Introduction

ABOUT THESE MATERIALS

Starting in Spring 2008, we at the University of Colorado at Boulder have undertaken a transformation of our upper division undergraduate Electricity and Magnetism ("Griffiths") course to make better use of ideas and materials from the PER community. These course transformations cover the first semester of junior E&M, which covers electro and magneto-statics.

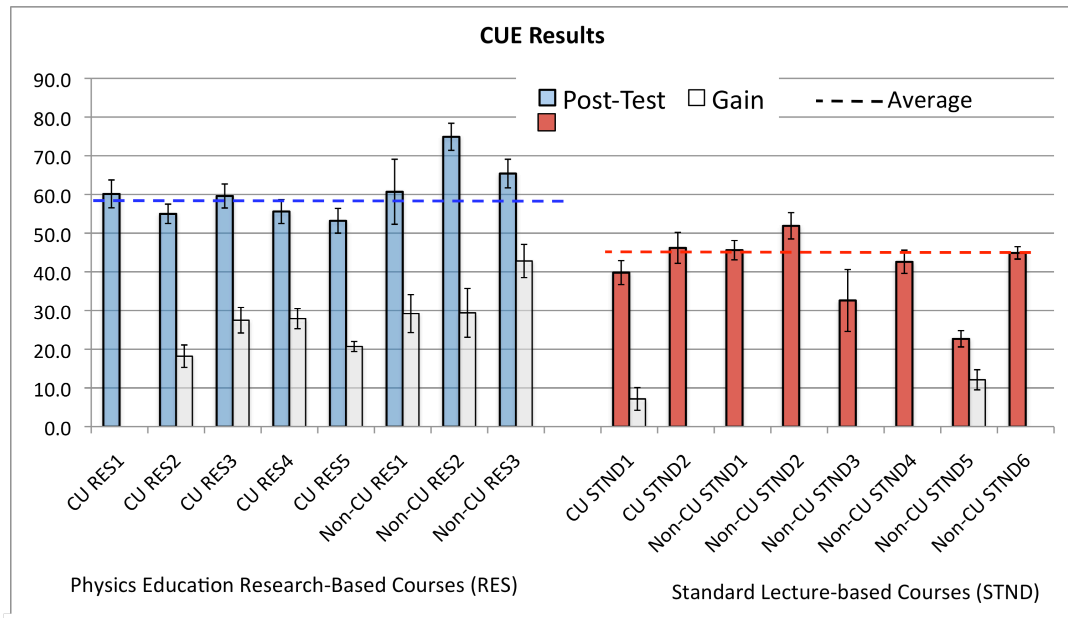
In this folder, you will find a number of materials we have borrowed or developed. Feel free to use what you like, but please attribute appropriately. We would like to share materials, but also believe in giving credit to sources whenever possible.

You can download the latest version of these materials at http://www.colorado.edu/sei/departments/physics_3310.htm. They are also available on Compadre at http://www.compadre.org/psrc/items/detail.cfm?ID=7891

If you want the course materials *including* assessments and exams, email us.
Steven.Pollock@colorado.edu
Stephanie.Chasteen@colorado.edu

IMPACT OF THESE MATERIALS

We have systematically studied the impact of these course transformations since 2008. We find that students in courses using these materials significantly outperform students in standard lecture-based courses, as measured by a conceptual exam (the Colorado Upper-division Electrostatics assessment, or CUE).



Error bar represent ±1 SE of mean. "Gain" represents student absolute gains on the 7-questions on the Post-test which match the 7-question Pre-test; Gain (and SE) estimated for TRAD and RES1 (based on consistent Pre-test data in later semesters). Non-CU TRAD is an average of three courses at another large research university. Non-CU RES is the average of three courses at three institutions that used our research-based materials. Post-test N's are as follows: CU TRAD(27), RES1-5 (20, 42, 27, 35, 59), Non-CU TRAD (221), Non-CU RES (31).

We also find that students overall enjoy the transformed courses and feel that the approach is beneficial for their learning. Faculty report high levels of satisfaction with the materials as well, indicating that clicker questions and tutorials allow a greater degree of interactivity, providing them with valuable information about student difficulties.

We have documented some of the elements leading to a successful course implementation – such as attention to the upper-division student difficulties documented by the project, explaining to students why the course approach is being used (to help with student buy-in), faithful implementation of the course approach.

Additional information on course assessments can be found in the Publications folder.

MATERIALS INCLUDED

01 Course User's Guide
This Guide.

02 – Course Learning Goals
Detailed set of skills that students should get from this course, developed by faculty.

A – Syllabus and handouts
Weekly schedule, syllabus, Maxwell's Equations posters, and crib sheets for students. Note that you can print the Maxwell Equations posters at Zazzle.com (for a fee) – just search for "Maxwell Equations". At CU-Boulder, they are located in the Lecture Demonstration area.

B – Publications on this work
Posters and papers on this transformation effort.

C – Materials by Topic
Instructional resources organized by content area (eg., Gauss' Law, Poisson's Equation). This is the recommended method of accessing these resources, as it offers a la carte access to all materials when you are ready to teach a particular topic.

D – Materials by Collection
Instructional resources organized by type of resource (eg., homework, clicker questions, tutorials).

E – Assessments
Exams, Homework Solutions, and a conceptual electrostatics assessment. You may not have this folder if you downloaded the archives from our main website – contact us for access to the secure, complete archive.

INSTRUCTIONAL RESOURCES

1- **Clicker Questions (**or "ConcepTests"). For use with peer instruction and classroom response systems
2- **Homework.** "Banks" of non-Griffiths homework questions, with information on some problems that we assigned in these courses
3- **Lecture Notes.** Instructor notes from two iterations of the course. Each instructor has a very distinctive style, so two sets are provided so you can find the lecture notes that suit your preference.
4- **Resources.** Common student difficulties, learning goals, class activities, and any notes on coverage of this particular material. These should be very useful documents for instructors.
5- **Tutorials.** Where applicable, a tutorial developed at CU for student-centered activities.

User's Guide

Included in this document:

- Text
- Course topics and ordering
- Mathematical Preparation
- Course Expectation
- Homework
- Lecture Techniques
- Whiteboards
- Recitations
- Tutorials
- Some Observations from Faculty

<u>Text</u>

The primary text for this course is D.J. Griffiths "Introduction to Electromagnetism," 3rd Edition (Prentice Hall, New Jersey, 1999).

The following additional texts are owned by the Science Education Initiative and are available to you. Please inquire with the PER faculty .

1. **G.L. Pollack and D.R. Stump. "Electromagnetism"** (Addison Wesley, San Francisco, 2002). A more mathematical text, including some material on numerical relaxation techniques. Several more problems worked out in text than Griffiths, and a more thorough coverage of currents, magnetostatics, induction and EM waves.
2. **J.R. Reitz, F.J. Milfrd, R.W. Christy.** "**Foundations of Electromagnetic Theory,** 4th edition" (Addison Wesley, Menlo Park, 1993). Nice chapters on microscopic pictures for polarization and magnetization, on plasmas, and on superconductors.
3. **J.D. Jackson, "Classical Electrodynamics,** 3rd edition" (Academic Press, New York, 1998). The graduate textbook, this is beyond what is accessible to most students in this course.
4. **R.P. Feynman, R.B. Leighton, M. Sands. "The Feynman Lectures on Physics, Volume II"** (Addison-Wesley, Reading Massachusetts, 1964). Still a classic, this volume has some extremely illuminating sections on E&M, including real-world examples and conceptualizations of the equations.
5. **R. Chabay and B. Sherwood, "Electric and Magnetic Interactions"** (John Wiley & Sons, New York, 1995). This introductory level textbook has a wealth of real-world examples of E&M.
6. **E.M. Purcell, "Electricity and Magnetism: Berkeley Physics Course Vol 2"** (McGraw Hill, New York, 1985). A sophomore level introduction to E&M, well-written and easily followed.
7. **A. Shadowitz, "The Electromagnetic Field"** (Dover Publications, New York, 1975). A well-written text which includes solutions for odd-numbered problems and many worked examples. Has a slightly more engineering bent than most physics texts.

<u>NRL Plasma formulary</u>

This booklet can be given **<u>FREE</u>** to students as a useful reference and/or exam booklet. It includes the basic equations of E&M including vector calculus and many other useful materials.. M. Horanyi used it as an exam booklet, and S. Pollock gave it as a reference guide. Student response was very positive in both cases. Copies can be ordered from The Naval Research Laboratory for free at http://wwwppd.nrl.navy.mil/nrlformulary/index.html

Course Topics and Ordering

The bulk of the material in this course is fairly canonical across universities. Following are some discussions on the presentation of particular topics and where they might appear in the course.

Presentation of Maxwell's Equations

Griffiths builds historically from electrostatics to the formulation of Maxwell's equations, such that all of Maxwell's equations are "uncovered" by the end of the first semester. Other texts (notably Shadowitz) begin instead from Maxwell's equations and present all subsequent material as falling under the umbrella of Maxwell's equations.

The approach of individual professors may vary, but several begin with Maxwell's equations regardless of Griffiths approach. In addition, one instructor doesn't give separate Maxwell's equations in matter – he presents all electromagnetism as falling under the single set of Maxwell's equations.

So, one approach to the course is to emphasize that all the seemingly disconnected laws we see in this course (Gauss, Coulomb, Ampere, etc.) are just different facets of the coherent theory of electromagnetism, which is contained in Maxwell's equations. As such, Maxwell's equations could be emphasized throughout the course as a guide. Posters have been developed for this purpose and can be printed from Zazzle.com, or are available at CU in the Lecture Demonstration area.

The counterpoint to this approach is that Maxwell's equations do not hold much meaning for students until they understand what an E and B field are. Going through the material in a more historical way allows students to see how the unification of E and B was a coup for physics, and that it allowed us to make sense of seemingly disconnected physical laws.

Dipoles and Multipoles

Most texts (Reitz Milford & Christy; Shadowitz; Marion and Heald; Pollack and Stump; Lorrain Corson & Lorrain) present dipoles (Griffiths Chapter 4) as a prelude to discussing the multipole expansion (Griffiths Chapter 3). It has been observed that most students have difficulty understanding the multipole expansion – what it means and why we would want to expand in multipoles, and what the multipole terms mean. Presenting dipole moments prior to multipole expansion could help alleviate some of this student difficulty.

Image charges and conductors

Several texts (Pollack & Stump; Purcell) present the method of images in conjunction with the properties of conductors. Griffiths instead treats the method of images in Chapter 3 (special techniques). Chapter 3 is quite a long chapter, with several seemingly (to students) disconnected problem-solving techniques. Presenting the method of images in conjunction with conductors in Chapter 2 may help students make more sense of it, and recognize that it is a technique that is specific to conductors (and perhaps dielectrics). The other techniques in Chapter 3 are more general. However, this approach would result in the method of images being presented before Laplace's equation.

E and B fields

One text (Shadowitz) presents both E and B fields in vacuum, and *then* E and B fields in materials. (Griffiths treats E fields in vacuum and materials, and then turns to B fields). This is a significant divergence from Griffiths, and we have no basis to recommend one method over the other.

Mathematical preparation

There are many mathematical prerequisites for this course, and students have varying degrees of comfort with this material. (See Learning Goals for detailed lists of prerequisites). Faculty may give a mathematical pre-test to students to both (a) assess where students are weak, and (b) send students the message that this is material they should already be familiar with. Note that not all students may have completed the math pre-requisites– instructors may wish to strongly discourage concurrent enrollment in Math Methods. See also Course Notes on Chapter 1 for ideas on how faculty have incorporated this chapter into the course.

Course expectation

In past experience, students come into this course with unreasonable expectations for the amount of work it will require. This course may be different from what they have encountered before in terms of the level of sophistication required from their involvement in the course; the amount of time that the homework will require, and the mathematical background that they will have to draw upon (and will not be explicitly taught).

To that end, making course expectations explicit may be useful in order to prompt students to shoulder the responsibility for their own learning to a greater degree than they have in past courses. This can include giving explicit learning goals for the course (as developed by the physics faculty in conjunction with the Science Teaching Fellow), and by framing the course appropriately from the beginning.

Dr. Betterton gave a handout to her students in 2210 (Math Methods) that worked well to set the tone of the course, explaining the challenging nature of the course and the expectations in terms of student time and effort.

Homework

There is a general consensus among faculty that the bulk of the learning in this course comes from doing the homework. This course is where students learn a certain level of sophistication in solving problems (*see Learning Goals*) and so assigned homework should reflect that higher expectation. The Science Education Initiative has compiled a homework "bank" of useful problems to draw on using the approaches below.

Some ideas for homework sets:

1. Use the course-scale learning goals as a guide in writing HW problems. This helps ensure that these goals are being met and that the HW is covering a broad range of skills.

2. Assign homework other than Griffiths problems. The solutions to Griffiths are widely available on the internet. Alternatively, take Griffiths problems and use different numbers and try not to let students know they are taken from Griffiths (although they can still figure it out, generally).

3. Assign just a few hard problems in each set. This gives students time to grapple with each one in depth. This is a method preferred by some instructors.

4. Assign tough "just for fun" problems (for extra-credit or not). This gives the stronger students a chance to flex their physics muscles and assure that they will be challenged in the course.

5. Assign the first homework problem each week as the submission of a correction of a homework problem from the previous week (as done in Wieman and Perkins Modern Physics course).
    a. Identify the question number you are correcting
    b. State (copy) your original wrong answer
    c. Explain where your original reasoning was incorrect, the correct reasoning for the problem, and how it leads to the right answer.
    d. If you got all the answers correct!!! Great ... then state which was your favorite / most useful homework problem and why.

6. Give two-part homework questions. One part is a standard calculation problem and one part a more conceptual, understanding-based question. For example, you may ask students to:
    a. *Apply the abstract formal problem to a real world problem.* Ie., use the results of their calculation to answer a question about a real life situation.

b. *Formulate the abstract formal problem when presented with a real-world problem*. This is a higher level skill that may wait until later in the semester.
c. *Formulate their expectations for what the solution to a problem might look like*, such as the direction, order of magnitude, units, sketching a field or charge distribution, or dependence upon coordinates, before beginning the problem.
d. *Explain in words what their answer means.*
e. *Explain in words what they did to solve the problem.*
f. *Justify their approach to a problem.*
g. *Sketch or graph* their answers
h. *Indicate the limiting behavior* of the calculated result

7. <u>Assign homework problems with a computational component.</u> Computational skill is important for students at this level, as well as understanding that you *can* solve for the field numerically when given the code. Pollack & Stump includes a section on relaxation techniques, for example. The amount of time spent on this topic will depend on individual faculty preference. These homework problems can take students a great deal of time. Homeworks using computational techniques could include:
    a. Using software (such as Mathematica) to plot the E or B field for a problem.
    b. Writing programs to solve a solution numerically – either when it can't be solved analytically, or to compare to the analytical method.
    c. Using existing code to solve a situation numerically through relaxation methods, etc.

8. <u>Assign some real-world ("context-rich") problems.</u> These can be Fermi problems (such as estimating the thickness on a lake) or context-rich (see, for example, http://groups.physics.umn.edu/physed/Research/CRP/on-lineArchive/ola.html)

9. <u>Assign some HW problems on a related topic from another course</u> (eg., "Gauss' Law" in gravitation) to keep students focused on the big picture and emphasize that they are responsible for material from prior courses.

Lecture techniques

There are a variety of lecture techniques which have been shown to be useful in student engagement.

1. Clicker questions

Many of the more simple, conceptual homework problems can be reworked into clicker questions, serving two purposes: (a) students engage in meaningful discussion about the concept rather than seeking the answer, and (b) leaving more time for longer problems on the homework set. A bank of clicker questions has been developed by faculty in conjunction with the Science Teaching Fellow. Clicker questions have proven very effective, though time consuming, in this course, generating a good deal of student discussion and highlighting student difficulties. In addition, because students' knowledge is tested often, it is easier for them to know where their difficulties lie. One student remarked that the clicker questions in this class worked better than in other classes because they were integrated deeply into the lecture – they acted to connect one topic to the next, instead of a 5-minute aside. They were a bridge rather than a break in lecture.

Are you having trouble with the formatting in our clicker question files?
Sometimes your "slide master" may have different settings than the "master" when the slides were created, which causes formatting difficulties (like questions that are too small to read, or answers that spill off the page). See the "readme" file in the "All-concept-tests" folder in the folder "D-Materials-By-Collection".

2. Interactive lecture

When solving a problem on the board, the lecturer can pause and ask the class for the next step. If the course culture has included the use of clicker questions, so that students are habituated to actually engaging with this sort of question (instead of waiting for the smartest student to answer), then this type of discussion can occur without the use of actual clickers in every instance. The class should be given a time limit (e.g., "You have 30 seconds, write down your answer") to focus their discussion. For example, solving for the B field around an infinite wire, students may be asked to give the form for script-r, or the direction of B.

3. Class discussions

In addition to clicker questions, faculty can pose open-ended questions (non multiple choice) for discussion in class, providing students an opportunity to engage with the concepts in class. The more that instructors are clearly open to discussion in class, the more students will feel comfortable posing spontaneous questions.

4. Whiteboards or Chalkboard work

We have successfully used whiteboards and student work at the blackboard in class and out of class – these are addressed separately below.

5. Don't repeat examples from the text

Students generally read the chapter as they work on the problem set. It may be useful to encourage students to read the chapter before lecture, if the professor does not intend to reiterate material from the book in lecture. In that case, lecture may be spent in productive discussion and engagement with the material. Students can easily read derivations and similar content in the book, and so professors may decide how much of that content should be included in lecture.

6. Kinesthetic activities

We have adapted a handful of kinesthetic activities from Oregon State University – for example, asking students to arrange themselves in the form of a line charge. These activities have met with mixed pedagogical success since there is often insufficient lecture time to delve deeply into the concepts brought up by the activities. However, as a method of engaging students and maintaining their attention, it has been very valuable.

7. Other techniques

A wide variety of other innovative techniques have been developed at Oregon State University and may be accessed from their wiki at
http://www.physics.oregonstate.edu/portfolioswiki/

Whiteboards

We use large (2x3 foot) whiteboards for group activities, and small (1x1 foot) whiteboards for individual or partner work. We have 6 large and 30 small whiteboards available for your use.

Reasons to use whiteboards:

- The instructor can quickly see what students are getting in a lecture (by walking around to individual whiteboards or by asking students to “publish” their results by holding up their whiteboards.
- Can provide more insight into student thinking and ability than clicker questions by allowing for more open-ended questioning than the limited choices presented by the multiple choice options in clicker questions.
- It gets students talking to one another
- In groups, students can work from a common discussion point and draw diagrams so that they (and the instructor) can more easily discuss together
- Because the whiteboards are, by nature, impermanent, students are less afraid to try out ideas on how to solve a problem than they are with pencil and paper

LA Darren Tarshis notes: *“Students seem more willing to throw ideas around when using whiteboards…. Notebooks and pen and paper are far more permanent than whiteboards, so careful students may approach a problem in an overly cautious manner (and therefore thinks in an overly cautious way). Whiteboards encourage students to take more risks, try new things, without feeling that it is "permanent." This may allow students to think differently and break through intimidating content barriers.”*

Prof. Steve Pollock notes: *“I've used whiteboards roughly one out of every 3 or 4 lectures this term. There are some obvious advantages, which take it even beyond the value of straight clicker questions. It gets a large fraction of the class visibly participating, it provides me with more direct feedback about their thinking (on concept tests, I only learn about student thinking as well as my best guessed distractors are!). It allows me to get students calculating (rather than just thinking about conceptual topics, a real virtue in an upper division course). I have tried using paper but students seem much more reluctant to commit a possibly wrong idea down to their lecture notebook. I appreciate being able to quickly look over their work (what's left on the boards after class.) It seems to facilitate their sharing and discussing of ideas (and I often use one board for every two students) Students seem to enjoy using them. It's similar to the role of the "napkin" at a physicists dinner gathering, (but larger, more visible and easier to* *erase.)*

Drawbacks of using whiteboards:

- Instructor must plan in advance to use the whiteboards (and thus bring them to class and have students pick them up as they enter class)
- The whiteboards are a little bulky and cumbersome
- Difficult for the instructor to circulate to see all whiteboards, and insufficient class time to discuss them in depth

Prof. Steve Pollock notes: *"The disadvantages of whiteboards are that I have to think up yet another class activity. It's also not always obvious what they should DO with the whiteboards. Whiteboards chew up much more time than even concept tests! The class logistics are a little awkward, esp getting the boards distributed (and then they are in the students' way if we return to a more traditional class)"*

How to use whiteboards effectively:

We are still experimenting with the best uses of whiteboards. For best practices, please see

1- http://www.physics.oregonstate.edu/portfolioswiki/strategy:smallwhiteboard:start?s=whiteboard
2- http://physicsed.buffalostate.edu/AZTEC/BP_WB/

Ways we've used whiteboards:

1 - Build a concept map of physics on the first day of class.
The goal here was to get them thinking about where E&M fits into the larger picture as well to begin to establish a new class culture where the students would be more involved in the course. Students responded very enthusiastically and had fun. It was not pedagogically valuable in this context, but did help establish the class culture.

2 - To sketch or graph in class
For example, pairs of students were asked to write down the equations connecting the E field, charge distribution, and Voltage (the equivalent of the Griffiths triangle). We were able to notice that they were comfortable with the integral forms of the equations but had not internalized the differential forms as well. On another day, students were given a situation with a conductor and a charge inside the conductor and asked to sketch the charge distribution on the conductor. These activities were very useful in generating student discussion, but it was difficult for instructors to visit all whiteboards and discuss with all students

to ensure that the main point was understood. The activity took substantial class time, but still seemed very valuable in getting students to wrestle with some key ideas. In Quantum Mechanics, the whiteboards were used to sketch the wave function for different eigenstates in different potential energy configurations, and provided good opportunity for students to check their understanding.

3 - To calculate in class

Students have been asked on numerous occasions to sketch out the beginning of a calculation, either spontaneously or as part of a clicker question. When given as part of a clicker question, the question is posed but the multiple choice answers are not displayed. The students calculate together on the whiteboards and the instructor can view their work. This has been very valuable, and the instructor for Quantum 1 indicated that this use gave him a startling insight into how little students were internalizing from lecture.

4 – Out of class group work

We run tutorials (small group activities out of class) and homework help sessions. In each type of group work, large group-sized whiteboards are laid flat on each group's table. This serves as a public place for groups to discuss, graph, sketch, calculate, and gesture. Instructors in the tutorials have found them incredibly useful in this venue as the printing is large enough so that all can see, and when creating or gesturing towards certain parts of a calculation or a diagram, all can follow the discussion.

Recitations

While recitations can't be mandatory for this 3-credit course, it is useful to offer an instructor- or TA-led session to work on issues in the homework. In the reformed course, we encouraged students to work in small groups on the homework. They learn by peer instruction with occasional input from the instructor, as in the tutorials. Each group has a group-sized whiteboard (see above), and problems are **not** worked out on the board by the TA, as has been traditionally the case. We have offered two homework help sessions – two nights and one night before the homework is due.

Our analysis of these recitations shows that, on average, any given student attends about 40% of these sessions. We also find that, when background variables are taken into account, students do better on the homework the more of these sessions that they attend – suggesting that these peer-led sessions benefit the students. (See PERC 2011 paper by Chasteen, in Publications)

Tutorials

We have offered optional Friday tutorial sessions which have been very successful. Tutorials are offered as an optional co-seminar, typically on Fridays, and a Learning Assistant is assigned to help facilitate them. The tutorials are written up separately, as is a Tutorial User's Guide.

The tutorials are highly rated by students, who see them as fun and engaging and an opportunity to think about the ideas brought up in lecture. Instructors are very positive about the tutorials as well:

> "The asset that came as a surprise to me, because I thought I knew it all, was how valuable the feedback is that I'm getting in the tutorials… The tutorials seem to reveal to me the students' thinking, or lack of it, in a way that watching them struggle with the homework doesn't…. It's just eye-opening." - Instructor

We also find that – even when the effects of background preparation (such as GPA in prior courses) is taken into account – tutorial attendance has a positive effect on students' conceptual understanding of course material.

See PERC 2011 paper by Chasteen, in Publications, for full information.