Advanced Undergraduate Electrodynamics (E&M II)
Guide to Course Materials

The guiding principle behind the creation of these materials was that students would gain more from being active (instead of passive) participants in the classroom. This document contains details on the organization of the course materials contained in this package, and a short summary of our transformation of an upper-division electrodynamics course (E&M II) at the University of Colorado Boulder. Instructors and education researchers are free to use, adapt and distribute them for non-commercial purposes, according to the Creative Commons license below. Please contact us if you plan to use all or part of these course materials for your own electrodynamics course. We would appreciate any comments or suggestions for their improvement, and would like to hear about your experiences with adapting and implementing them. **We ask for your cooperation in not making any solutions you may create for the homework (and exam problems, clicker questions, etc.) available on the open web, out of respect for instructors and students at other institutions, and for maintaining the integrity of our research.** If you would like to be notified when these materials are updated, please contact us and we will be sure to keep you informed!

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Contents:

I. Creative Commons License

We encourage everyone to use these course materials for non-commercial purposes. In order to facilitate their adoption and adaptation, the source files (in Word and PowerPoint format) have been included along with the PDF files in this package (generally located in a "Source Files" subfolder in each category). If you choose to distribute any work derived from these materials, it must be done with attribution, and under the same (or similar) license. For more detailed information visit:

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II. Organization of Course Materials

We briefly describe here the contents and organization of this course materials package. There are 9 separate folders, labeled A-I:

- **A** – Guide to Materials
- **B** – General Documents
- **C** – Clicker Questions
- **D** – Tutorials & In-Class Activities
- **E** – Homework Problems
- **F** – Preflight Questions
- **G** – Past Courses at CU (archive)
- **H** – Assessments (password-protected)
- **I** – Solutions (password-protected)

Folder A – Guide to Materials:

There are 4 category-specific documents describing individual aspects of the materials (clicker questions, homework problems, preflights, and tutorials), which can additionally be found in each of the relevant subfolders.

Where are the exam questions? - PDF versions of full exams can be found in the individual course folders in Folder G – "Past Courses at CU (archive)". In contrast to the homework problems (Folder E, where they are organized by topic), entire exams are provided as part of the course materials from each semester. Each exam was crafted keeping in mind the emphasis, level of difficulty, and other factors specific to individual courses, and should be seen in that context. Also, we have no reliable estimates for how long students may spend answering individual exam questions, but know that most students can complete each of the exams in 1-1/2 hours (2-1/2 hours for finals). Handwritten solutions to these exams are available by contacting us directly.

Folder B – General Documents:

Course Calendars – HTML versions from the FA11 and SP12 transformed E&M II course at CU. These show when specific topics were covered over a 15-week semester, and when the various preflights and homework were assigned. [Contains active links to PDF versions of the actual assignments.]

Electrodynamics Topic Coverage Across institutions – This table provides a brief overview and comparison of the coverage of electrodynamics topics at CU and four other institutions.

Exam Formula Sheet – We provided this 2-page list of vector calculus identities and electrodynamics equations (similar to the front and back inside covers of Griffiths) to our students for use during exams.

Learning Goals – Lists of topic-specific and broader learning goals for advanced electrodynamics students; a similar list for the first semester of this upper-division course sequence (E&M I, electrostatics) is also provided for comparison. A description of the method used for their development can be found in the supporting article: "Developing Consensus Learning Goals".

List of AJP E&M articles – 40 *American Journal of Physics* articles on electricity and magnetism that were useful for understanding student difficulties, and for clarifying topics in advanced electromagnetism that are often ignored, unclear, or glossed over in undergraduate textbooks. Some are written from a pedagogical perspective, others are investigations of interesting problems in electrodynamics. Many of these articles (particularly numbers 1-26) are at a level of difficulty where upper-division physics students should be able to comprehend the majority of the content (at least with a little effort).

Recommended Electrodynamics Textbooks – These electrodynamics texts were recommended by instructors at CU Boulder, and by various physics faculty from other institutions.

Supporting PER Articles – A number of supporting physics education research articles from CU Boulder, relevant to advanced undergraduate electromagnetism and upper-division course transformation (complete list of references included).

Syllabus – Used in the FA11 and SP12 transformed E&M II course at CU. Contains information about the philosophy of the course, grading practices, expectations for students, etc.

Folder C – Clicker Questions:

Questions are organized by topic, according to the order of presentation in Griffiths. PowerPoint slides contain each of the clicker questions, with instructor comments in the "notes" section for each slide. Due to occasional Mac/PC compatibility issues, PDF versions are also provided to show how each question is meant to appear, in case any equations or figures become distorted in PowerPoint.

Notes on Clicker Questions – Contains information about the organization and annotation of the questions, and ideas for their effective use in upper-division physics classrooms.

Folder D – Tutorials & In-Class Activities:

Tutorial Instructor's Guide – Notes and tips on their implementation, and a summary of each of the 20 electrodynamics tutorials we developed as part of this project (also described below). This list provides a brief description of each guided activity, the amount of time students required to complete it, and notes on observed student difficulties. Source materials (in Word format) are also available, to facilitate their use and adaptation by others.

In-Class Activities (Pollock FA11) – Handouts and PowerPoint slides for the various short in-class activities used in the FA11 E&M II course at CU (also described below). Activities are generally accompanied by instructor notes and reflections on their implementation.

Folder E – Homework Problems:

A collection of electrodynamics homework problems, organized by topic, in PDF format (with source files in Word format). For the transformed E&M II courses, homework assignment dates are available in the Course Calendars for FA11 and SP12. If you would like to see all of the original, complete homework sets, these can be found in the Past Courses at CU archive folder. Handwritten solutions to the original homework sets are available in Folder I – "Solutions" (password protected, contact us for access).

Notes on Homework Problems – Explains the "Pre-Instruction Diagnostics" and the problem-solving sessions used in both semesters of the transformed course at CU; also contains a list of the available homework problems by topic.

Folder F – Preflight Questions:

Preflights are short online questions or tasks, used to orient students to upcoming material (to encourage reading the textbook before coming to class, and to reflect on key points in the material). Student responses were used to inform our preparations for lectures, so we could focus on specific difficulties students were having with new material.

Folder G – Past Courses at CU:

An archive of lecture notes, exams, homework problems and other materials (as available) from five recent E&M II courses at CU. The FA11 and SP12 transformed courses are included; special thanks to Professors Ed Kinney, Tobin Munsat and Chuck Rogers.

Folder H – Assessments (password-protected):

Notes on Assessments – Information on the development and implementation of the *CURrRENT* (Colorado UppeR-division ElectrodyNamics Test) – an assessment of fundamentals from advanced electrodynamics. Also contains descriptions of individual questions, and a summary analysis of student responses (from the SP12 E&M II course at CU, and one other institution). This folder is only available by contacting us directly for a password. If you should decide to administer this assessment at your own institution, we would be willing to grade and summarize student responses using the rubric we've established, with a reasonably short turn-around time.

Folder I – Solutions (password protected):

Contains solutions to the homework assignments and exams that are found in the archive of past courses at CU. [Folder G] This folder is only available by contacting us directly for a password. We provide these solutions as a resource, but we strongly encourage instructors to first work out any problem they would assign on their own.

III. Transforming Upper-Division Electrodynamics

Abstract: Favorable outcomes from ongoing research at the University of Colorado Boulder on student learning in junior-level electrostatics (E&M I) have led us to extend this work to upper-division electrodynamics (E&M II). We describe here our development of a set of research-based instructional materials designed to actively engage students during lecture (including clicker questions and other in-class activities); and an instrument for assessing whether our faculty-consensus learning goals are being met. We also discuss preliminary results from several recent implementations of our transformed curriculum, plans for the dissemination and further refinement of these materials, and offer some insights into student difficulties in advanced undergraduate electromagnetism

INTRODUCTION

There is substantial evidence from physics education research (PER) that introductory physics students learn and retain more when they are active participants in the classroom. [1, 2] Ongoing research at the University of Colorado (CU) and elsewhere has shown that *upper-division* students can likewise benefit from the use of in-class "clicker" questions and other student-centered activities. [1, 3-7] This work has demonstrated that active engagement can lead to increased learning in advanced physics courses (compared to standard lectures), and that junior-level *electrostatics* (E&M I) students are often still struggling with basic concepts. [8, 9] These important results have naturally motivated us to expand the context of this research at CU to advanced undergraduate *electrodynamics* (E&M II).

We have compiled a suite of clicker questions, in-class activities, homework and exam problems, covering E&M topics from the second part of Griffiths; namely: the time-dependent Maxwell equations, conservation laws, EM waves in vacuum and media, potentials and gauge transformations, radiation, and special relativity (with additional material on *AC* circuits). This package of course materials also contains implementation guides, an archive of several past E&M II courses at CU, and other supporting documents (e.g., explicit learning goals). We encourage others to evaluate these materials, and to adapt them for their own use, so we include source files (in PowerPoint and Word format) in order to facilitate their implementation elsewhere.

COURSE TRANSFORMATION NARRATIVE

The *Science Education Initiative* model for course transformation [10] is an iterative process, where three key steps are used to inform all aspects of the transformation: establish explicit learning goals in collaboration with experienced faculty; apply education research to develop materials and teaching strategies to help students achieve these goals; use validated assessments to determine what students are (and aren't) learning.

We followed this model by first holding a two-day meeting in summer 2011 of 15 physics faculty members from a total of eight institutions (including CU), all having experience in PER and curriculum development, in order to brainstorm on student difficulties in advanced E&M, and to define our research goals. We found that the coverage of electrostatics was fairly standard across institutions, but topics from electrodynamics were often treated differently. [See: Folder B – "Electrodynamics Topic Coverage Across Institutions".] At CU Boulder, electrodynamics is taught in the second half of a two-semester sequence, with classes of 30-40 students meeting for three 50-minute periods each week. Our usual text is Griffiths [11] (chapters 7-12), though instructors often add topics (e.g., *AC* circuits) or omit them according to preference. Physics majors at other institutions may instead cover most of advanced undergraduate E&M in a single semester, use a different textbook, and/or learn about wave optics and relativity in separate courses. To reach the greatest number of institutions, we decided to follow the presentation of topics in Griffiths, and to focus the assessment on core material likely to be covered in most electrodynamics courses.

This meeting was supplemented by individual interviews with six instructors who had recently taught E&M II at CU. We sought to understand how experienced physicist-teachers had approached this course in the past, what they felt were its essential elements, and their ideas on the particular challenges students face when the Maxwell equations become time-dependent. They also shared their homework problems, exams, lecture notes, and some clicker questions. [See: Folder G – "Past Courses at CU".] Student interviews were held with five volunteers from the Spring 2011 (SP11) semester of E&M II, which confirmed many of the student difficulties these instructors had reported (e.g., trouble parsing the numerous vector quantities that appear in representations of electromagnetic plane waves). Our collaborations with non-PER faculty members at CU continued into Fall 2011 (FA11) with 3 one-hour meetings to establish explicit learning goals, and to vet assessment questions (see below).

We also arranged for ourselves to teach E&M II at CU in the FA11 [SJP] and SP12 [MD] terms. The instructors for both of these courses typically used 3-5 clicker questions per class, interspersed throughout, comprising an estimated 20% of a 50-minute class period. [See: Folder C – "Clicker Questions".] Homework and exam questions rewarded reasoning and sense-making, along with traditional problem-solving skills. There were twice-weekly sessions outside of class where students could work together on homework (with occasional guidance from an instructor). Weekly online "preflight" questions oriented students to upcoming topics, and their responses informed our class preparations. [Ref. 12; see also: Folder E – "Notes on Homework Problems".] Homework and exams from every student were photocopied and archived for research purposes.

The FA11 course also occasionally used short, small-group activities to further engage students during class (e.g., working out an equation that might have otherwise been derived for them by an instructor at the board). These student-centered tasks (as well as other in-class discussions) were additionally facilitated by two undergraduate Learning Assistants, [13] who also met with us regularly outside of class to reflect on the course and discuss student difficulties.

To test the in-class tutorials under development, we recruited three FA11 students to participate in weekly group interviews throughout the semester. This interview format was chosen so we could observe the same students as they progressed through the course, simultaneously interacting with both the materials and each other. The interviewer mostly listened as students engaged with the tasks, but occasionally asked clarifying questions, and provided guidance when needed (as would be typical of an actual tutorial setting). The activities were variously inspired by in-class observations, anticipated student difficulties, and *AJP* articles. [See: Folder B – "List of AJP E&M Articles".] The topics were chosen to follow the lecture presentation, so as to capture students as they were first exposed to new material. We were thus able to gauge how students would interpret the wording and diagrams in the tutorials, the time required to complete them, and their overall usefulness for student learning.

These tutorials were modified for clarity and timing, and then used in the SP12 E&M II course at CU. [See: Folder D – "Tutorials & In-Class Activities".] About 40% of the lectures were partly or fully replaced with student-centered activities, each lasting from 10 to 50 minutes, and we typically had time to orient students to the upcoming tasks with a short lecture or series of concept tests. Audio recordings of single-group interactions were used to supplement our personal observations, which informed our subsequent revisions. The use of tutorials during the regular class period was fairly new to many of our students, and some initially needed additional encouragement to work with others (we found it helpful to remind them that scientific argumentation is a skill that is learned with practice). Overall, most aspects of the two transformed courses were extremely popular, with a large majority of students from both semesters rating them (in an end-of-term online survey) as either *useful* or *very useful* for their learning. [Fig. 1]

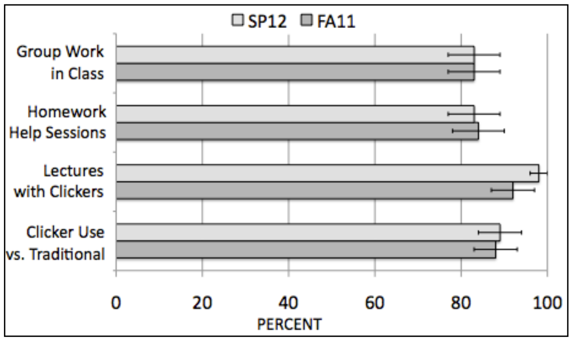

FIGURE 1. Percentage of SP12 (N=35) & FA11 (N=27) E&M II students at CU who rated aspects of the transformed courses as either *useful* or *very useful* for their learning. Error bars represent the standard error on the proportion.

LEARNING GOALS

This transformation process relied heavily on having explicit goals for student development. The method we used for creating a list of broad and topic-specific learning goals is described in detail elsewhere. [See: Folder B – "Developing Faculty Consensus Learning Goals".] Our biggest issue was whether the broader student goals for E&M II (regarding their general development as physicists) would differ at all from those already articulated for E&M 1. [See: Folder B – "Learning Goals".] One addition to this list concerns the increasingly mathematical nature of learning in advanced physics courses, particularly with electromagnetism as a classical field theory. The consensus of our working group was that students should understand the important role of formal mathematics in learning and applying physics; more specifically, know how the assumptions made when deriving an important equation define its range of validity.

CLICKER QUESTIONS

Clicker questions can be effectively incorporated into upper-division classrooms in a variety of ways, [See: http://stemclickers.colorado.edu] though they're most often associated with gauging *conceptual understanding* of newly presented material (i.e., questions that don't require mathematical calculation). [Fig. 2] They might also be used, for example, to underscore an essential point in the middle of a long derivation, to have students apply results to a novel situation, or to make direct connections between mathematical equations and the physical situations they describe. Further details can be found among the clicker questions, [Folder C] which are annotated with prior student responses, instructor notes, and comments on the in-class discussions they inspired.

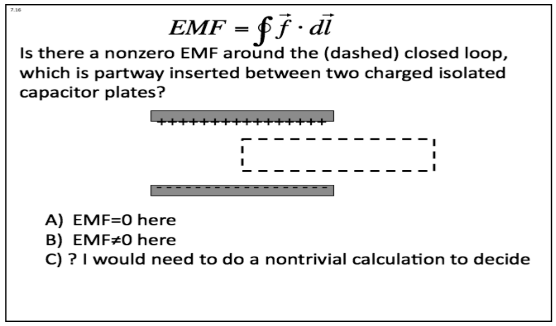

FIGURE 2. A *conceptual* clicker question that inspired important in-class discussions. 30% of FA11 E&M II students at CU were initially incorrect, either forgetting the existence of fringe fields, or not seeing how these contributed to the line integral. Even knowing that the EMF should be zero here, many students could not argue for this using Maxwell's equations.

ASSESSMENTS AND PRELIMINARY RESULTS

The *Colorado UppeR-division ElectrodyNamics Test* (CURrENT) is an assessment of fundamental skills and understanding in core topics from advanced undergraduate electrodynamics. [See: Folder H – "Assessments"; included only in the password-protected materials.] The basic (though **not** introductory-level) nature of these six multi-part questions reflects our premise that a more sophisticated understanding of advanced E&M is unlikely for students who haven't yet mastered essential concepts. Its open-response format follows from an expectation that more advanced students should be able to generate their own answers, and to justify their correctness. The focus is *conceptual*, though some mathematical manipulations are required (per our learning goals); in particular, Q4 asks students to transform a curl equation to its integral form via Stokes' theorem. More typical of the assessment would be Q3, which asks whether the E-field just outside of a current-carrying wire is *zero* or *non-zero*; and likewise regarding the divergence of the steady-state current density inside the wire. [See Fig. 3]

FIGURE 3. Diagram from Q3 of the CURrENT, showing a radially decreasing wire that carries a steady current density **J**. The parallel components of the E-field are continuous across any boundary, making the field non-zero just outside the surface of the wire. $\nabla \cdot \mathbf{J} = 0$ inside the wire by charge conservation (or, the continuity of the field lines).

The CURrENT was given in SP12 at CU (N=24), and also at a small, selective engineering college ("X"; N=11). Instructor X was present at our summer meeting in 2011, had access to the FA11 CU course materials, but did not use the guided in-class tutorials. Students in both courses were encouraged to not study for this ungraded assessment, and instead use it to judge their understanding before preparing for the upcoming final exam. Responses from both institutions were scored using a consistent rubric, and the average CU SP12 scores were significantly higher for Q3 and Q4 ($p \leq 0.001$), and for the total score ($p < 0.05$). [Fig. 4] Scores were not significantly different for the other questions, though X-students performed better than CU on Q2, regarding the fields produced by a time-varying solenoidal current.

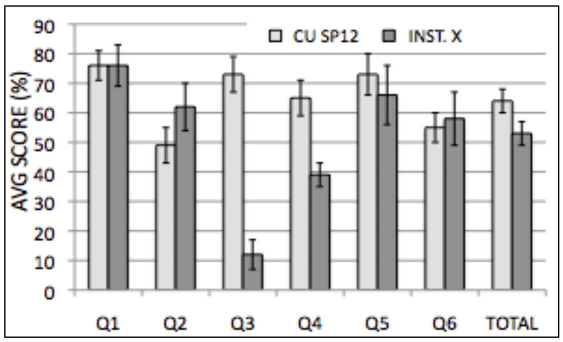

FIGURE 4. Average CURrENT scores (by question and total) for CU SP12 (N=24) and Institution X (N=11). Significant differences are seen in Q3 & Q4 ($p \leq 0.001$) and the total score ($p < 0.05$). Error bars represent the standard error on the mean.

The relatively high CU SP12 results for Q4 can be attributed (at least in part) to our emphasis on the equivalency of the differential and integral forms of Maxwell's equations, and on the coordination of lines, surfaces and volumes when applying the integral forms. 13/24 of our students were able to correctly and completely explain each of their three steps in this short derivation; only 3/11 X-students reached the final result, though none of them offered complete and correct reasoning for each and every step. Instructor X reported that he hadn't reviewed the Divergence and Stokes' theorems since the first semester.

Q3 can be answered without any calculations, but requires an understanding of the microscopic version of Ohm's law ($\mathbf{J} = \sigma\mathbf{E}$), boundary conditions on electric fields, and conservation of charge. These topics are directly addressed in many of the clicker questions (as well as several of the tutorials), and most SP12 CU students answered both parts of this question correctly. However, 10/11 X-students *incorrectly* thought the divergence of **J** would be non-zero inside the wire (the remaining student left this question blank), because the magnitude of **J** is increasing to the right. At least half of them were distracted by the appearance of "converging" field lines, which they took to represent a non-zero divergence. Only 1/11 X-students could correctly explain why the electric field just outside the current-carrying wire should be non-zero (the parallel components of the E-field are continuous across any boundary, as required by Faraday's law). Student reasoning was varied here, though several incorrectly applied Gauss' law to argue that the electric field in the region just outside the wire is zero because the charge density there is zero. This is consistent with our observation that E&M II students may still sometimes think that a vanishing divergence (or line-integral) of a field implies that the field itself is zero.

FUTURE STEPS

The richness of student responses to both the assessment and tutorial questions indicate the promise of these materials as tools for research into student learning in advanced E&M, and we continue to collect data to evaluate their use and reliability. Further modifications to the in-class activities and assessments will be made following individual student interviews over the summer, and again after their implementation at CU in the FA12 semester. The latest version of the CURrENT is scheduled to be given at another institution (different from "X"), where the course will be taught by a PER instructor. We strongly encourage instructors elsewhere to adopt these materials and/or give our assessments in their own courses, and to share with us their results and reflections. This would allow us to make further comparisons of different teaching approaches and student populations, and to assess the effectiveness of this active-learning curriculum relative to traditional modes of instruction.

ACKNOWLEDGMENTS

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