A Preliminary Study of Upper-Division Tutorials Explicitly Built on a Problem-Solving Framework

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Abstract: Students' perceptions of problem-solving (PS) tutorials in upper-division first-semester electromagnetism (EM1) were studied over a two-semester, mixed-methods approach to inform the authors about tutorial design from students' perspectives. This study is part of a larger-scale EM1 tutorial design study which seeks to address two issues: first, the tendency of PS tutorials to either focus on a single element of a PS framework, or on specific conceptual topics; and second, the need for increased instructional flexibility in design. Results indicate that a PS framework developed for introductory-level problems can be useful for upper-division EM1, with adjustments to avoid frustrations with perceived linearity and redundancy. Feedback on perceived difficulty of individual topics – both stand-alone and within a tutorial set – suggests students find certain topics to be more difficult than others, requiring more attention. Finally, we observe a strong correlation between performance on the tutorials and performance within the rest of the course.

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I. INTRODUCTION

Giving students incentives in a first-semester upper-division quantum mechanics (QM) class to rework their mistakes on unit exams was shown to significantly improve their problem-solving (PS) on the final exam [1]. Similar results were found for first-semester upper-division electromagnetism (EM1) [2,3]. This current study on tutorials in EM1 continues that research as part of a longer-term project for developing interventions to assist with scaffolding within a cognitive apprenticeship theoretical framework for problem solving [4,5].

Regarding PS frameworks, it has been demonstrated that graduate students tend to approach upper-level problems less expertly than introductory problems [6], and student cognitive processes and PS frameworks [7,8] may vary in structure between intro and upper-level physics courses [9,10]. PS frameworks meaningfully impact learning, and problem tutorials can be used to assist intro level physics students in solving problems more conscientiously [11,12].

Explicit intervention in upper-division EM has tended to be in the form of tutorials primarily focused upon conceptual understanding [13,14,15] rather than on PS. This reflects the more general trend of literature on upper-division physics tutorials to either be tailored to specific topics – e.g. Gauss' law within EM [16] – or a focus on a singular aspect of PS such as conceptual understanding [17] or mathematical methods [18].

As noted in Ref. 3, this raises a question as to whether a PS framework as often used at the introductory level [10], can be similarly applied to the upper-division level. For example, Ref. 10 applies the following PS framework to introductory physics problem solving: 1) Useful Description (identifying target variable(s), knowns/unknowns, drawing pictures, etc.); 2) Physics Approach (what physics principles are appropriate); 3) Specific Application of Physics (correctly applying the chosen physics principles to the problem information); 4) Mathematical Procedures; and 5) Logical Progression (solution is clear, focused, and logically connected from starting point to the goal point). Many PS frameworks have similar points covered in differing ways.

Students at the upper-division level may welcome the level of scaffolding afforded by a framework designed for introductory physics, or alternately may find certain aspects of the introductory framework unnecessary and/or unhelpful. Attitudinal survey data suggests that students at the graduate level are more expert-like than introductory students, yet not as expert-like as faculty members [6]; accordingly, it needs to be established whether upper-division physics majors in this course may or may not need as much scaffolding as introductory students.

One aspect of student experience that differs between upper-division EM and QM is arguably that students typically have an introductory physics course to prepare them conceptually for upper-division EM. While many undergraduate curricula include all or part of a modern physics course to prepare students for QM, upper division QM typically introduces new concepts (e.g. physical states as a linear combination of eigenstates) which are a cause for student struggle in and of themselves [13,14,16]. However, in advanced EM, difficulty with topics such as Gauss' law [16] may arise either from incomplete understanding of the concepts in the lower division course, or from issues involving higher mathematical rigor even if the concepts are well understood at an introductory level.

To address the questions of if or how PS tutorials can be implemented in upper-division courses and what the student experience will be like, in this paper the authors introduce the development of a set of tutorials for upper-division EM1. Our longer-term goals for the tutorials are two-fold. First, a PS framework will be incorporated in full that will apply to a broader range of problems within the course. Second, we aim to maintain flexibility within the tutorial designs, for increased versatility and usefulness across different institution types and instructional methods. The development is in two parts. In Part 1, we discuss the implementation of a preliminary PS tutorial, in which focus group interview data and survey data were collected. This in turn informed Part 2, in which a set of 10 tutorials were developed and implemented over the length of the EM1 course.

The authors' research questions are as follows. First, we investigate the perceived benefits and drawbacks of tutorials for learning PS at the upper-division level, as expressed by the students undertaking them. Second, we examine what topics in EM1 the students find most challenging, and hence could benefit from tutorials the most – whether in toto, or for different portions of a PS framework. Third, we are interested in how much the tutorials' framework-based structure affected student performance and perceived difficulty with the problem.

II. PROCEDURE

Two sections of first-semester upper-division EM at a large, private research university in the Mountain West were selected for the study, for which tutorials were designed by their respective instructors. We present the overall methodology in terms of "Part 1," the preliminary trial of two sample tutorials accompanied with feedback data, and "Part 2," a development of a suite of tutorials for EM1 informed by the results of Part 1. For both semesters, a feedback survey on the perceived difficulty of each topic in the course, and on their overall experiences with the tutorials, were also collected and analyzed.

These two parts took place respectively within EM1 sections for Fall 2022 (Part 1), taught by one author, and Fall 2023 (Part 2), taught by another author. Both sections of the course were in a traditional lecture format with 3 hours/week on MWF for a 15-week semester schedule, and both used the traditional textbook by Griffiths [19].

Part 1 was a preliminary tutorial evaluation during Fall 2022. Two tutorials were piloted during the semester, one on the electric quadrupole field, and the other on displacement current causing a magnetic field inside a charging capacitor. The entire 50-minute class period was used for these tutorials.

After the quadrupole tutorial (week 8 of 15), a subset of 11 students (out of a class of 49) participated in focus group interviews with 1-3 students each, in which one of the authors asked questions about how they felt they were performing in this course, whether they felt their course backgrounds helped them prepare for this course, whether the tutorial was helpful in terms of the specific topic, and whether this was a generally helpful format for the overall course. Answers to these focus group questions were used to inform the researchers' decisions for the second semester. After the displacement current tutorial (given Week 14), a written survey was sent to consenting students which included questions specific to the second tutorial along with summary questions about the whole semester, and 11 students replied anonymously.

Part 2 was a more complete development of tutorials during Fall 2023. Here, the instructor designed the tutorials to typically focus on the more explicit PS framework described above [10]. Time spent on tutorials ranged from 20 to 50 minutes, depending on the tutorial, with an average of 30 minutes. Students were expected to submit the completed tutorial for grading by end-of-day of the following class period; this was to permit students enough time after class to finish the tutorial if needed. 14 students volunteered for the study out of a class size of 33 students, with 10 of the 14 consenting to focus groups and a post-semester survey; with the other four consenting the survey only. Feedback from the Fall 2022 section was incorporated to include considerations for topics that were mentioned as relatively conceptually or mathematically difficult, and to anticipate whether students might be expected to have prior preparation from other physics or math courses for a given tutorial. Table 1 contains a list of all tutorial topics across the two semesters.

The intention of this choice of format was to assess the experience of upper-division students in EM1 with regards to PS tutorials, e.g. given their increased expertise in comparison to introductory students about which more is known. The Fall 2023 instructor accordingly designed the tutorials to focus on the following steps: a) either drawing and sketching, or interpreting a drawing or sketch, of the problem situation (which maps to "Useful Description" in the framework); b) asking conceptual questions to clarify the physics principles ("Physics Approach"); c) setting up a solution attempt ("Specific Application of Physics"); d) obtaining the solution ("Mathematical Procedures" and "Logical Progression"); and e) follow-up conceptual or limiting-case questions to check whether the solution makes sense ("Logical Progression"). They also included three self-reflection questions that were consistent across all tutorials, asking students whether they thought were correct and what items they were/were not confident about.

Following the in-class sessions, interviews/focus groups with the 10 consenting students were conducted in groups of 1-2 students as with the Part 1 participants, and an end-of-semester survey sent out to all 14 participants.

TABLE I. Tutorials developed for Fall 2022 and Fall 2023.

Term	Tutorial #	Tutorial Topic
F22	A	Quadrupole moments and potentials
	B	Displacement current
F23	1	Point charges and electric field
	2	Gauss's law
	3	Gauss's law part 2; electric potential
	4	Solving Laplace's equation
	5	The quadrupole electric field
	6	Dielectrics (D field; boundary conds.)
	7	Dielectrics 2 (sep. of variables)
	8	Magnetic dip. moment; Ampere's law
	9	Magnetic matter (H field; bndy conds)
	10	Displacement current (alt. version)

III. RESULTS

A. Perceived Benefits and Drawbacks of Tutorials

Overall, in both semesters, there was a strong indication that focus group participants understood the "step by step" structure. The guidance through the PS process at the upper-division stage was often seen as a benefit by several respondents in this way: "*There were more steps in the problems and the increase in the number of steps made it easier to find the correct path forward*" (Student 8). However, other students perceived the PS framework as being presented in too linear a fashion, with predetermined steps as opposed to freedom for students to find their own way, such that they believed it to be a drawback when trying to learn how to solve problems at the upper-division level: "*I don't feel like I have a lot of room to set it up my own way*" (Student 9). This student later remarked that "*sometimes it feels like you have to go in order with the steps... which I think is helpful for some people if you don't know where to go. [But] sometimes it gets overwhelming, I think.*"

There was close to an even split in the students with their preferences between linearity and nonlinearity. For example, a Part 1 focus group student stated that, "*Once we broke [the problem] down into smaller parts it was easier*" and the Part 1 post-semester survey indicated that six students preferred more structure with its increased guidance, as exemplified by this comment: "*It also helped to identify what I knew and what I was looking for, rather than just fumbling through some equations until I stumble upon the right answer*" (anonymous student from survey). However, in the Part 1 final survey, four students preferred less structure, and comments from focus groups included: "*I skipped straight to [using math procedures]*" and "*[the later parts of the tutorial] forced me to go back.*" Similarly, among the focus group participants from Part 2, there was a split among participants' opinions on this matter, with Student 9 expressing comments against the linearity, Student 8 preferring it, and Student 5 not having indicated a strong preference.

B. Which Topics Require More Attention?

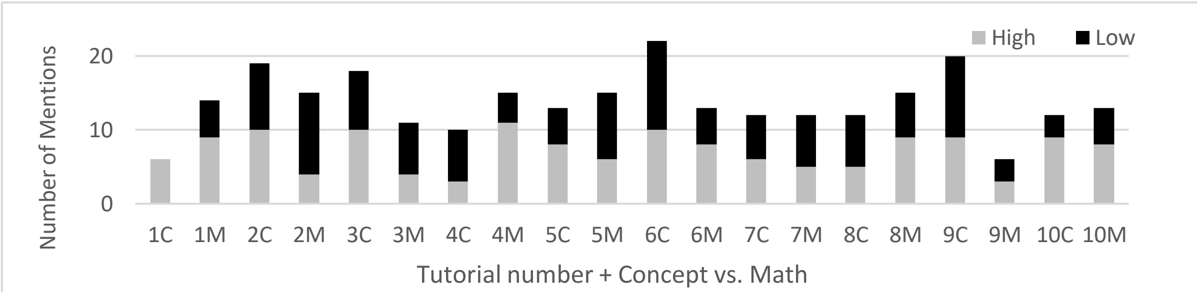

FIG. 1. Number of mentions in F23 post-tutorial assessments that expressed either high confidence (gray) or low confidence (black) about each respective tutorial, labeled 1-10. A large (black – gray) difference indicates an overall lack of confidence. A "C" indicates comments about concepts and an "M" indicates comments about mathematics. For example, students overall were uncomfortable with the mathematics in Tutorial 2 (Gauss's law), as evidenced by many comments describing low confidence and few describing high confidence; whereas with Tutorial 4 (Laplace's equation) students are more comfortable and the situation is reversed.

Each of the tutorials across both parts of the study was polled for students' responses about confidence, both per tutorial and per individual EM1 topic. (Some tutorials addressed more than one topic; compare Tables I and II.)

For Part 1, the main topics with low confidence dealt with "script r" vectors, or $\boldsymbol{\mathscr{r}}$ vectors (defined as $\boldsymbol{\mathscr{r}} = \mathbf{r} - \mathbf{r}'$, where $\mathbf{r}'$ is the position vector of a charge with respect to the origin and $\mathbf{r}$ is the position vector of a point of interest in space with respect to the origin). Problems involving these topics involve integrating charge or current densities to find various fields at other points in space. Students explicitly mentioned this as a hard topic in survey responses: "*For some reason the script r method was always really hard for me, I think I struggle with abstract space visualizations,*" and "*Really hard to wrap my mind around some of the topics, especially script r.*" In addition, the topics of "Finding **A** from current densities" and "Biot-Savart Law for current densities," both of which scored low on the survey, involve script r.

Figure 1 shows mentions within student responses about each tutorial in Part 2 of expressing respectively high confidence (gray), and low confidence (black), towards each given tutorial. The responses are sorted respectively regarding the concepts and the mathematics for each tutorial, e.g. "1C" regards students' confidence about concepts in Tutorial 1 and "2M" regards confidence about mathematics in Tutorial 2.

For Part 2, tutorials 6 (Dielectrics part 1) and 9 (Magnetic Matter) had the most mentions of conceptual difficulty in Fig. 1, whereas tutorials 2 (Gauss' Law) and 5 (Electric Quadrupole Field) had the most mentions of mathematical difficulty. These tutorials largely had to do with abstract fields, i.e. the electric displacement field **D**, magnetic vector potential field **A** and auxiliary magnetic field **H**, as well as their relationships to the electric polarization field **P**, and the magnetization field **M**. One (anonymous) student said on the survey: "*I didn't really understand the relationship between the **D** field and the **E** field, or the **A** field and the **B** field. **H** and **M** are still a mystery to me.*"

Student survey results also indicated which of the individual topics were considered easier or more difficult. Table II presents an average rating of the degree to which students across both parts of the study perceived difficulty for each given topic, sorted from most to least perceived difficulty. Topics were rated on a 5-point Likert scale where 1 indicates that a student struggled a lot on a given topic, and 5 means that a student experienced little to no difficulty on a given topic. 17 students responded across both parts: 11 from Part 1 (Fall 2022) and 6 from Part 2 (Fall 2023). Also indicated in the "#" column is the approximate order in which the topics are covered during the semester.

Expanding to include both Part 1 tutorials (A and B) and Part 2 tutorials, students generally expressed lower conceptual confidence on electric and magnetic moments, e.g. dipoles and quadrupoles. This was consistent with the Likert scale survey responses for those topics as shown in Table II, in which students tended to express those concepts were more difficult than the median topic.

C. Effect of Framework-Based Structure on Student Performance and Perceived Difficulty

Figure 2 shows a plot of the Part 2 students' overall course grades for all other materials in the course besides their tutorial grades, versus their average tutorial grades. Tutorial grades are out of 10 points per tutorial, whereas overall course grade is in terms of a percentage out of 100%. Only nine of the 14 students submitted all 10 tutorials whereas the other five students failed to submit between 1-3 tutorials for grades, and consequently received a score of zero for their unsubmitted tutorials. To avoid scores of zeroes inordinately influencing the overall tutorial average, only the nine students who completed all tutorials are presented in the graph.

Overall, the data confirms that average tutorial score correlates strongly with average overall course grade outside the tutorials. The correlation found here is $R = 0.597$, which is strong despite the small sample size. If the additional five students are included in the regression, then the correlation becomes even stronger ($R = 0.699$).

The survey topics "Ampere's law for **H**," "Finding **E** given **P**," and "Finding **B** given **M**," were rated more difficult than the median. The **H** field was also explicitly mentioned by

TABLE II. Major topics from most to least perceived difficulty; lower ratings indicate more difficult (17 students responding).

#	Topic	Rating
16	Finding capacitance	2.71
13	Electric quadrupole moments and potentials	2.76
20	Finding **A** from current densities	2.76
22	Magnetic dipoles	2.76
12	Electric dipoles	2.94
28	Boundary conds. for all fields	2.94
29	Force, torque, and pot. energy	2.94
15	Finding **E** given **P**	3.00
21	Energy stored in **B** field	3.00
2	Grad, div, and curl theorems	3.06
23	Ampere's law for **H**	3.06
14	Gauss's law for **D**	3.13
9	Numerical solns. to Laplace's eq.	3.18
24	Finding **B** given **M**	3.18
7	Finding V from charge densities	3.24
8	Energy stored in **E**	3.35
17	Biot-Sav. law for current densities	3.35
19	Finding **B** from **A**	3.35
11	Image problems	3.41
18	Ampere's law for **B**	3.41
26	Finding **E** from a changing **B**	3.47
27	Finding **B** from a changing **E** (displace. current)	3.47
6	Finding **E** from V and V from **E**	3.53
25	EMF and Faraday's law	3.53
10	Separation of variables	3.65
4	Coulomb's law for charge densities (electric field)	3.71
5	Gauss's law for **E**	3.71
1	3d integrals and derivatives	3.94
3	Electric field lines	4.35

Students 9 and 10 in focus groups/interviews.

From the focus group interviews, several individual students maintained the stance that the linearity of the PS framework in the tutorials is different from their typical PS approaches. Student 9, for example, indicated that linearity can make it confusing to know how to begin (see Section IIIA), which appears related to the student's prior quote about the tutorials seeming "*overwhelming*". When the interviewer followed up for clarification, asking "*So it may not exactly always help with identifying principles or effectively describe the problem, like we talked about in step one?*" the student replied, "*I think so.*"

However, respondents still said that the framework applied well across many topics within the course: "*I think the framework applies just as well in every topic that I've done; I think the framework is fine, I definitely use it*" (Student 9). Student 5 mentioned that while the framework works well for the nature of physics problem solving, a different style of tutorial might be needed if the tasks were asking students to argue a point: "*If the sort of tasks we were doing were different, like if we were writing argumentative essays on this sort of thing, I think the format would have to change dramatically.*" Student 8 also commented about conceptual questions: "*And [this format] hasn't helped as much with those because it's less of a problem that you're supposed to solve, [but rather] a problem you're supposed to figure out what the problem is.*" Students therefore may perceive the tutorial format as working less well for other types of problems.

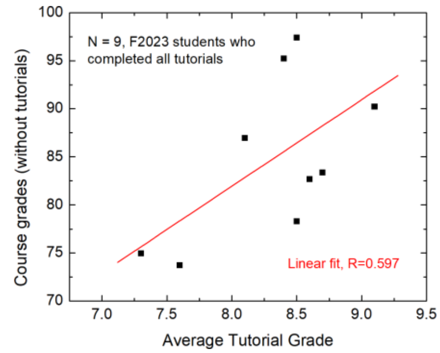

FIG. 2. Plot of course grade vs. average tutorial grade across Part 2 student sample. Note that only the nine students who submitted all tutorials for grading are included; please see text for further details.

IV. CONCLUSIONS AND DISCUSSION

Students appeared to perceive the main benefit of tutorials as helping organizing their thought processes when they were not sure how to proceed with solving a problem. On the other hand, a prominent drawback that some students perceived was the linear structure of tutorials not allowing for more independent approaches to PS. While some of this reaction exhibited a novice-like tendency (e.g. wanting to jump into the mathematics while disregarding the rest of the solution process), other comments (e.g. being made to "go back" by later parts) imply a possible future direction in which to consider adding more flexibility to tutorial design. Additional encouragement or suggestions to check their work and reflect on possible mistakes, might also be a way to make tutorials more nonlinear within the same PS framework.

Of the individual topics in EM1, Table II and Fig. 1 provide some detail in which topics students find relatively difficult; these include finding capacitance, electric quadrupoles, electric and magnetic dipoles, finding **A** from current densities, dielectrics and magnetic matter, and Gauss's Law. Tutorial sets written by us and others should be sure to pay attention to these topics.

According to Fig. 2, there is a strong correlation between students' tutorial grades and students' overall unrelated course grades. Whether this effect has to do with effort or inherent study ability remains to be seen; an element of effort is suggested when students who failed to turn in at least one tutorial for credit are included in the regression model. We note the limitations of a relatively small sample size in the work so far, in particular how that pertains to analysis for quantitative results; more data from future sections will refine quantitative results accordingly.

Students' overall reaction to the introductory-level framework appears to suggest the framework's usefulness as a base model to tailor towards an upper-division framework. Student feedback about perceived difficult topics may assist instructors with flexibility of tutorial design as well.

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