estimate item characteristic parameters and examinees' latent abilities. In particular, since our test is dichotomous (correct–incorrect), we used the Rasch model, which uses the item difficulty as its only parameter (1PL IRT). The goal is to position both the student's ability θ and the item's difficulty β on a single, continuous measurement scale, the logit unit. The ability θ is primarily estimated based on the student's total score (the number of correct answers), which is considered a sufficient parameter. The estimated θ value represents the ability level at which the student has exactly a 50% probability of correctly answering an item whose difficulty is equal to θ . The item difficulty β , conversely, is estimated by analyzing the performance of the entire sample on that item—the proportion of correct answers obtained. The β value indicates the item's intrinsic difficulty and represents the point on the scale where a student with ability $\theta = \beta$ has a 50% probability of success. The estimates for θ and β are obtained simultaneously through iterative statistical methods in a co-calibration process (we used the jamovi software, which, through the added module *snowIRT*, utilizes the Marginal Maximum Likelihood method [21]). This ensures both parameters reside on the same logit scale, making the probability of success dependent only on the difference between the student's ability and the item's difficulty $\theta - \beta$. In the following equation the item difficulty of the item i is denoted as β_i , while the ability of the student j is denoted as θ_j . Using these notions, the mathematical expression of this logistic model is given by:

$$P_{ij} = \frac{e^{\theta_j - \beta_i}}{1 + e^{\theta_j - \beta_i}}. \quad (5)$$

Where P_{ij} is the probability to obtain score β_i at item i for the student j . In addition to the above application, IRT can be used to evaluate the functions of distractors in each item.

A graphical representation of the Rasch analysis is the Wright map (see figure 2), that presents both item difficulties and person abilities arranged along the same logit scale, where 0 logit corresponds to a 50% probability of answering the question correctly ($\theta = \beta$). The Wright map helps with evaluating the targeting of the test to the sample and the structure of the test. If large gaps between items are detected, new items of appropriate difficulty should be added. If too many test items of the same difficulty are found, some of them can be removed. The Wright map shows that the test has good overall measurement effectiveness, as demonstrated by the strong alignment between the distribution of student ability and item difficulty around 0 logit. This overlap indicates that the test is appropriate for the majority of the sample, which is concentrated in the average ability range. Although a concentration of items in the mid-range is noted, the main area for improvement is the significant gap in the upper end of the scale (above +2 logit). This gap means that there are not enough difficult items to precisely measure the most capable students. However, this gap is acceptable, given that the students with the highest ability are a distinct minority of the sample (only 2 out of 267 answered all questions correctly). Overall, the items are well-calibrated for the examined population. In Rasch analysis, the so-called 'infit' and 'outfit' statistics tell us how well test response data aligns with the model. Specifically, outfit is the arithmetic mean of simple squared residuals, while infit is a weighted mean of squared residuals. Both measure discrepancies between observed and expected responses, but infit is more sensitive to small discrepancies, while outfit detects more extreme ones. Since infit and outfit are nearly identical and close to 1.00 (table A1 in appendix), it means the data fits the model almost perfectly. We can conclude there are no unexpected responses distorting the measurement, behaviors are consistent, and both test items and respondents behave as predicted.

4. Results and distractor analysis

The previous section focused on statistical methods and their application to establishing the consistency and reliability of the CRCI. In this section, besides presenting the detailed structure of the questionnaire, we focus on its implications for classical relativity education. Student responses and explanations showed that students had common difficulties, which were consistent with the findings of the individual interviews reported in [22]. Many students had difficulty distinguishing between trajectories in different inertial frames, understanding the

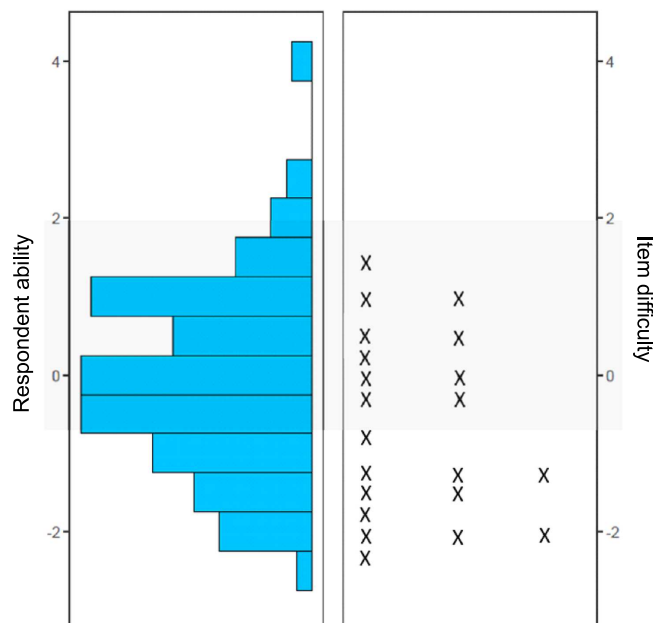


Figure 2. The Wright map. Its main purpose is to display the distribution of person abilities and item difficulties on the same logit scale, the standardized unit of measurement used in IRT models which, by expressing the logarithm of the odds of success, serves to calibrate and align the ability of people and the difficulty of items on the same continuous scale. This is possible because the Rasch model calibrates both these parameters on the same metric. On the left side is the distribution of respondent abilities, and on the right side is the distribution of item difficulties. The higher you go vertically, the more both ability and difficulty increase. Ideally, a well-constructed test should have a wide range of item difficulties that aligns with the breadth of abilities of the people being tested, and it should not show a homogeneous distribution, without large gaps in difficulty or ability. For the IRT analysis we used Jamovi software [21].

absence of fictitious forces in appropriate contexts, and predicting how liquid surfaces behave under different types of motion. Significant challenges also emerged when considering pendulum motion in accelerating systems and the concept of weightlessness in free fall. The percentage of student responses for each of the choices on each question is presented in table 4. We will now proceed with a specific analysis of the responses and distractors, to deduce the main difficulties encountered by students and derive some general characteristics of learning about relative motion. Difficulties are categorized by main conceptual areas, and the most problematic questions are then analyzed in detail.

4.1. Questions related to frame of reference in general

This conceptual area is closely related to questions Q1 and Q5, asking about the presence or absence of forces and accelerations in frames of reference that are either fixed to or not fixed to a body. In general, questions related to this area show medium to high correct response rates, suggesting a solid understanding of the reference system concept by students; note that questions in this section do not specify whether reference systems are inertial or not. Any misunderstandings concern the concept of reference system itself and the principle of inertia, although they seem to have been well understood by students.

4.2. Questions related to the principle of relativity and Galilean transformations

Questions Q2, Q3, Q4, Q7 and Q8 fall in the area of the principle of relativity and Galilean transformations, focusing on the transformation of trajectory and velocity when moving from one inertial reference system to another. Questions Q7 and Q8, in particular, have higher correct response rates than other areas, indicating students' relative familiarity with Galilean composition of velocities and observation of motion in inertial systems.

Item Q2, which asks to describe the path taken by a drone in uniform rectilinear motion from the perspective of two inertial frames of reference in relative motion (a person standing on a bridge and a boat moving along a river), most students who answer incorrectly indicate a curved trajectory, failing to visualize the motion of the boat and the motion of the drone separately. Some students identify a mirrored straight path, assuming for the drone a horizontal displacement concordant with that of the boat. Item Q3, on the other hand, asks whether or not an apparent force is present in one of the reference frames in the situation described in Q2. It should be noted that most incorrect answers indicate a force directed to the left, consistent with the error in the previous question, suggesting that students attribute the non-rectilinear trajectory to the action of a force. In

Table 4. Percentages students' responses to individual questions, divided among the different alternatives. The correct answer is in bold. Question 21 is the only one with two correct alternatives.

Q. No	A	B	C	D	E
Q1	87	13			
Q2	15	78	1	5	1
Q3	18	4	78		
Q4	84	9	1	6	
Q5	14	86			
Q6	7	43	40	10	
Q7	7	67	26		
Q8	76	19	5		
Q9	38	8	54		
Q10	12	76	12		
Q11	30	30	40		
Q12	10	86	3	1	
Q13	0	24	1	75	
Q14	20	25	55		
Q15	30	21	30	8	11
Q16	22	4	24	11	39
Q17	27	6	31	9	27
Q18	32	7	8	8	45
Q19	13	19	49	9	10
Q20	42	5	53		
Q21	10	2	30	7	51

Q7 and Q8, the request is still to outline the trajectory of a body, but this time the object is in free fall and one of the two reference frames is in uniform motion (these questions were adapted from the relativity concept inventory [12]).

4.3. Questions related to non-inertial reference systems (with constant acceleration in a horizontal plane)

Questions related to non-inertial reference systems (with constant acceleration on a horizontal plane) focus on effective acceleration and are associated with questions Q6 and Q9. Performance in this area is mixed; Q6, in particular, proved difficult, showing problems in the application of principles in non-inertial systems and the correct composition of motions. This question concerns the motion of an apple falling from a tree as seen by an observer on a uniformly accelerating train: analysis indicates that 40% of students answered correctly (uniformly accelerated rectilinear motion), but it is interesting to note that over 43% selected distractor B (parabolic motion). Confusion regarding the composition of motions in two dimensions is evident; students, perhaps accustomed to dealing with parabolic motion problems, considered the case of the composition between uniform motion and uniformly accelerated motion. The composition of two motions (in this case uniformly accelerated motion) led most students to extend an interpretive line based on concepts learned in other situations, without reflecting on the process of extrapolating the object's trajectory from the laws of motion, highlighting indiscriminate use of equations while ignoring the associated validity condition.

4.4. Questions related to non-inertial frame of reference (inclined plane)

This area includes questions about the motion of a pendulum (Q10, Q11) and the position of a liquid surface (Q15, Q16) on an inclined plane. Analysis shows generally low success rates for Q11, Q15 and Q16, highlighting significant difficulties for students in dealing with non-inertial reference systems on inclined planes and conceptualizing the balance of forces and motion in such contexts.

Item Q10 concerns the small-amplitude oscillations of a pendulum placed inside a car going down an inclined plane. Most students answered Q10 correctly (about the centre of the oscillations), but analysis of item Q11 (about the period of oscillation) suggests that this may indicate only a superficial understanding. In fact, only 30% of students answered correctly that the period increases, 30% think the period decreases, while the majority (40%) believe the period is the same as in a car at rest. Thus, complete failure can be seen, as the answers are distributed almost equally among all possibilities. It is intuitive from everyday experience to think that, during the motion of the car, the pendulum tends to move in the direction opposite to the motion, but when asked to apply the law of period there are obvious difficulties in relating the system to the known situation (with vertical force) but with different acceleration.

Item Q15 is about a tank containing water descending on an inclined plane without friction. Only 21% of students answered correctly (surface parallel to the plane), while a significant number opted for solutions A and C, according to which water should accumulate on the front or back wall of the tray. Interestingly, in the previous, conceptually similar question, more than 50% of the students answered correctly. The difference is due to the presence of an inclined plane, which, even without friction, leads students to imagine a different situation from the fall motion. It is also interesting to make a comparison with item Q10: in the descent along an inclined plane, the pendulum motion tilts toward the rear of the car, so it is perhaps easy to conclude that water also accumulates in the rear of the container. There are obvious gaps in the acquisition of the concept of the balance of forces, which could mean that the correctness of many answers to Q11 is still due to a misconception that there is a force that somehow pushes both the pendulum and the water backward, thus not thinking about the balance of forces involved. It is also worth considering some ambiguity in the text, which may have caused some incorrect answers. Assuming the tank is initially stationary may lead students to consider the moment immediately after departure when the water is still in a dynamic situation and far from equilibrium.

Item Q16 is similar to Q15, but with the presence of friction. The results in this case are better: about 39% of the students answered correctly. In addition, 22% selected option A, which is conceptually similar to the correct one, according to which water still tends to accumulate downhill (perhaps not noting that, for option A, the water surface would be perfectly horizontal). The presence of friction on the inclined plane generates a less ambiguous situation for students: in this case, it is not a free-fall motion, and the presence of a force is evident. Interestingly, for many students, the presence or absence of friction does not produce qualitatively different effects, but simply increases (or decreases) the amount of water that accumulates asymmetrically on the container walls. However, for items Q15 and Q16 we cannot rule out the possibility that, as in the case of the pendulum, students' difficulties are partly due to inadequate knowledge of the physics of fluids, which are sometimes treated as if they were rigid bodies.

4.5. Questions related to the principle of equivalence and the free fall reference system

This area includes various applications of the PE in a free-fall or equivalent system. It covers questions Q9 (horizontal accelerated motion), Q12–Q13–Q14 (spring), Q17–Q18 (pendulum), Q19 (fluid) and Q20 (horizontal motion) in free fall, as well as Q21 (orbital motion/ISS). In general, these items show average correct response rates, indicating some difficulty for students in applying the PE and understanding the concept of apparent absence of gravity in a free-fall reference. Notably, Q12, Q13, and Q21 show a higher correct response rate; Q17, on the other hand, is distinct in that only a third of students answered it correctly.

Item Q9 concerns the relationship between the angles formed by two suspended objects of different masses (m and $2m$) within an accelerating car. About 54% of the students answered correctly ($\alpha = \beta$), while 38% opted for distractor A ($\alpha > \beta$). The latter choice was probably misled by the concept of inertia: the object with greater mass, possessing greater inertia, should be less affected by the acceleration of the car and move away from the equilibrium point with more difficulty. However, using Newton's laws, that the angle depends only on the acceleration of the car and not on the mass of the bodies; it is therefore a hasty conclusion based on a partial consolidation of the concept of inertia. This question allows to test students' understanding of PE, as its direct application is the quickest and most intuitive method for a correct answer. In this sense, negative results highlight their difficulty in applying it, likely preferring a more Newtonian approach in terms of the (erroneous) application of the laws of motion.

Items Q17 and Q18 deal with the motion of a pendulum in an elevator in free fall. Most of those who answer incorrectly in Q17 think that the detachment of the elevator does not affect the motion of the pendulum, which would therefore continue to oscillate with the same period, or that it would stop due to the sudden disappearance of the constraint. It is noticeable how difficult it is for students to visualize the action of the constraint, which allows the pendulum to follow a certain trajectory, in the passage from an inertial to a non-inertial frame of reference.

In Q19, regarding the flow of water out of a perforated bottle in free fall, students concluded that since the bottle is moving, the jets must be different than in the case where the bottle is stationary. The answer, although generic, is incorrect because it presupposes that the water continues to flow, albeit in a different way, contrary to what actually happens, as the jets disappear completely. It's possible that, for simplicity of reasoning, many opted for the more general solution ('The jets will be different than in the case where the bottle is stationary,' without indicating how).

Regarding item Q20, about the horizontal motion of an object during an elevator's free fall, 53% of students were correct. Is notable that a large portion (42%) chose the wrong answer (distractor A), believing the object should only move horizontally during the fall. Their error might stem from assuming the rope cutting only affected the elevator and attached items, but not the free-floating object. It is possible that they thought this

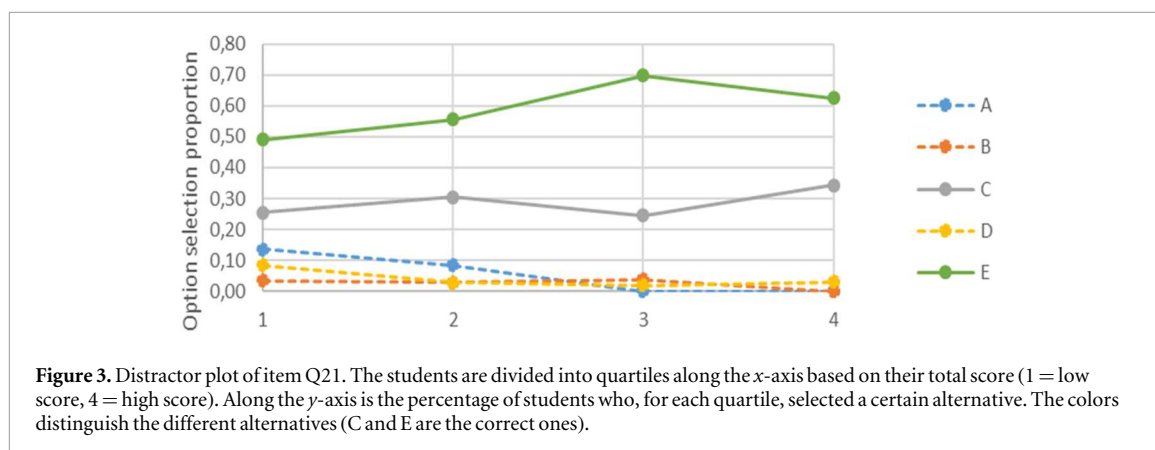


Table 5. Distribution of answers for item Q21.

Item Q21							
Key	Correct	<i>n</i>	%	Lower	mid50	mid75	Upper
A		24	9	0,14	0,08	0,00	0,00
B		9	3	0,03	0,03	0,04	0,00
C	*	80	31	0,25	0,31	0,25	0,34
D		13	5	0,08	0,03	0,02	0,03
E	*	136	52	0,49	0,56	0,70	0,63

object in free-fall, having its weight canceled out, it would continue to move horizontally, as if it were massless and thus not undergoing the gravitational acceleration equally to the table and the elevator.

The result is also interesting in comparison with item Q21, where, on the other hand, the absence of gravity in the case of a free-falling body seems clearer, perhaps because in the latter case the situation is more familiar and they are likely to have encountered explanatory material showing in practice the experiment conducted on the ISS. Q21 differs from the previous items in that it has two possible correct answers, in which the same phenomenon is explained in the two conceptually different ways: with the appearance of fictitious forces or with the PE; for this purpose, the reference frame to be considered is not specified, in order not to force students to assume the point of view of an inertial reference frame rather than a non-inertial one. It is therefore interesting to analyze how the answers are distributed (considering that 81% of students answered correctly anyway), particularly differentiating the choice according to students' total scores. Therefore, students were divided into quartiles based on the final score obtained. It can be seen (figure 3 and table 5) that the option most selected by all groups is E, according to which the ball remains stationary because, since the reference system is in free fall, it behaves as if there is no gravitational field. Notably, 52% of the total number of students responded this way, and the proportion is also similar within individual quartiles (49%–70%). The proportion halves (from 25% to 34% for individual quartiles, corresponding to 31% of the total) when option C is considered, which involves explanation by explicitly referring to centrifugal force. Thus, it can be seen that students, in this case, were more confident in their use of the equivalence principle. The most pronounced difference is seen for the third quartile, where option E was chosen by three times as many students as option C.

5. Discussion

As we have shown in the previous sections the CRCI effectively served its purpose in identifying persistent and widespread conceptual difficulties among university physics students in the domain of classical relativity. These findings corroborate and extend previous research in physics education, offering concrete evidence of the specific conceptual areas where students struggle. The recurring nature of these misunderstandings underscores the critical need for targeted pedagogical interventions [4–10, 20, 22].

Beyond its diagnostic value, the CRCI can also serve as a useful instrument for supporting research on the impact of different instructional approaches in this domain. The nature, timing, and emphasis of teaching interventions—whether they promote explicit reasoning about reference frames, the use of Galilean transformations, or the operational meaning of fictitious forces—can significantly influence student performance on the CRCI items. Conversely, instruction that remains anchored in procedural or purely Newtonian approaches

may leave such difficulties largely unaddressed. It is therefore important to consider that the outcomes of the questionnaire may reflect not only students' spontaneous reasoning, but also the conceptual perspectives and heuristics fostered by instruction. Used as a pre/post-instruction instrument or in comparative studies across different teaching practices, the CRCI can provide valuable evidence on the effectiveness of various pedagogical strategies for promoting a more robust and flexible understanding of classical relative motion.

Future teaching strategies should actively address these identified alternative conceptions, encouraging abstraction from everyday experience, providing explicit guidance on applying principles in diverse reference frames, and emphasizing the conceptual underpinnings of force and motion rather than merely the rote application of formulas. By confronting these persistent conceptual hurdles, educators can significantly enhance student learning in classical mechanics, ultimately preparing them more effectively for advanced physics coursework and a more accurate relativistic worldview.

To support this goal, several concrete instructional strategies can be implemented. It is important to explicitly introduce reference frames as central physical constructs, dedicating time to discuss operational definitions of inertial and non-inertial frames and highlighting how the description of motion and forces depends on the chosen frame. Visual and interactive tools, such as video analyzes, computer simulations, and graphical overlays, can be integrated to enable students to compare the same physical situation from multiple reference frames in real time [23–28]. Furthermore, fostering qualitative reasoning before introducing formal transformations can be highly beneficial: students should first be encouraged to predict qualitatively how the observed motion will change between frames, thereby promoting conceptual flexibility and avoiding purely procedural application of formulas.

Two simple, well-known examples of instructional interventions can exemplify these strategies. In the first, students analyze the motion of a small mass on a cart, initially at rest relative to the cart, which can be set to move either at constant velocity or with a uniform acceleration with respect to the lab frame. The experiment is conducted in two phases: first with the cart moving at constant velocity, then with the cart uniformly accelerating. In both cases, students are asked to predict and observe the motion from both the ground frame and the cart frame, using side-by-side video displays. When the cart accelerates, students directly observe that in the cart frame the mass exhibits an apparent acceleration in the opposite direction, requiring the introduction of a fictitious force to account for the observed motion. This activity not only reinforces the concept of relative velocity but also provides an intuitive, operational understanding of how non-inertial effects manifest and how forces must be interpreted frame-dependently.

In the second intervention, a small mass is set to move along a straight path on a rotating turntable. The motion is recorded and displayed both from an external inertial camera and from a camera rotating with the turntable (GoPros and similar devices are perfectly suited for this purpose). Guided analysis of the apparent curved trajectory and of the need to introduce fictitious forces in the rotating frame allows students to further consolidate their understanding of frame dependence and the operational meaning of fictitious forces. This example complements the cart experiment by extending the reasoning to rotational motion, where such prior ideas are often particularly persistent.

Notably, both of these experimental situations were already proposed with great success in the context of the PSSC physics curriculum in the 1960s [22], a project that, despite its age, remains pedagogically valuable. With the addition of modern digital technologies for data acquisition and visualization, these classic experiments can today be implemented even more effectively, offering students a clear and engaging exploration of frame-dependent phenomena [25–28].

The choice of these specific experimental situations is also directly motivated by some of the difficulties highlighted in the CRCI results and discussed in this work. In particular, common errors observed in questions regarding the transformation of trajectories and the perception of forces across inertial frames (Q2, Q3, Q4, Q7, Q8), as well as in questions concerning motion and force interpretation in non-inertial frames (Q6, Q9, Q10, Q11, Q15, Q16, Q17, Q18, Q19), strongly suggest the pedagogical value of targeted activities explicitly addressing these critical conceptual areas. The proposed experiments can provide concrete opportunities to confront and correct these initial ideas through guided observation and analysis.

In summary, the CRCI and the instructional approaches discussed here provide practical means to address well-documented conceptual difficulties in classical relative motion. Their combined use can contribute to more effective and conceptually grounded teaching in this important area of classical mechanics.

6. Conclusion

This study undertook a comprehensive investigation into university physics students' understanding of core concepts in classical relativity, specifically RF, PR PE. To achieve this, we developed and administered the CRCI, a 21-question multiple-choice questionnaire. The primary aims of this article were twofold: to rigorously

validate the CRCI as a reliable diagnostic tool and to analyze some of the specific alternative conceptions in classical mechanics that the test effectively revealed among the student population. The statistical validation of the CRCI demonstrated its robustness and reliability as an assessment instrument. Classical test analysis yielded strong indicators of quality and confirmed the test's good internal consistency. IRT and Rasch analysis corroborated these findings, showing a good distribution of questions across ability levels. The in-depth analysis of student responses, augmented by qualitative insights from interviews, consistently revealed significant and recurring conceptual difficulties within classical relativity.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Appendix A. Statistical details

Table A1. Statistic values for each question. In the last row the mean values.

Item	DI	ULI	PBC	Rasch measure	Infit	Outfit
Q1	0.87	0.14	0.18	−2.20	1.16	1.50
Q2	0.78	0.44	0.41	−1.52	1.02	1.06
Q3	0.78	0.49	0.52	−1.49	0.92	0.84
Q4	0.84	0.38	0.47	−1.94	0.94	0.78
Q5	0.86	0.27	0.35	−2.13	0.98	1.02
Q6	0.40	0.50	0.45	0.47	1.02	1.03
Q7	0.67	0.62	0.56	−0.87	0.87	0.82
Q8	0.76	0.51	0.58	−1.39	0.83	0.69
Q9	0.54	0.60	0.49	−0.18	1.00	1.01
Q10	0.76	0.42	0.42	−1.39	1.01	1.10
Q11	0.30	0.07	0.11	1.03	1.25	1.52
Q12	0.86	0.15	0.02	−2.13	1.14	1.36
Q13	0.75	0.48	0.47	−1.32	1.02	1.05
Q14	0.55	0.47	0.42	−0.25	1.01	1.00
Q15	0.21	0.35	0.42	1.57	0.97	0.98
Q16	0.39	0.21	0.21	0.52	1.25	1.36
Q17	0.31	0.65	0.56	0.96	0.88	0.79
Q18	0.45	0.72	0.62	0.26	0.86	0.81
Q19	0.49	0.63	0.55	0.06	0.96	0.95
Q20	0.53	0.71	0.61	−0.14	0.94	0.93
Q21	0.81	0.28	0.39	−1.73	0.98	0.91
MV	0.61	0.43	0.42	−1.00	1.00	1.02

The abbreviations denote: DI discrimination index; ULI upper-lower correlation index; PBC point biserial coefficient.

Appendix B. The classical relativity concept inventory

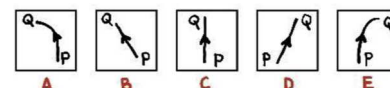
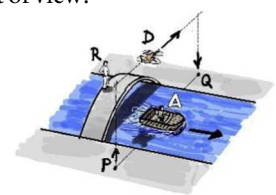
The CRCI is presented below. The correct answers are explicitly stated in table 4.

Q1. A body will always have zero acceleration when measured in a frame of reference that is, at every instant, comoving with the body itself.

- (A) True
- (B) False

Q2. Roberto is sitting on a bridge and sees Alice passing by on a boat traveling at a constant speed along the river. Just as Alice is passing by, a drone D starts from point P and flies at a constant speed to point Q on the opposite bank. What is the drone's trajectory from Alice's point of view?

- (A)
(B)
(C)
(D)
(E)



Q3. With reference to the previous question: is there an 'apparent' force acting on the drone in Alice's frame of reference? If so, what is it like?

- (A) Constant, towards the left.
(B) Non-constant, towards the left.
(C) There is no apparent force.
(D) Constant, towards the right.
(E) Non-constant, towards the right.

Q4. With reference to the previous question: How intense will the drone's speed be in Alice's frame of reference?

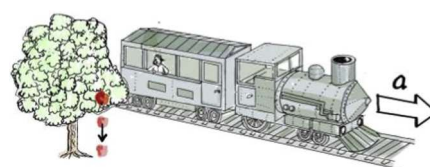
- (A) Greater than the magnitude of the drone's velocity in Roberto's frame of reference.
(B) Equal to the magnitude of the drone's velocity from Roberto's frame of reference.
(C) Impossible to determine without knowing the magnitude of the boat's and drone's velocities.
(D) Less than the magnitude of the drone's velocity from Roberto's frame of reference.

Q5. If a body appears at rest in one frame of reference, but in motion in a second frame of reference, it means that one or more fictitious forces appear in the second frame of reference, which are responsible for the motion.

- (A) True.
(B) False.

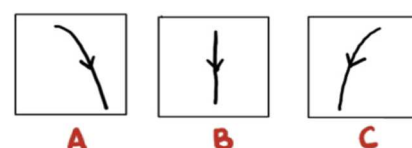
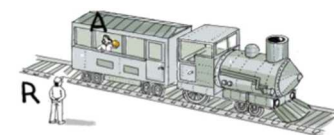
Q6. Consider a train that begins to move with uniformly accelerated rectilinear motion relative to the ground. Consider a frame of reference attached to the train, and an observer inside the train, at the window. The instant the train begins to accelerate, an apple detaches from a tree. The observer sees it. From his point of view, that is, in the frame of reference attached to the train, the apple moves with:

- (A) uniform rectilinear motion.
(B) parabolic motion.
(C) Uniformly accelerated rectilinear motion.
(D) It's impossible to answer without knowing if acceleration ' a ' is greater than or less than gravitational acceleration ' g '.



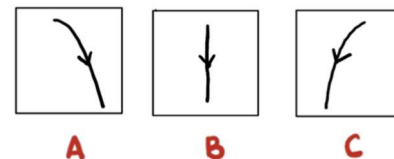
Q7. Alice is on a train moving at a constant speed. Roberto is at the station and sees the train rush by from left to right. Alice, leaning out the window, drops a ball. Neglecting air resistance, what is the trajectory observed from Alice's reference frame?

- (A)
(B)
(C)



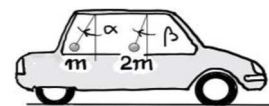
Q8. With reference to the previous question, what is the trajectory observed by Roberto's frame of reference?

- (A)
(B)
(C)



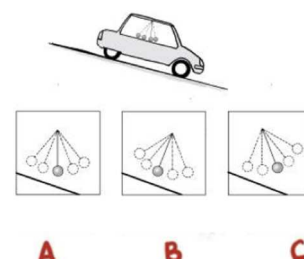
Q9. In a car, two point masses (m and $2m$) are suspended by two inextensible cords as shown in the figure, thus forming two simple pendulums. When the car is stationary, the pendulums are in their vertical rest position. The car begins to accelerate with constant acceleration, and during this phase, the two pendulums arrange themselves to form a certain angle with the vertical. What is the relationship between the two angles?

- (A) $\alpha > \beta$
(B) $\alpha < \beta$
(C) $\alpha = \beta$



Q10. A pendulum is hung from the ceiling of a car and oscillates with small amplitudes. The car then begins to descend an inclined plane, accelerating downwards freely. How do the pendulum's oscillations behave?

- (A)
(B)
(C)



Q11. With reference to the previous question, how will the period of the pendulum be while the car is descending the inclined plane (making small amplitude oscillations) compared to when the car is stationary?

- (A) Greater.
(B) Smaller.
(C) Equal.

Q12. The upper end of a spring is hung from the ceiling of an elevator, while a small ball is attached to its lower end. Everything is initially at rest in equilibrium. If the cable supporting the elevator is cut, what happens to the ball in the frame of reference of the elevator?

- (A) The ball stays still.
(B) The ball begins to oscillate, initially moving upward.
(C) The ball begins to oscillate, initially moving downward.
(D) The ball begins to oscillate, but it is impossible to know whether it will initially move upward or downward.

Q13. If the ball in the previous question was oscillating and moving at the moment the rope was cut, what happens once it is cut?

- (A) The ball stays still.
(B) The ball continues to oscillate, initially moving upward.
(C) The ball continues to oscillate, initially moving downward.
(D) The ball continues to oscillate, but it is impossible to know whether it will initially move upward or downward.

Q14. The upper end of a spring is hung from the ceiling of an elevator, while a small ball that is oscillating is attached to its lower end. The cable supporting the elevator is cut, and the ball continues to oscillate in the frame of reference of the falling elevator. How does the period of oscillation of the ball's simple harmonic motion in the falling system compare to the period of oscillation of the ball before the cable was cut?

- (A) Greater.
(B) Smaller.
(C) Equal.

Q15. A tank containing water is sliding down a frictionless inclined plane. How will the liquid arrange itself during the descent?

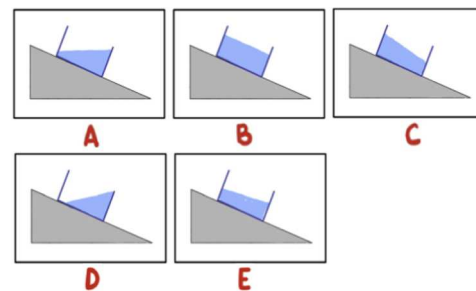
(A)

(B)

(C)

(D)

(E)



Q16. A tank containing water is sliding down an inclined plane with friction, but the friction is not enough to keep it stationary. How will the liquid arrange itself during the descent?

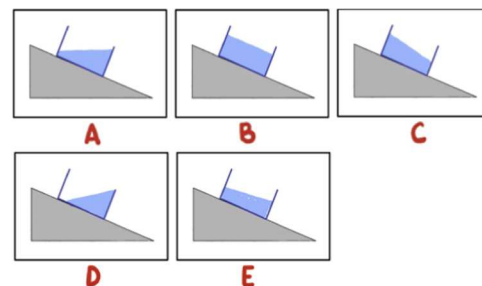
(A)

(B)

(C)

(D)

(E)



Q17. A pendulum consists of a very thin rigid rod of negligible mass and a point-like object of mass m . The pendulum is hung from the ceiling of an elevator and is initially oscillating, when suddenly the cable supporting the elevator is cut. At the instant the cable is cut, the pendulum is at its equilibrium point. How does the pendulum move when observed from the frame of reference of the elevator? Consider air resistance negligible.

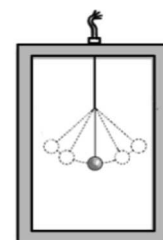
(A) Continues to oscillate periodically.

(B) Parabolic motion.

(C) Uniform circular motion.

(D) Uniformly accelerated downward motion.

(E) Stay still.



Q18. With reference to the previous question, consider the case in which, at the moment the cable is cut, the pendulum is at its maximum amplitude. How does the pendulum move as observed from the frame of reference of the elevator?

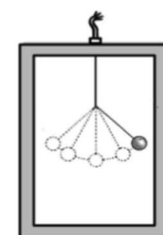
(A) Continues to oscillate periodically.

(B) Uniform circular motion.

(C) Uniformly accelerated upward motion.

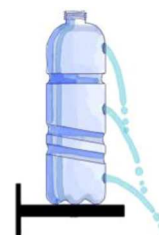
(D) Uniformly accelerated downward motion.

(E) Stay still.



Q19. Three holes are made in a plastic bottle at three different heights from its base. The bottle is filled with water and left open. Water begins to flow out of the holes, when the bottle is dropped from a certain height. What happens during the fall? Neglect air resistance.

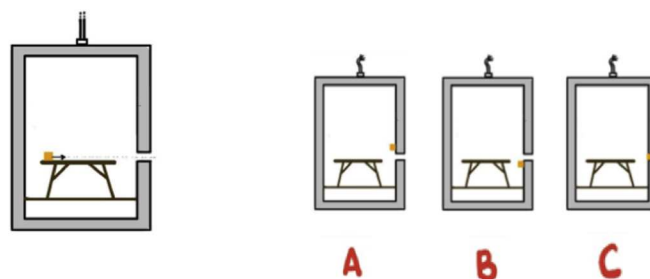
- (A) The jets will be different compared to the case where the bottle is stationary.
- (B) Water will also exit from the top opening of the bottle and the intensity of the jet from the side holes will change compared to when the bottle is stationary.
- (C) Water does not exit from any hole.
- (D) Water starts coming out from the top, and the jets from the three holes go upwards.



- (E) Water will exit from all three holes with three jets of equal intensity.

Q20. Consider an elevator with a table anchored to it, as shown in the figure. A cube is placed on the table with an initial velocity such that it can reach the edge of the table, despite the friction with it. The elevator has a hole the size of the cube, which would allow the cube to exit the elevator if it moved horizontally relative to the table's surface. After the cube has been launched, when it is at the center of the table, the cable supporting the elevator is cut. What happens?

- (A)
- (B)
- (C)



Q21. Astronaut Samantha is in the International Space Station (ISS) orbiting Earth. Samantha has a small ball clenched in her fist. She suddenly opens her hand. The ball.

- (A) It does not move (remains suspended) because in the space station, the gravitational field is negligible given the large distance from the centre of the Earth.
- (B) It falls towards the centre of the Earth with an accelerated motion with acceleration g (as on the Earth's surface).
- (C) It does not move (remains suspended) because the gravitational force is canceled out by the centrifugal force acting in the opposite direction.
- (D) It falls towards the centre of the Earth with an accelerated motion with acceleration less than g , the acceleration measured on the Earth's surface.
- (E) It does not move (remains suspended) because the space station is in free fall, therefore it behaves like an inertial reference frame without a gravitational field.

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