Designing Upper-Division Undergraduate Physics Course Problem Tutorials

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Physics 492R Capstone Project Report

Abstract

This undergraduate capstone project report focuses on the development of problem tutorials for upper-division undergraduate physics courses. The project aims to improve the problem-solving skills of physics students by providing them with targeted exercises that build on their existing knowledge. The report describes the development process, including the identification of common problem areas, the selection of appropriate problems, and the creation of tutorials that guide students through the problem-solving process. Previous literature suggests that tutorials are a useful tool for improving student problem-solving skills and can help address common challenges faced by upper-division physics students. Overall, this project contributes to the ongoing effort to improve physics education and support the success of undergraduate students in the field.

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Background & Motivation

Physics education is a constantly evolving field, with educators and researchers constantly seeking new ways to improve the learning experience for students. As an undergraduate student of physics, I have developed a deep passion for physics education, which has motivated me to pursue this capstone project focused on creating problem tutorials for upper-division physics courses.

My interest in physics education was sparked by my own experiences as a tutor for high school and lower-level undergraduate physics courses. I found that students often struggled with problem-solving and conceptual understanding. Over time, I learned that these challenges were common among almost all physics students, especially as they progressed to more advanced coursework. Through my job as a physics tutor, I received training about how to let students figure things out on their own. Our office motto was to “Let the student hold the pencil.” As I began to explore ways to improve my tutoring and their learning, I became interested in the research surrounding physics education and the various approaches being developed to support student success.

As I progressed in the skills required to let students travel down the path of discovery, I have come to appreciate the importance of guided problem-solving exercises. These types of exercises can help students build on their existing knowledge, develop critical thinking skills, and gain confidence in their abilities. However, I have also observed that many textbooks and course materials do not provide enough support for students struggling with these concepts. While I took an upper-division physics course for myself, guided problem-solving tutorials were used to help us understand the material more deeply. Dr. Colton provided these resources and eventually reached out to the class to see if anyone was interested in helping to develop these types of tutorials. As I have participated in this capstone project, I have become more motivated to create problem tutorials that provide students with the guidance and structure they need to succeed in their upper-division physics coursework.

My passion for physics education has been further fueled by the ongoing research in the field. Researchers are continually investigating new ways to improve physics education, from the use of technology to the development of new teaching approaches. I am excited to contribute to this research by developing and evaluating problem tutorials that can support student learning and success in physics.

Overall, my motivation for this capstone project stems from a desire to improve the physics education experience for students and contribute to the ongoing effort to advance physics education research.

Introduction

One might say that a skilled physicist is one who masters complex concepts and develops advanced problem-solving skills that are not always intuitive. Many physics students struggle with these challenges, especially as they progress to upper-division coursework.

One approach to supporting student success in physics education is the development of problem tutorials that guide students through the problem-solving process. The importance of problem tutorials lies in the fact that they provide students with the guidance and structure they need to develop their problem-solving skills in an environment where help is readily available. These tutorials apply a learning framework that has been shown to improve long-term understanding of complex concepts. By providing this structure, the tutorials help students build on and apply their existing knowledge and develop their critical thinking skills.

Furthermore, problem tutorials can also help address common challenges faced by physics students, such as a lack of conceptual understanding and difficulty with mathematical calculations. The tutorials provide opportunities for students to practice and reinforce their understanding of key concepts and equations, as well as develop their skills in applying them to common problems. All of these skills must be correctly synthesized in order to successfully solve physics problems.

This capstone project report focuses on the development of problem tutorials for upper-division undergraduate physics courses. The report describes the process of identifying common problem areas, selecting appropriate problems, and creating tutorials that guide students through the problem-solving process.

Prior Research

Physics education research emerged from the need to better understand how students can effectively integrate problem-solving skills, comprehension of complex concepts, and advanced mathematical tools to solve physics problems. Due to the interdisciplinary nature of the subject, specialized education research was required to enhance students' learning outcomes.

A significant portion of this project is based on the framework of the cognitive apprenticeship model introduced in *Knowing, learning, and instruction: Essays in Honor of Robert Glaser* [1]. The cognitive apprenticeship model is an instructional approach that emphasizes learning through apprenticeship-style interactions with more knowledgeable others. The model is based on the idea that learning is best achieved through social interaction and guided practice, rather than simply through the acquisition of isolated facts or skills. According to the cognitive apprenticeship model, effective learning requires several key elements. These include modeling, coaching, scaffolding, articulation, and reflection. “Cognitive apprenticeship teaching methods are designed to bring these tacit processes into the open, where students can observe, enact, and practice them with help from the teacher and from other students” (pg 458).

Ferguson *et al.* [2] conducted research that delved deeper into the specifics of improving student problem-solving skills and provided some of the methods for creating these tutorials. Their study, "On the quality of knowledge in the field of electricity and magnetism," revealed that the difference in cognition between lower- and upper-level undergraduate students is the method of organizing knowledge. This insight led to the development of the structure of problem tutorials that help restructure knowledge in the brain.

In 2009, Singh [3] discussed the importance of breaking down learning into smaller "knowledge chunks" at a lower level. This observation was made because it had been frequently observed that merely increasing the time spent on a subject did not necessarily enhance understanding. Singh found that by creating tutorials for students, they could be guided through the learning process and develop some problem-solving skills independently. Singh synthesized previous research that showed that the three main components of cognition are knowledge acquisition, organization and retention in memory, and knowledge retrieval from memory to solve problems appropriately. The conclusion drawn was that students need to walk through this process themselves and construct their understanding. Guided tutorials can be helpful for students to enhance their physics problem-solving skills.

Based on this, the Colorado Upper-Division Electrostatics method (CUE) was developed to help students begin the problem-solving steps. It includes free-response conceptual questions that ask the student to describe the strategy they will use to solve the problem. Zwolak *et al.* [4] switched to using a multiple choice version of the questions as they were much easier for instructors to grade. They assessed the efficacy of this modification and found success. Later, Wilcox *et al.* [5] confirmed these results, stating "Previous research demonstrated that the multiple-response and free-response versions of the CUE resulted in similar student performance and showed a high degree of consistency on multiple measures of test validity and reliability."

Further expansion of the CUE model was conducted by Baily *et al.* [6], forming the Colorado UppeR-division ElectrodyNamics Test (CURrENT) to include more questions to better assess student understanding. They found that this expansion of questions asked did indeed lead to greater understanding as well as made grading more simple for instructors. Xue [7] confirmed these results at University of Washington in 2021. "The overall results of the posttest version of the CURrENT suggest that the performance of UW students is similar to that of traditional CU and non-CU-Boulder transformed course structures."

Later, similar frameworks were applied in physics settings but with slightly different applications. Wilcox *et al*. [8] applied this to a mathematical tutorials that relate to physics problems and Caballero *et al.* [9] applied this to computational physics projects. In this specific study, they found that their model "gave most students (>80%) the confidence to attack open-ended problems and to explore physics on their own."

Methods

To begin with, the selection of the course for the problem-solving tutorials was based on careful consideration, and Physics 441, Electricity and Magnetism (or its equivalent at other academic institutions) was chosen as the target course. This course is a prerequisite for most undergraduate physics majors and requires students to integrate knowledge from multiple courses to achieve success, making it a suitable test bed for evaluating previous research.

The goal of my project was to create five tutorials to be used in future research. To create these problem-solving tutorials, we used a three-step process. The first step was to identify the more difficult concepts in the course. We consulted with the course instructor (Dr. John Colton) and reviewed course materials, including lecture notes, textbooks, exams, and our own experience in the course.

After identifying the more challenging concepts in the course, we began the process of developing problems that applied these concepts in a meaningful and challenging way. The aforementioned sources provided us with a wealth of problem types to choose from, which allowed us to create tutorials that challenged students' understanding of key concepts in different ways.

In order to ensure that our problems were properly aligned with the course objectives and expectations, we worked closely with the Dr. Colton throughout the development process. The instructor provided valuable feedback on the problems we created and helped us to refine our problem set to better reflect the level of rigor expected in the course.

We also took great care to ensure that our problems were distinct from the examples provided in class or assigned as homework. This was important to avoid any confusion or overlap between our problems and the materials provided by the instructor. By creating unique and challenging problems, we aimed to provide students with a valuable tool for improving their problem-solving skills and deepening their understanding of the course material.

Finally, we created the tutorials themselves. Each tutorial was focused on a specific concept and a problem that applied that concept. A series of questions were provided after the problem statement that were designed to guide the students through the process. See Appendix A for an example of a problem tutorial. The following topics were covered in the problem tutorials: electric dipoles, capacitance with dielectrics, Biot-Savart law, quadrupole moments, and vector potentials.

In order to comprehensively evaluate the efficacy of our problem-solving tutorials, we developed two distinct versions of each tutorial. The first version was intended to be undertaken by individual students while alone and included detailed guidance aimed at facilitating independent problem-solving. Specific targeted questions were included to point the students to the correct concepts they had previously learned. This version was designed for use in a variety of settings, including in exams or home study environments. The second version was developed for group or class-based settings and contained reduced guidance to encourage students to engage in collaborative problem-solving, with instructor support. By creating two versions of the tutorials, we aimed to evaluate their effectiveness across diverse scenarios and to assess how students' problem-solving skills varied depending on the level of guidance provided. Furthermore, the two versions of each tutorial were designed to promote independent and collaborative learning, which has been shown to facilitate better understanding of complex concepts and improved knowledge retention.

Following the initial problem-solving step (Part A), a second phase with a series of questions was included to solicit feedback from the students regarding the learning process (Part

B). This list of questions was identical from tutorial to tutorial. This feedback mechanism was a principal method of data collection for the research project's final results. The second phase was intended to provide insights into how the students approached the problem-solving task and identify areas where they required additional assistance. Through this approach, we sought to evaluate the effectiveness of the problem tutorials in improving the students' problem-solving and critical thinking skills and deepen our understanding of how to optimize such tutorials for maximum learning outcomes.

Conclusion

This capstone project aimed to increase understanding of a long-standing challenge in undergraduate physics education - improving students' problem-solving skills. Through the identification of the most difficult concepts in a course and the development of problems that applied these concepts in a meaningful and challenging way, we were able to create problem tutorials for students that facilitated the integration of problem-solving skills, understanding of difficult concepts, and complex math tools to solve physics problems. We drew on a range of sources and worked closely with the course instructor to ensure that the problems were aligned with the course learning objectives and reflected the level of rigor expected in the course. Our project also created two versions of each tutorial to provide diverse scenarios of testing.

Preliminary feedback from the students showed that the tutorials helped them to improve their problem-solving skills and that the feedback collected could be used to make improvements to the tutorials. This project highlights the importance of physics education research and the significant impact it can have on student learning outcomes. It also emphasizes the critical role of collaboration between researchers, instructors, and students in creating effective teaching materials.

The success of this capstone project provides a foundation for future work in physics education research, with implications that extend beyond undergraduate physics education. The methods developed and lessons learned from this project can be applied to other STEM disciplines and beyond, as educators continue to seek ways to improve student learning outcomes and prepare them for success in their careers.

These problem tutorials will be implemented across multiple universities to assess the efficacy of them. They can be implemented in future research to further evaluate their effectiveness in supporting student learning and success in upper-division undergraduate physics courses. The tutorials can be integrated into existing physics courses and evaluated using the provided student feedback section. The data collected from these evaluations can provide valuable insights into the effectiveness of problem tutorials as a learning tool, as well as inform future revisions and improvements to the tutorials. Additionally, the implementation of these tutorials in future research can contribute to the ongoing effort to improve physics education, support the success of undergraduate students in the field, and can demonstrate the value of research-driven approaches to addressing academic challenges.

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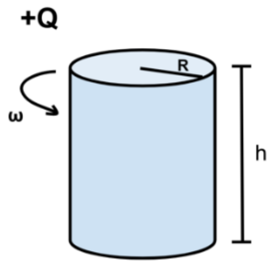
Appendix A

Vector Potential Problem Tutorial

Part A



A cylindrical shell (pictured above) of radius R and height h has a charge of q over the surface. Assume there is no top and bottom to the cylinder, only the "wrapper". The cylinder rotates with an angular velocity of ω. Find the vector potential A it produces at point r.

1) Describe below what you have to work with in terms of givens, knowns, unknowns, target variables, etc. as applicable. (Keep in mind that you can always come back to any step here and re-address it as needed.)

2) What are the underlying principles and concepts here? Describe it below, in words and/or with appropriate formulas.

- How do you find the surface charge density?
- How are angular velocity and tangential velocity related?
- How do you find the surface current density from the surface charge density?
- What equation is needed to find the vector potential from the surface current density, K?
- How should vector potential behave/ how could it fall off with large distance/ what direction?

3) Come up with a plan to solve this problem, and use that plan. Describe what you're doing with each step, in words, below.

4) Is there a way you can check your answer - whether it makes sense, whether you think one of the steps above needed to be addressed, etc.?

5) How is this similar to the vector potential of a solenoid?

Part B

1) First of all, do you think you have the right answer? If so, what makes you think so? If not, do you think you are on the right track to eventually get it?

2) When solving the problem, were there any steps you felt particularly confident about? What made you confident about those steps?

3) When solving the problem, were there any steps you didn't feel confident about? What did you do to address those issues in that case?

4) What do you think of this overall format, in terms of its assistance with problem solving, for this particular topic?

5) Do you think this format would be particularly helpful for any other topic you've seen this semester?