Problem-Solving Frameworks for Tutorials in Upper-Division Electricity and Magnetism

James Hecht,[1] Andrew J. Mason,[2] Matthew Rundquist,[1] Seth Read,[1] David Neilsen,[1] and John S. Colton[1]

[1]*Department of Physics and Astronomy, Brigham Young University, Provo, UT 84602*
[2]*Department of Physics, Astronomy, and Engineering, University of Central Arkansas, Conway, AR 72035*

Abstract: We explore the use of tutorials to assist upper-division electricity & magnetism (E&M) students with problem solving. Specifically, we test two versions of tutorials; one that implements a problem-solving framework, and another with the framework removed. Data examined in this paper includes student exam problems, an end-of-semester survey, interviews, and problem-solving exercises administered using a think-aloud protocol. Preliminary results when considering exam scores alongside student comments offer some evidence that tutorials structured on a problem-solving framework may improve conceptual parts of problem solving for students. Student problem-solving processes are also examined, and we find that these upper-division students struggle with practices of checking their reasoning, an area for future attention.

2025 PERC Proceedings edited by Pawl, Zwolak, and Leak; Peer-reviewed, doi.org/10.1119/perc.2025.pr.Hecht

I. INTRODUCTION

Problem solving is one way to show mastery of physics theory and skills that an expert physicist would use. For example, a novice physicist might begin a physics problem with little strategy or thought about what the problem will involve, whereas a more experienced physicist might consider deeper physics principles rather than superficial features before beginning calculations [1]. One intervention to assist students with obtaining these problem-solving skills is to provide them with a problem-solving framework (PS framework), which scaffolds expert-like problem-solving skills into instruction [2, 3]. This framework may include elements such as asking students to draw a picture, describe information they know about the physical situation, write down principles or equations they think they will use, or perform a check on their work when they are done with the problem. Such interventions are common for students' introductory courses at the university level, but not so common for the upper-division level, where it may be assumed that students are already using such skills even though this is not always the case [4].

We are studying interventions to assist upper-division electromagnetism students with problem-solving skills, particularly through scaffolding within the context of cognitive apprenticeship theory [5, 6]. Here, the particular intervention we study is the implementation of PS frameworks in physics tutorials to be used at the upper-division level. These tutorials are intended for use in a first semester upper-division electricity and magnetism (E&M) course. Interventions and tutorials have been previously studied for this topic and at this level, but often with a focus on specific physics concepts or aspects of problem solving [7, 8, 9], whereas here we are interested in developing tutorials to assist with problem solving comprehensively.

In our prior research, such tutorials focused on problem solving have already been shown to be of benefit to and favored by students, providing structure and guidance to the process of learning how to solve E&M problems, as well as an opportunity to engage in the material and collaborate with other students more than they would in the traditional college lecture [10, 11]. They have had the notable drawback of feeling overly linear to some students, particularly to students who are not used to structuring their problem-solving approach or using other expert-like problem-solving practices. While tutorials structured on PS frameworks have been shown to have benefit in previous research, they have not yet been directly compared to traditional upper-division tutorials, which may involve aspects of solving problems but not a comprehensive framework. This largely guided the direction of research during the Fall 2024 semester, which will be the primary focus of this paper.

We first address the impact of PS framework-focused tutorials, as opposed to those not structured around a PS framework, on student understanding. This is discussed in terms of problem-solving approaches and in terms of performance while completing E&M problems on exams. In addition, we also offer insights pertaining to students' problem-solving practices at this level of physics and further assess whether it is accurate to assume that they are implementing problem-solving strategies they might have been taught in their introductory physics courses.

TABLE I. Fall 2024 tutorial topics and versions assigned. Version A implements the PS framework, while Version B does not.

Tutorial #	Tutorial Topic	Group 1 Version	Group 2 Version
1	Point charges and electric field	A	B
2	Gauss's law	B	A
3	Laplace's equation	A	B
4	Quadrupole **E** field	B	A
5	Dielectrics	A	B
6	Magnetostatics and Ampere's law	B	A
7	Displacement Current	A	B

II. PROCEDURE

Two versions of physics tutorials were tested in a single 36 student section of upper-division E&M over the course of Fall semester 2024. The content of each tutorial was based on the topics used during Fall 2023 of this same study, and would guide students through physics problems they would regularly see in their first semester of upper-division E&M. The version of these tutorials structured using the PS framework are referred to as Version A, while the tutorials that remove the framework are referred to as Version B. To study the impact of the PS framework, the class was split into two groups of students, Group 1 and Group 2, where group placement was assigned by which side of the room the student was sitting in. For the first tutorial, Group 1 was given Version A (i.e. with PS framework) and Group 2 was given Version B (no framework). The two groups then alternated between tutorial versions thereafter. Thus for each tutorial, half of the class used the version with the PS framework and half used the other version, and each half of the class used a PS framework half the time. Alternating the tutorials in this manner allowed us to see the impact of the PS framework on each group of students while also allowing us to control for other factors such as one group consistently outperforming the other group overall. The list of topics and the tutorials administered to each group are given in Table I.

A. Design of Tutorial A compared to Tutorial B

Both versions of the tutorials were modified versions of the tutorials used during Fall 2023, with both types including the same problems and similar procedures as the Fall 2023 versions and as each other. What differed between the two versions of tutorials was the framework: the type A tutorials specifically included elements of a PS framework, whereas the type B tutorials did not.

Version A was structured using a PS framework based on the framework given in [2]. This separates problem solving into five major steps, which are as follows: describing the problem, identifying principles associated with the problem, applying principles, using proper mathematical procedures, and checking the solution. When modifying the tutorials from Fall 2023, the problems were restructured using the PS framework; for example, for a tutorial about separation of variables with Laplace's equation, we organized the Version A tutorial steps for solving such a problem as follows.

1. *Describe:* List information about the voltages and symmetries of the situation.
2. *Identify:* Deduce from the given information that we can use Laplace's equation and why.
3. *Apply:* Write Laplace's equation in the coordinate system of the problem.
4. *Mathematical procedures:* Perform separation of variables and apply boundary conditions to obtain a solution to Laplace's equation.
5. *Check:* Verify that the solution gives the boundary conditions when tested at the boundaries.

For each tutorial, Version A included all of the explicit framework steps, whereas all of the questions that pertained to the framework but were not required to solve the problem (such as directly asking why one should use Laplace's equation in a given scenario) were removed from Version B. Questions that were required steps for solving the problem, but which had previously also involved the framework, were modified to avoid alluding to the framework.

B. Participation of Students in Study and Data Collected

During Fall of 2024, the study involved 24 students at various levels of participation: six students consented to full participation, where they were interviewed, took an end-of-semester survey, and allowed us to use their coursework for the purposes of the study; another fifteen students consented to reduced participation, where they took the end-of-semester survey and allowed us to use their coursework; three more students allowed us to use their coursework without participating in the survey or interviews.

The coursework we collected included post-tutorial self-assessments, the tutorials themselves, and exam problems or parts of exam problems specifically relating to topics from the tutorials. We regraded the exam problems which specifically related to tutorial topics according to a rubric that assessed how accurately students invoked the correct concepts ("invoking", worth 50% of each problem), and how accurately they applied the concepts as they worked toward a solution ("applying", also worth 50% of each problem). This is similar to what has been done in a previous study by the authors [12, 13]. Finally, interviews and the end-of-semester survey largely collected data concerning students' opinions on the tutorials. We also administered a problem-solving exercise at the end of interviews using think-aloud protocol and took video footage of the papers on which students completed their work for these exercises.

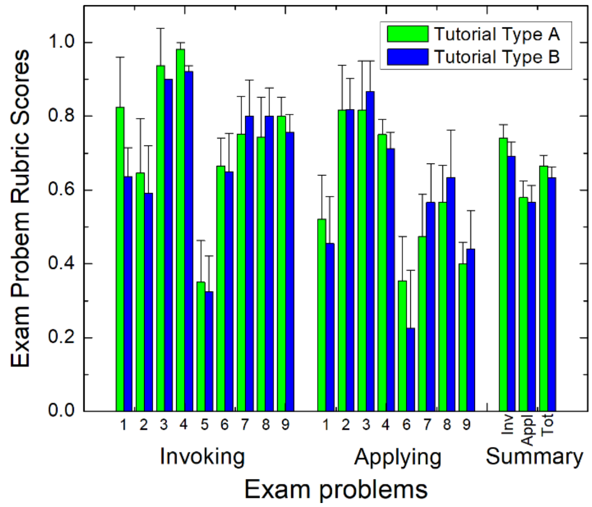

FIG. 1. Exam scores on problems related to tutorial topics. "Tutorial Type A" refers to the average score of students who used Version A of a tutorial related to that exam problem, and the same for "Tutorial Type B." Error bars are given by the standard errors.

III. RESULTS

A. Effect of Tutorials on Student Understanding

We scored nine tutorial-related problems over three different exams that students took during the semester. We found that Group 2 consistently outperformed Group 1, so to account for this covariate we renormalized the scores for the students in Group 2 by subtracting the difference between groups from Group 2's scores, thus arriving at the same means across groups. This was done separately for the invoking and the applying scores. The data was then analyzed according to tutorial version (Type A vs. Type B). Averages of the invoking and applying scores by tutorial, as well as standard errors, are shown in Figure 1.

No significant difference was measured between how the two groups performed when looking at individual problems. When looking at the average across all exam problems, we find a 4.9% difference between the two tutorial versions' invoking scores, only 1.3% difference in the applying scores, and a 3.2% difference between the overall scores. p-values for the differences in means are 0.36, 0.84, and 0.45, respectively, indicating that results are not statistically significant. Cohen's d also shows that the effect size would be small, as the invoking scores, the largest difference, yield 0.14. While the higher difference in invoking scores seems to hint that PS framework tutorials assist students with conceptual parts of problem solving, the quantitative data on its own does not strongly support this due to the small differences and small sample sizes.

Considering interview data may suggest that the tutorials help students with the conceptual parts of problem-solving. Student 3 said in an interview: *I think I've started [to]* *understand better some of the more qualitative questions like “what principles are you applying?” and “how would you apply this to different scenarios?” ... At the beginning of semester, I felt like I really just wanted to do the quantitative stuff, like I just wanted to get the right answer.* This student perceived a personal growth from being more performance oriented to becoming more mastery oriented [14]. Notably, the questions that he referenced were characteristic of the tutorial versions that used the PS framework.

Not all students displayed this same type of growth in their interviews. Student 5 described their problem-solving process at the end of the semester as follows: *I approach the problem and I'll think, “What am I looking at? Where are the things I need to pay attention to?” And then what? Look at my formula sheets, go “what formula can I apply here to get some answer?”* Though some aspects of the PS framework are still present, such as identifying important aspects of the problem and equations that will be relevant, their motivation is still focused on getting an answer to the problem.

B. Student Perception of the Tutorials and Formats

Students in general do not seem to take much thought as to the differences between the two versions of the tutorials. For instance, in the end-of-semester interviews, no student indicated noticing differences between Version A or Version B of the tutorials, and six students on the survey similarly remarked not noticing differences between the versions when asked if one was more helpful than the other. In response to this same survey question, four students remarked that they preferred tutorials structured around the PS framework; still, it is unclear whether they understood what the PS framework was and which version implemented it, since one of these students who indicated a preference for the PS framework indicated a preference for Version B on the next question. Thus, our results given here indicate what students would like from tutorials, but certain effects may be difficult to attribute directly to the framework, even if students have referenced it in their comments.

One survey question showed students Version A and Version B of a tutorial side by side and asked them which tutorial they would prefer, the results of which are contained in Table II. Here, students tend to develop a slightly stronger preference for a format of tutorial and are able to articulate reasons for their preferences. Among the ten students who took the survey, five indicated that they preferred Version A, one indicated a preference for Version B, and the remaining four indicated not having a preference, not being able to identify a difference, or mentioning that it would depend on the topic. Students who indicated a preference for Version A mentioned that it was *less ambiguous*, and *forces you to look into the details of a problem rather than just scraping the surface*.

Two students on the survey remarked that they liked that the tutorials broke problem-solving into steps, showing a preference for this approach to learning how to solve problems. These students also attributed the step-like approach to the PS framework.

TABLE II. Survey results on what tutorial preferences students selected on the end-of-semester survey.

Tutorial Version Preference	Count
Tutorial A	5
Tutorial B	1
No preference between formats	2
Cannot identify a meaningful difference	1
Preferred format would depend on topic	1

In comments from students on the survey about the tutorials in general (both versions), they also indicated that the tutorials were helping them with both qualitative and quantitative aspects of problem-solving. Some students remarked that the tutorials *helped [their] conceptual understanding and [their] application of the things [they] learned*, while another student remarked, *I think looking at things qualitatively is helpful, but I often have a very incomplete understanding of the actual quantitative methods .... Getting help with the quantitative methods in a classroom setting is helpful for me.* Students seem to benefit from the tutorials’ deeper look into the concepts involved, as well as the tutorials’ ability to aid them with the quantitative methods in problem-solving.

However, other comments from surveys and interviews indicate that students felt expectations were unclear on parts of the tutorials, which is especially highlighted in conceptual steps and questions that pertained to thinking about the framework. Two examples that Student 3 gave in their interview were the problems from Version A of a tutorial, *List some of the mathematical procedures you can think of needing to use to solve Laplace’s equation*, and *What about the situation would help you to know that Laplace's equation can help you solve the potential?* They then explain their difficulty with these questions: *I don't think it's because the question is intrinsically hard. But it's like, I'm trying to figure out what kind of response is expected.* Later in the interview, they continue on this difficulty: *Maybe that's just me as like, a STEM major not knowing how to qualitatively answer questions as well as I can just like spit out a number.* While they recognize that the expectations of the conceptual and PS framework questions are different from what is typically expected of them – getting exact answers – they are still confused about what is expected for these types of questions they see on tutorials. Despite initially being unsure of how to respond to these questions, this student later remarked that they better understood these questions (see section IIIA). Still, these types of questions seem to pose some difficulty for students that are not used to them.

C. Patterns in Student Problem-Solving

We observed patterns in student problem solving through interview footage as well as trends observed in the exam data. Twelve problem-solving exercises were administered in total:

TABLE III. How students used the framework in problem-solving exercises administered in interviews. Frequency is how often that practice occurred – for example, in four of the exercises, students checked their work. Correctness is how often that practice was done correctly – for example, among the ten times students carried out calculations, they arrived at the correct expression six times.

Problem-Solving Step	Frequency	Correctness
Describing	12/12	12/12
Identifying	12/12	10/12
Applying	11/12	8/11
Mathematical Procedures	10/12	6/10
Checking Work	4/12	2/4

two per student, per interview, with six interviews in total. Students' use of the PS framework is summarized in Table III and discussed here.

It appears that overall, students are competent in the initial set-up of a problem. All students in interviews started the problem by drawing a depiction of the physical situation, often labeling the drawing with variables or quantities described in the problem. Following this, in all except two of the exercises administered in the interviews, students were able to correctly identify a physical principle that would help them solve the problem. On the exams, we note that students in general scored higher on their ability to invoke concepts than their ability to apply them. While this makes sense, as one generally needs to identify the correct concepts in order to arrive at a correct solution, this also indicates that students unable to solve a problem correctly are often struggling with applying the concepts properly to the problem, rather than getting stuck at the initial phases of considering the physical principles related to the problem.

Students tend to struggle significantly more with checking their work. One student said of the tutorials that they *struggled with the lack of solutions for the tutorials, as this meant [they] had absolutely no way to check [their] work*. Another student remarked that *in class it was sort of a free for all, and if you were lucky you'd get the professor or the TA to answer your question*. In both instances, students seem to have little confidence in their answers unless validated by class resources. In addition, though the tutorials contained problems which were intended to provide a means for students to check their work, especially for Version A, these student comments suggest that such problems did not significantly increase students' confidence in their own work.

In addition, it was uncommon for students to check on their work when completing problems in their interviews. For only four of the twelve problems administered did students perform any check that their answer made sense after they had completed the problem. With some students, this seemed to reflect that they were already confident in their answers. For example, Student 6 demonstrated a high amount of confidence in their work, making comments such as *I could be more rigorous about that but that's the right answer* and *that one's pretty easy*, and did not perform any formal checks on either problem during their interview. On the other hand, Student 1 demonstrated a lower amount of confidence that they were solving their problems correctly but only performed checks during one of their problems. There seems to be little correlation between students' confidence in their work and when they choose to check it.

While upper-division physics students in this study were competent in problem set-up, they were less competent in applying physical principles to arrive at a correct solution, and particularly struggled with checking work on their results.

IV. CONCLUSIONS AND DISCUSSION

Considering the exam scores alongside student comments offers some evidence that PS framework tutorials could help students with conceptual parts of problem solving. However, we note that even when considered together, these are preliminary, but not fully conclusive results. Results could be better refined either through further statistical analyses, such as an analysis of covariance, or collecting further data using this method if no statistical method reveals any significant difference in exam performance.

One challenge of this study was that students did not seem to recognize differences in the tutorials in class, possibly since students may not know the framework well, and the changes to tutorial version can seem minor if not considering the theory behind the framework. Future studies could further clarify student perceptions of these tutorials by more explicitly informing students about the framework and how it is used.

Still, students seem to prefer tutorials structured explicitly around a PS framework and perceive advantages of these tutorials when comparing them side by side. One of these advantages is improving the step-by-step structure appreciated by students, as PS framework can provide a methodical way for instructors to break problems into steps. However, structuring a tutorial around the PS framework will introduce some types of problems that students are less used to, such as conceptual questions and ones that ask students to think metacognitively about their problem-solving processes. While we see that students can improve at these types of problems, initially they may be difficult for students who are used to obtaining specific numbers or expressions as answers to their physics problems.

Overall, it appears an explicit implementation of a PS framework at the upper-division level benefits students in classroom performance and assists them towards expert-like conceptual understanding in a way many students can perceive. That being said, instructors must be aware of limitations when deploying explicit PS tutorials at the upper-division level so that the level of scaffolding is appropriate.

Finally, while upper-division physics students have internalized some aspects of problem solving, such as steps taken to set up a problem, they seem to struggle with other aspects, like checking their work. This is a particular part of problem solving that likely merits future attention in interventions to assist with student problem solving.

[1] M. T. H. Chi, P. J. Feltovich and R. Glaser, "Categorization and Representation of Physics Problems by Experts and Novices," *Cognitive Science A Multisciplinary Journal,* vol. 5, no. 2, pp. 121-152, 1981.

[2] K. Heller, The Competent Problem Solver for Introductory Physics, Greyden Press, 2000.

[3] G. Polya, How to Solve It, Princeton University Press, 1945.

[4] A. Mason and C. Singh, "Surveying graduate students' attitudes and approaches to problem solving," *Physical Review Special Topics - Physics Education Research,* vol. 6, no. 2, p. 020124, 2010.

[5] A. Collins, J. S. Brown and S. E. Newman, "Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics," in *Knowing, learning, and instruction: Essays in honor of Robert Glaser*, Routledge, 1989, pp. 453-494.

[6] V. P. Dennen and K. J. Burner, "The cognitive apprenticeship model in educational practice," in *Handbook of research on educationsal communications and technology*, 1989, pp. 425-439.

[7] J. P. Zwolak and C. A. Manogue, "Assessing student reasoning in upper-division electricity and magnetism at Oregon State University," *Physical Review Special Topics - Physics Education Research,* vol. 11, p. 020125, 2015.

[8] B. Xue, *Identifying and Addressing Student Difficulties with the Source-Field Relationship using Tutorials in Upper-Division Electromagnetism,* University of Washington, 2021.

[9] A. Maries, S. Y. Lin and C. Singh, "Challenges in designing appropriate scaffolding to improve students' representational consistency: The case of a Guass's law problem," *Phyiscal Review Physics Education Research,* vol. 13, no. 2, p. 020103, 2017.

[10] A. Mason, J. Hecht, D. Baldwin-Bott, D. Neilsen and J. S. Cotlon, "A Preliminary Study of Upper-Division Tutorials Explicitly Built on a Problem-Solving Framework," in *PER Conference series*, Boston, MA, 2024.

[11] J. Hecht, D. Baldwin-Bott, D. Neilsen, J. S. Colton and A. Mason, "Designing and Testing Upper-division Electromagnetism Tutorials," in *AAPT Summer Meeting*, Boston, MA, 2024.

[12] A. Mason, J. M. McCardell, P. A. White and J. S. Colton, "Improving Performance in Upper-Division Electricity and Magnetism with Explicity Incentives to Correct Mistakes," *Physical Review Physics Education Research,* vol. 19, p. 020104, 2023..

[13] B. R. Brown, A. Mason and C. Singh, "Improving performance in quantum mechanics with explicit incentives to correct mistakes," *Physical Review Physics Education Research,* vol. 12, p. 010121, 2016.

[14] A. Mason, "Learning goals and perceived irrelevance to major within life science majors in introductory physics," in *PER Conference Series*, Provo, UT, 2019.