Active learning techniques for improving student's understanding of classical mechanics - Group 3

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Abstract

In the initial years of undergraduate physics education, lectures predominantly rely on traditional teaching methods. This project proposes a method for restructuring physics instruction to include active learning strategies, with a particular focus on the classical mechanics course that many first-year students encounter. The restructuring involves using active learning strategies to engage students actively through quizzes, discussions, lab sessions, problem-solving activities, and self-reflection on their learning. The strategy specifically aims to address and correct misconceptions in physics, thereby significantly enhancing understanding and learning in courses such as classical mechanics. A practical example of a typical lecture in classical mechanics is proposed, organized around pre-class preparation, in-class participation, and post-class assessments. This approach fosters an environment where students can explore and comprehend classical mechanics, and physics in general, in diverse ways.

1 Aim and goal

The primary aim of our project is to transform the traditional lecture environment within physics courses, particularly classical mechanics, into a more inclusive and engaging learning experience for students. Recognizing the passive nature of many lectures in the physics curriculum, we have identified a need for pedagogical strategies that not only involve students more actively in their learning process but also effectively address and correct common misconceptions in physics.

Our goal is to propose a possible way to restructure the classical mechanics course, and include active participation, critical thinking, and a deeper understanding of the subject matter among students. This initiative stems from the realization that misconceptions in fundamental physics concepts can significantly hinder a student's ability to apply these concepts to more advanced topics. Our project seeks to implement teaching methodologies and tools that encourage students to engage directly with the material, and thereby we hope that students will gain a more profound and accurate comprehension of classical mechanics.

To achieve this, we want to bring active participation in the learning process, and develop and integrate teaching practices that build on diverse learning styles and levels of understanding. To do so, we propose to include interactive elements such as quizzes, in-class discussions, in-class labs, and problem-solving sessions. These activities will require students to actively participate in the learning process, thereby increasing their engagement of the material. Specifically we also propose to target common misconceptions in classical mechanics. This will involve the use of literature to identify misconceptions early on and the implementation of strategies designed to correct these misunderstandings through direct engagement and clarification.

Incorporated in the project is also a specific example that underscores the approach: to transform the way we teach kinematics, a basic part of classical mechanics. This plan highlights three steps: before class, teachers prepare by pinpointing common misunderstandings regarding acceleration and making resources to tackle them; during class, interactive tools are used like simulations of moving objects and in-class lab sessions are performed with falling objects, for activating student participation; and after class, reflection and assessment are made. By utilizing innovative teaching methods and real-world applications to demonstrate the relevance of classical mechanics, we hope to make the topic more interesting. In this example the intended learning outcomes include students being able to identify common misconceptions about acceleration, explain and apply key concepts of motion accurately, and actively apply theoretical knowledge to real-world situations, thereby fostering a deeper, practical understanding of classical mechanics. With active engagement, we hope for a shift away from purely lecture-based delivery of the intended learning outcomes.

In conclusion, our projects aims at improving the educational experience in classical mechanics by making lectures and laboratories more sense-making, engaging, and effective in addressing misconceptions. Through the integration of active learning strategies and a focus on correcting misunderstandings, we hope to create a learning environment where students not only achieve academic success but also develop a lasting interest and understanding of physics.

2 Background

2.1 Misconceptions in physics

It is known from literature [1, 2] that science learning generally suffers from the existence of *misconceptions*. These are false or incorrect understandings of scientific concepts that contradict accepted scientific theories.

Many can be the root causes of misconceptions, such as religious or cultural influences. However, the main source of misconceptions is frequently some practical experience. Students never come to school with no preconceptions; they have already met several scientific phenomena in their daily life: not only in their personal experiences but also in TV and movies they have already come across concepts like gravity, energy, light and acquired inaccurate information.

From a more naturalistic point of view, the formation of misconceptions is not a real drawback, since it is the natural creation of an *intuitive knowledge* that enables humans to interact with the world in which they evolved [3]. However, this kind of *survival* knowledge is no longer useful or appropriate for the world in which we live, being at odds with modern scientific theories. On the contrary, it represents a disadvantage for students of all ages.

For this reason, identifying and addressing misconceptions has become a key issue in science teaching. Several techniques have been developed and tested to solve misconceptions: in particular, evidence suggests that active learning could be a key in the solution of this problem [4, 5].

In physics, in particular, in classical mechanics, where misconceptions are very common among students, teaching techniques related to active learning have attracted particular interest and turned out to be more effective than the traditional lecturing approach [6, 7, 8].

2.2 Active learning in physics

Active learning refers to numerous instructional methods that engage students in their learning. These methods aim to provide students with purposeful activities and to support active student engagement. They encourage students to think about what they learn.[9] Traditional instruction in higher education such as lectures or laboratories can be well complemented by activities of active learning. Each activity can be associated with one of learning approaches such as inquiry-based learning (IBL) [10], problem-based learning (PBL)[11], blended learning [12], Predict-Observe-Explain (POE) strategy [13] or collaborative learning [14] and Just-in-time teaching (JiTT) technique [15]. These approaches have the potential to promote active learning effectively on grounds of constructivist learning theory [16], and they can be studied, implemented and evaluated as individual entities. Basic definitions of these approaches are provided below:

- IBL is an approach in which the answer or solution following an inquiry, a problem or hypothesis is actively searched by students. It should promote problem-solving skills and provide students with an authentic experience of thinking as a scientist. This approach overlaps with PBL.

- PBL is an approach in which a group of students seek a solution to a problem given by a subject-related scenario.
- Blended learning promotes online instructions and learning activities to students to complement their in-person classes.
- POE makes students active and engaged by letting them foretell the result of an experiment.
- JiTT is a strategy in which students study the background knowledge of a given topic before the actual class resulting in more time available for active learning in a classroom.

There are challenges of all the mentioned instruction approaches that need to be considered before their introduction into instruction. The most obvious limitation of all of them is that their success greatly depends on the level of engagement of students. Blended learning is vulnerable to technical problems and JiTT requires sensitive time management.

There are many other limitations related to the approaches mentioned in this section, but we want to reflect on some empirical pieces of evidence that IBL and PBL approaches with minimal guidance are less efficient than approaches where thorough guidance is provided to students [17]. Kirschner et al. (2006) [18] argue that approaches like IBL and PBL can be feasible in instruction only if students have sufficient prior knowledge to guide them-self on their own to solve a problem. This is explained by cognitive overload which occurs when students encounter a new problem and have a full capacity of their working memory used only to conduct a search. In this state, students do not learn, and no new knowledge is transferred to their long-term memory. It was proven that humans can only solve problems efficiently when they can build on knowledge and experience stored in their long-term memory. The worked-example effect is often mentioned to support the need to provide students with worked examples and proper guidance during the instruction since these students will store more knowledge about the subject in their long-term memory, and be able to solve problems related to the subject more efficiently than students that, on the other hand, are provided with no worked example and guidance and must learn about the subject only based on problem solving and discovery learning approaches. However, following the conclusions in [19], we still believe that IBL, or PBL and other problem-solving-based techniques can be efficient if students are provided with a sufficient amount of worked examples and guided instruction in a given subject, so they form sufficient schemes in their long-term memory before IBL or PBL is used in the instruction. This approach can be supported by the expertise reversal effect that occurs for student with enough prior knowledge, and expertise in a given field and fully guided instruction could lead to a higher cognitive overload than solving subject-related problems on their own.

2.3 Active learning approaches for assessment

Active learning methods can enhance assessment and evaluation in science, particularly in the classic mechanics course. The literature emphasizes the value of integrating active learning into the assessment pattern of science learning activities. Lamon et al. (2020) [20] found that incorporating an active learning framework into continuous assessment creates a dynamic and interactive learning environment that supports student success and provides instructors with timely insights into student progress. Similarly, Zapata-Rivera (2021) [21] demonstrated that continuous assessment, including regular assignments, project work, and participation in discussions, offer ongoing feedback and encourages consistent engagement with the course material. They also revealed that administering small quizzes at the end of each lecture reinforces key concepts and measures immediate understanding. Mercat's (2022) [22] study showed that involving summarization activities, such as writing a summary of the lecture or solving a problem that encapsulates the main points, helps consolidate learning and provides a quick assessment of students' grasp of the material. Moreover, Nikolic et al. (2021) [23] demonstrated that integrating active learning methods into assessment and evaluation strategies creates a more dynamic and engaging learning environment, promoting deep understanding and retention of the course material. They also highlighted how this approach helps students develop critical thinking, collaboration, and communication skills, ultimately enhancing their overall learning experience and academic success.

3 Design

From the previous analysis, we can identify the following problems of the traditional instructions in physics:

- students are generally expected to passively follow the lectures;
- there is no focus on the possible misconceptions students could have from their previous educational background;
- laboratory sessions are either not incorporated, or students are only guided through a set of laboratory exercises that can be accomplished without thinking about what they are doing. [24]

We think that these problems can be addressed by active learning approaches to restructure lectures and laboratory sessions. We propose the following three-phase scheme:

3.1 Pre-class phase

First, it is important to encourage students to prepare before a class to get them familiar with the topic that will be taught. Blended learning is a key tool to attain this: videos and quizzes focusing on the main lecture questions should be provided to the students before class.
This will be especially fruitful for first-year students: indeed, it is well known that the transition from secondary education to higher education is usually a big hurdle for students, as not all of them are able to organize themselves for classes. Providing videos and quizzes before each class will give them a guide to cope with a new lecturing experience. However, at this stage it is simple for a teacher to fall into the mistake of creating videos and quizzes that are too long, causing students to be overloaded [25]. The videos and the quizzes should be short and focused on the main questions that will be discussed during the lectures: in general, at this stage, the teacher could use the JiTT to provide students material a short time before any lecture[1].

3.2 In-class phase

Second, a teacher prepares the lecture for in-class instruction. The main difference with traditional instruction is in our case that the teacher will not simply follow a textbook and explain different topics in a passive and monotonous way, but will also introduce active learning components. A teacher should also reflect on major major misconceptions in a given field [2] when preparing the in-class instruction. In addition, the activities for the lecture should also be designed to encourage students to think and discuss misconceptions: the POE strategy could be beneficial at this stage together with asking students to watch a demonstration and discuss it together.
The *In-class phase* can be well complemented by laboratory sessions to improve students' understanding of concepts [27], their sense-making [28], i.e. making connections between theory and phenomena, and problem-solving skills. Laboratory exercises need to be designed in a way that students cannot accomplish them without active participation and thinking. For example, a problem or even a whole scenario can be introduced to a group of students according to IBL or PBL approaches. Subsequently, students need to discuss it and propose an experimental set-up, take and analyze measurements to find a solution or an answer. A lab supervisor can further engage students by letting them predict the result of an experiment that they propose according to the POE approach. While basic support like help with equipment or clarification of a problem can be provided to students, solutions to these laboratory exercises should not be revealed to students.

3.3 Post-class phase

Third, any lecture should end with a *One-Minute Paper* [29], in which students are asked two questions: first what they found most interesting in a lesson. They use this to reflect on everything they saw in

[1] Depending on the time schedule, the material could be provided either just one hour before the lecture or the day before. The main point is to not make students spend too much time on those activities.

[2] There are many online resources, but a good starting point could be IOP: misconceptions page [26].

class. Second what aspect of the lecture is not particularly clear. This information can be used by the teacher to structure the next lectures.

The main advantage of such a structure is that it allows students to actively participate in the lectures or laboratory sessions. Moreover, although the skeleton of the lessons is always well defined by the outline presented above, the way topics are discussed depends greatly on the type of interactions students have in class. In this way, lessons are not static but grow with the educational growth of the students.
Nevertheless, this approach has its disadvantages. First, the teacher's workload is much greater than in a traditional class. In addition, given the presence of many activities during lectures, a course structured in this way will never be able to cover the same amount of topics as a course taught in a traditional way. However, we believe that providing students with more interactive courses that are more focused on real understanding of topics is better than simply presenting many topics without caring about learning outcomes.

3.4 Practical example: a lecture from the classical mechanics course

In the following, we consider a specific example of higher education course and propose a structure of instruction based on the ideas above. We chose the classical mechanics course for this example since it is one of the first courses physics students encounter and since it is also one of the few physics courses that are also required for students in other science majors.
In particular, we suggest a possible way to organize a lecture on kinematics, one of the first topics discussed in this course, aiming to achieve intended learning outcomes such as enabling students to identify and correct common misconceptions about acceleration, explain and accurately apply key concepts of motion, and actively apply theoretical knowledge to real-world situations. This should not be understood as a complete example, but rather as a sketch of how the actual lesson should be structured.

- *Pre-class phase*
  Before the actual lecture, a teacher should look for the major misconceptions related to the topic. For example, the teacher could decide to address the following misconceptions:

  - Many pupils have an unclear idea of acceleration and cannot reliably separate it from speed [30]
  - Many students think a heavier object will fall faster than a lighter one of the same general shape or size [31]
  - Many students think that the object's acceleration is always in the direction in which the object is moving [32]

  Then, a teacher could prepare short videos (2-3 minutes each) in which the concept of acceleration and the related equation of motion are briefly presented. When presenting the equations, the teacher should particularly focus on making connections between the mathematical equation and the scientific phenomenon [33]. The teacher could even create quizzes based on examples from literature[3]. In this case, applets such as *Socrative* could be very useful, as they would allow the teacher to analyze the students' background knowledge before the actual lesson.

- *In-class phase*
  A good starting point for this specific lecture could be the use of the online applet *The Moving Man*[4] by PhET combined with a POE strategy to let students think about the videos they have watched in the previous phase. The teacher could show simulations with different initial conditions and ask students to guess and explain the graphs of position, velocity and acceleration. Then the teacher could show the actual graphs and ask students to compare them to their predictions. Then, after the discussions, the teacher could proceed with a traditional explanation of the topic. A possible advantage of this approach is that students will be much more enticed to follow the lesson after actively participating in the first part.

[3] An example could be the exercises proposed in Exercise 1 [34] and Exercise 2 [35].
[4] The Moving Man [36].

This topic is particularly suitable for laboratory sessions too. One of the possibilities is to provide students with a video of *hammer-feather* experiment in vacuum and ask students to explain what they observe based on accurate velocity and acceleration plots that they calculate. They can, for example, install an app like *Tracker*[5] for the measurements. They can also be asked to conduct a similar experiment and analysis for objects falling in a classroom and compare with previous results.

- *Post-class phase* At the end of the lecture, students are asked to complete the *One-minute paper*, from which the teacher can get a first impression of students' understanding.
  Moreover, the students can also be asked to answer a short quiz using software like *Socrative* or *Canvas*.

4 Assessment and evaluation

As mentioned earlier, adopting active learning methods necessitates a specific design of the assessment pattern to promote better comprehension and retention of course materials. Moreover, the assessment should be utilized to provide with a picture of student's understanding for a teacher to be able to reflect on the effectiveness of chosen activities and instruction approaches. We propose these approaches for designing assessment and evaluation using active learning methods in a classical mechanics course:

- Peer assessment: Design your lecture to promote students working in pairs or small groups to solve problems or complete tasks related to the content covered in the lecture. For instance, you can assign students to build a model demonstrating Newton's laws of motion. First, students can be divided into groups. Then, to facilitate them, a teacher can provide clear guidelines to be used when assessing their peers' work. Students may conduct their assessments and then present the findings to their peers first, where they must assess and provide feedback on the work of another group using the predetermined criteria. Later, students may discuss the feedback they received with their group members. Getting feedback from their peers encourages students to use the feedback they receive to make improvements to their projects. Finally, students may reflect on the peer assessment and may show the benefits gained from their peers. By doing so, they can have a favourable environment for discussing their findings with each other and providing feedback to their partner or group. This not only reinforces their learning but also helps them develop critical thinking and communication skills (Mora et al., 2020) [38].
- After a lecture, pose a question or problem to the class and give students a few minutes to think about it individually. Then, let them discuss their thoughts with a partner before sharing their answers with the rest of the class. For example, a teacher may ask students to calculate the acceleration of a free-falling object. Here, the teacher may start by introducing the question. Later, after giving students the opportunity to think individually, the teacher can pair up students to discuss the given question. Finally, the teacher may bring the whole class together for a whole-class discussion. Demirci and Duzenli (2017) [39] showed that this approach not only encourages active participation but also enhances students' engagement in the learning process.
- Designing the assessment involves assigning students to create concept maps or diagrams that summarize the key concepts and relationships covered in the lecture. Concept maps are more analytical and focused on showing relationships between concepts in a hierarchical manner. They are opposed to mind maps, which are centered around a single central concept from which related ideas branch out radially in all directions, leading to their less hierarchical structure (Koc, 2012) [40]. For instance, the teacher could select Newton's Laws of Motion as the concept mapping assignment. In this case, the teacher should begin by providing clear instructions to students, explaining that they need to create a visual representation that depicts Newton's Laws of Motion. Students will commence by identifying the main concept in the centre of their map and then branching out to other related definitions, examples, and equations using lines, arrows and connecting words to illustrate the connections between concepts. This visual representation can assist them in organizing and connecting their understanding of the material, while also identifying any gaps in their knowledge (Boff et al., 2022) [41].

[5]The basics of the software Tracker [37] could be explained in one of the short videos of the *pre-class phase*.

- At the end of each lecture, we suggest administering a short quiz or using software like Socrative or Canvas portals to gauge student understanding of the main concepts discussed. For instance, this is an example of a multiple-choice question quiz:

  A hammer and a feather are dropped from a cliff. Which of the objects will reach the ground first in free fall? (ignore air resistance)

  - A. Feather
  - B. Both will reach the ground at the same time
  - C. Hammer

  By selecting the correct answer (A) and clicking the submit button either on Canvas or Socrative portals, students receive immediate feedback on their understanding of the topic. These platforms provide immediate feedback to both the students and the instructor, highlighting areas that may need further clarification or reinforcement;

- Application projects or exercises: In the assessment pattern, we suggest incorporating real-world examples or practical applications of the concepts learned in the lecture into assessment tasks. For example, a teacher may provide this problem: "A car is travelling at a constant speed of 30 m/s and comes to a stop in 5 seconds. Calculate the deceleration of the car." To solve that problem, a teacher may start by breaking down the problem into its component parts to easily identify the equations to be used. Later, together with the teacher, students may solve the problem. Once the problem is solved, the teacher may interpret the results in the context of the scenario. Then, the teacher may provide similar problems with different scenarios and variations. We believe that this may help students see the relevance of the material and develop problem-solving skills in a context that mirrors the challenges they may encounter in their future careers (Paolucci and Wessels, 2017) [42].

Using active learning methods, we propose so-called "application-based questions" as an effective way to design summative exams in a classical mechanics-related course. These questions should require students to demonstrate their understanding of concepts covered during the lectures. For example, the lecturer may pose a question that utilizes "Newton's laws of motion" scenario involving an object in motion. Students would then be asked to analyze the forces acting on the object and compute its acceleration. The benefits of this scenario are twofold: it tests students' knowledge of the principles of mechanics and their understanding of real-world applications. Moreover, an instructor may incorporate concrete examples, including questions that require students to interpret graphs or diagrams related to classical mechanics principles. This will assist the teacher in detecting at an early stage whether or not students have memorized the information learned. Instead, this kind of assessment will help students apply their knowledge in a real-world setting, which is the core foundation of critical thinking and problem-solving ability. Furthermore, to foster teamwork while helping students apply the theories they have learned, an instructor can design a group project that requires collaborative teamwork. This way, students can work together to solve complex problems.

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5 Process report

- **15 of February 2024 at 3 pm**
  This was when we first met. We finalized topic and focus of our project. We started preparing the project plan in Google Docs. It was a collective effort of all group members.

  Group discussion - comments and suggestions - Blahoslav: Proposed project main topic to be active learning in physics and how to use active learning in labs. Gabriele: We should look into active learning in classical mechanics since this subject connect us. Moreover, there are many misconceptions. Isabella: We should clearly divide work on each section of the project report to each group member. Gilbert: We should meet next time in-person. Since the group project will be prepared in Overleaf, need additional guidance.

  We finished draft of the project plan during the meeting. We agreed that we will read through it again and fix minor issues remotely.

  In the end, we agreed on following division of work for the group project:

  - Everyone: Title
  - Everyone: Abstract.
  - Isabella: Aim and goal of the project: Make lectures more inclusive and make students follow in an active way, with a focus on classical mechanics. Make classical mechanics more interesting and avoid common misconceptions.
  - Blahoslav: Background: introduce active learning, approaches to active learning, misconceptions in classical mechanics.
  - Gabriele: Design: Quizzes, flipped classroom, labs during the course/lecture where students test the theories themself, discussions.
  - Gilbert: Assessment and evaluation: Continuous assessment, small quizzes during the course, 1 minute paper at the end of each lecture to summarize what was learned.
  - Everyone: References.
  - Blahoslav: Process report.

  We agreed on place and time of the next meeting (21 of February 2024 at 9 am).

- **21 of February 2024 at 9 am**
  In-person meeting.
  Our progress:

  - Isabella: Completed aim and goal section.
  - Blahoslav: Prepared Overleaf template and started working on background section. Prepared template for our group project presentation on Google Drive.
  - Gilbert: Completed assessment and evaluation section.
  - Gabriele: Wrote draft of design section.

  We read through all the sections together.

  Group discussion - comments and suggestions - Gabriele: Proposes to write more about misconception difference between acceleration and speed - provided with this reference https://spark.iop.org/many-pupils-have-unclear-idea-acceleration-and-cannot-reliably-separate-it-speed. Blahoslav: Assessment and evaluation section should focus on concrete examples to test if our goals with active learning are met. And if students grasp what we expect from them. Gilbert: We should give examples of continuous assessment. Isabella: We should provide a concrete example of our active learning approaches in classical mechanics.

We agreed on the next meeting to take place in-person (23 of February 2024 at 4 pm).

- **23 of February 2024 at 4 pm**
  In-person meeting.
  Our progress:
  - Isabella: Proofread all the sections. Started preparing our group presentation.
  - Blahoslav: Completed active learning in physics in background section, also added lab session into Design section.
  - Gilbert: Moved his text from Assessment and Evaluation section into Background section. Completed references for his text.
  - Gabriele: Completed Design section and also added misconceptions in physics section.

  We went together through all sections in group project on Overleaf. We collectively proofread and made suggestions for changes.
  Proposals and comments from group discussion -
  We agreed on the next meeting to take place over Zoom (26 of February 2024 at 4 pm).
  Group discussion - comments and suggestions - Gabriele: Need to improve assessment and evaluation section with more concrete examples of assessment fitted to classical mechanics. Gilbert: We should keep our focus on active learning for classical mechanics course, we need to state that clearly in Design and Assessment and Evaluation sections. Isabella: We should not forget about paragraphs to make the project report easier to read. Blahoslav: We should aim to use academic terms and phraseology.

- **26 of February 2024 at 4 pm**
  Zoom meeting.
  Our progress:
  - Isabella: Wrote abstract.
  - Blahoslav: Proofread whole document. Added contribution into practical example and design about labs. Completed process report.
  - Gilbert: Helped with providing concrete examples of assessment and evaluation.
  - Gabriele: Completed Assessment and Evaluation Section and practical example.

  Everyone worked on the group presentation.
  We proofread the whole document all together before submission for feedback.

6 Feedback summary

Feedback summary following the feedback meeting. In the Aim and Goals section, we have detailed our specific lecture example on Classical Mechanics, to establish a stronger connection with the rest of the report.
In the design section, we were advised to replace bullet points with subsections, a change we have implemented.
We reflected on limitations of active learning approaches in the background section including the low efficiency and cognitive overload if IBL and PBL approaches are introduced without students having sufficient prior knowledge.
For our example lecture on kinematics in Classical Mechanics, we have outlined the intended learning outcomes: students should recognize common misconceptions about acceleration, explain and apply concepts of motions, and apply theoretical knowledge to real-world scenarios. Additionally, when suggesting that

teachers present equations in videos before class in our practical example, we emphasize the importance of highlighting connections between mathematical equations and scientific phenomena. Links have also been added to all examples of misconceptions provided in the Practical Examples section.
We have updated the quiz example in the Assessment and Evaluation section. Rather than asking which equation is correct, we now reference the hammer-feather experiment, requiring students to engage in deeper reflection on how objects move. Also, we have included references in the section discussing concept maps and further clarified that concept maps must contain lines, arrows, and connecting sentences to distinguish them from mind maps. Group 2 recommended we use full names for learning approaches instead of abbreviations. We have decided against this, maintaining that it is standard practice to only mention the full name once followed by an abbreviation that can be used in the rest of the report.
Finally, we have proofread the report for typos and missing words.