

# **2012-2013 Annual Report**

## **for the**

## **CU Science Education Initiative**

Covering periods August 2012-July 2013

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## **2012-2013 Executive Summary of CU's Science Education Initiative**

The goal of CU's Science Education Initiative (SEI) is to improve undergraduate education in the sciences. For each course, this process involves a three-part process:

- 1) establishing well-defined learning goals through faculty consensus,
- 2) creating valid assessment tools for measuring attainment of these learning goals,
- 3) creating and using pedagogically effective materials and teaching approaches that are:
  - aligned with the learning goals,
  - based on and aligned with established research on how people learn,
  - based on research into student thinking about and learning of the content, and
  - improved through research (assessment and iteration).

Achieving this goal requires substantial changes to the standard university departmental and faculty culture surrounding undergraduate education. The funding provided to departments through the SEI has enabled the hiring of 2 or 3 Science Teaching Fellows (STFs) within each department. The STFs facilitate, guide, and support faculty as they learn about research on learning and engage in transforming their own and the departments approach to teaching. The STFs also investigate student thinking and measure student learning, and by doing so, provide faculty with the data they need to make informed choices about teaching approaches.

After 7 years, a significant number of faculty in 7 departments over the lifetime of the SEI (APS, CHEM, EBIO, GEOL, IPHY, MCDB, PHYS) have been impacted by the SEI, modifying their teaching, creating and using learning goals, and using information on student thinking to guide their teaching. Faculty are engaging in research-based teaching methods and educational issues. The SEI project has also impacted a large number of courses, through in-depth interaction with faculty teaching those courses, developing learning goals in collaboration with faculty, and developing and administering validated assessments of student learning. These changes have impacted over 10,000 students per year, considering courses in which STFs have been both fully and partially involved. The SEI has also impacted departmental culture, affecting the frequency of discussions about teaching and learning in departments, and leading to numerous grants to continue the work begun by the project.

In summary, faculty, current and future students, individual departments, and the university as a whole are substantially benefitting from the investment CU has made in the SEI project. The learning environments and structures are overall more effective; the faculty have defined their learning goals and the curricular materials focuses on achieving those goals; the faculty are better educated in research on teaching and learning, particularly as they apply to the specific content of their courses and how students think about that content; and the faculty engage in and value research on their own student's learning – e.g. through the use of formative assessment tools such as clickers to probe and immediately respond to their students' thinking.

See later reports for more detailed numerical impacts of the SEI.

## **I. Overview of the Science Education Initiative**

The CU Science Education Initiative is designed to implement and coordinate departmental-wide improvement of undergraduate science education. The major goal of the SEI is to bring about the sustainable transformation of the teaching of science on a department-wide basis to employ the research-based methods that have been shown to be highly effective in achieving faculty-defined learning goals.

While it is essential to improve science education at major research universities, the task is formidable. These science departments are large entities with established practices and are subject to a variety of economic and external constraints, providing barriers to change. The approach of the SEI is two-fold: 1) to have the faculty and the department initiate their involvement in and commit to participation in the SEI, and 2) to lower the time and money challenges by providing the funding needed to carry out these department-initiated activities.

The SEI efforts in each department are focusing on sequentially targeting courses for improvement, often beginning with the large introductory courses. Working in conjunction with the participating department, the major elements of the SEI-department efforts for each targeted course include:

- 1) establishing well defined learning goals,
- 2) creating valid tools for diagnostic assessment of attainment of learning goals,
- 3) identifying student thinking,
- 4) creating and using pedagogically effective materials and teaching approaches, and
- 5) developing faculty knowledge and practices.

Below, we provide details on the central SEI activities that are being conducted in support of the project, followed by a summary of the SEI budget. In the last five sections, the participating departments summarize the structure of the SEI project within their department, the course-related activities in 2012-2013, faculty involvement in the SEI, and departmental goals for 2013-2014.

## **II. Central SEI Activities**

### **A. Update on central staffing**

Dr. Stephanie Chasteen continues to serve as the outreach director for the project, creating videos about effective teaching, conducting faculty workshops, maintaining the website, and serving as a resource for the STFs. In September 2011 Dr. Chasteen was promoted to Associate Director, and undertook additional responsibilities related to the SEI such as reporting, STF training, and other duties.

Dr. Kathy Perkins continues to serve as director of the program, and Oliver Nix continues to spend a portion of his time assisting with administrative tasks for the SEI.

### **B. Funding departmental-based efforts**

Several departments have completed their SEI programs. In 2011, CHEM, GEOL, IPHY completed their programs. MCDB and PHYS have continued their SEI programs, with new hires in each department beginning in the previous reporting year (2011). Additionally, two

departments began new SEI programs in 2011: APS and EBIO. One new hire has been added in 2012-2013, to replace a departing STF in APS.

A summary of the activities in each department is provided in the last sections of this report.

### **C. Activities to support departmental-based efforts**

The SEI central staff (Kathy Perkins, Stephanie Chasteen, and Oliver Nix) support the departmental-based efforts in a variety of ways. Programmatic support from SEI Central has been gradually phased out as the SEI reaches maturity and activities are coming to a close.

1. Perkins and Chasteen serve as resources to all of the STFs: advising them on the results of learning research, techniques of education research, and new effective teaching practices; reviewing their activities and progress and providing guidance and advice where needed; and providing them with appropriate professional development opportunities. In addition, they provide central support for certain activities where appropriate (e.g. resource materials for workshops or for administering surveys).
2. To foster communication between departments, Perkins and Chasteen hold occasional meetings with all the STFs – promoting STFs sharing with and getting feedback from the other STFs.
3. In May 2012, Perkins hosted the seventh end-of-term SEI sharing session – a half day even in which each of the participating departments presented some highlights of their activities over the course of the term with time for discussion among the faculty. This event was held in coordinate with the Integrating STEM (iSTEM) initiative on campus and served as a connection-point for diverse stakeholders in science education across campus.
4. Chasteen provides pedagogical support materials (videos, booklets) to STFs for use as they work with faculty on teaching innovations.
5. Chasteen and Nix provide periodic updates to the website on SEI and STF activities.

### **D. Resources for faculty**

The central SEI staff currently provides and is creating additional central resources for faculty working on improving science education on campus.

#### **1. Workshops**

Chasteen and Perkins provide periodic workshops through the Faculty Teaching Excellence Program on the use of learning goals and clickers/peer instruction. These workshops are open to all SEI departments, as well as the campus at large. These workshops have impacted over 100 faculty during the course of the SEI project, with potential to impact several thousand students. Materials from past workshops are on our website at <http://www.colorado.edu/sei/fac-resources/workshops-clickers.htm>

## 2. Teacher guides

In collaboration with the UBC SEI project, we have created a series of teacher guides covering some of the key pedagogical findings from education research and some practical advice on various pedagogically effective teaching practices. Additionally, a detailed resource page on the use of clickers and peer instruction, including videos of use, were developed in previous years. These are listed on the SEI website, <http://www.colorado.edu/sei/fac-resources/>.

## 3. "Framing" project

In order to support instructors in creating a positive climate for active learning in their classroom, Chasteen has collaborated with researchers at external institutions (Andrew Boudreux, Western Washington University and Jon Gaffney, Eastern Kentucky University) to identify approaches used by instructors to promote student buy-in of non-traditional instructional techniques. These resources, and preliminary research on instructor use of these materials, are on the SEI website, <http://www.colorado.edu/sei/fac-resources/>.

## 4. Workshop materials

Dr. Chasteen has provided numerous workshops at CU and elsewhere on learning goals and the use of clickers and peer instruction. These workshop materials have been organized and archived, and broadly advertised, in the spirit of open dissemination of this work, for use by facilitators of such workshops elsewhere.  
<http://www.colorado.edu/sei/fac-resources/workshops-clickers-materials.htm>

## 5. Website

The SEI website provides general information about CU's SEI project and serves as a source for faculty to access information about various education research findings (both general and discipline-specific), handouts and PowerPoint slides from SEI workshops, as well as extensive archives of course materials developed during the SEI. The UBC SEI has a more extensive collection of faculty resources which have been recently mirrored on the SEI website. The website can be found at: <http://www.colorado.edu/sei/>.

In addition, the CU SEI effort collaborated with the UBC SEI effort to build a much more sophisticated database of resources for faculty that allows faculty to upload their own resources or to search existing resources. This software has been piloted by CU and UBC STF's and faculty, and is available at <http://www.sei.ubc.ca/materials>Welcome.do>

### **III. SEI in Astrophysical and Planetary Sciences**

The SEI program in Astrophysical and Planetary Sciences began in September 2011. The report for the 2012-2013 academic year is included in the 2013-2014 report.

### **IV. SEI in Ecology and Evolutionary Biology**

#### **A. Departmental Structure**

Andrew Martin is the departmental liaison. Sarah Wise has continued as an STF in the department, and Anne-Marie Hoskinson was hired in August 2011, leaving the program in September 2013.

#### **B. Course Support Activities**

From June-September of 2012, Sarah was on maternity leave. However, during this time she managed the work of two graduate research assistants (Rachel Wildrick and Loren Sackett) as they completed specific support tasks for the General Biology course. These were:

- clicker data catalogs for Becca Safran (BS), Piet Johnson (PJ), and Kendi Davies (KD)
- exam catalogs for BS and PJ
- the incorporation of clicker data into lecture .ppts for BS, PJ, KD
- generation of .ppts containing only clicker questions+data for future SEI archiving/dissemination, for BS, PJ, and KD
- collection of gestural data from archived lecture videos of KD
- summary of student free response data from surveys, for KD
- detailed guidelines for construction of future exam and clicker catalogs

##### **1. General Biology I (Genetics)**

Upon returning to her faculty support duties during the second quarter of fall 2012, Sarah supported Sam Flaxman and Dan Medeiros in their teaching of General Biology I (genetics). Dan largely adopted Sam's lecture materials which had been revised with Sarah's input during fall 2011. Sarah supported each of these faculty with her "typical" slate of support activities. Due to her part time schedule she was not able to attend every lecture, but she attended  $\frac{1}{2}$  of Dan's lectures and  $\frac{2}{3}$  of Sam's lectures weekly. Sarah observed continued progress by Sam in refining his clicker questions and case study, and in requesting student reasoning during the wrap-up of clicker questions. Having not taught for two years (due to sabbatical and paternity leave) Dan was less confident in his teaching but grew visibly more comfortable with all aspects of lecturing and using clicker questions over the quarter. Dan readily incorporated Sarah's suggestions for clicker question implementation. Both Sam and Dan continue to be active in the SEI.

During the first quarter of spring 2012, Sarah supported Becca Safran and Piet Johnson in their teaching of General Biology I (evolution, animal diversity and physiology). Sarah provided her “typical” slate of support activities to both, but because Becca and Piet wanted to engage in more intensive revision and dove-tailing of their lectures, Sarah only observed 3 of Becca’s classes and listened to audiorecordings of 2 others. She observed 2/3 of Piet’s lectures and met with Piet briefly after each one. Sarah also met with Becca, Piet, and Cesar Nufio (course coordinator) weekly to discuss ideas and plans for revisions to the course. In addition, Sarah, Piet, and Becca collaborated on developing, implementing and analyzing a pre-post assessment from the most conceptual and higher-order Bloom’s level questions from their exam catalogs. During this quarter Sarah observed that Becca responded well to advice to incorporate more student reasoning into clicker wrap-ups, while Piet incorporated student reasoning extremely well after just a small amount of coaching. During their weekly meetings, Becca and Piet developed a long list of creative ideas for continued course transformation, focusing on the difficult problems of integrating the “march of the phyla” with the history of life, challenging students to construct phylogenies, and embedding animal physiology within interesting case studies. In April 2013 Becca and Piet submitted a proposal for a Chancellor’s Award for STEM Transformation to fund their time over the summer to engage on continued intensive “overhauling” of their lectures toward these goals in conjunction with Sarah and Cesar.

During the second quarter of spring 2013, Sarah supported Kendi Davies and Brett Melbourne in teaching General Biology I with her “typical” slate of support activities, attending ½ of Kendi’s lectures and 2/3 of Brett’s lectures. In addition to this work, Sarah engaged Kendi and Brett in an analysis of their pre-post results from 2012 and targeted assessment item and instructional revisions based on those results. Several questions were reworded to assess whether clarity affected performance, while two other instructional sequences were altered to attempt to improve student performance for specific learning goals. To better support instruction, Sarah developed two new in-class exercises for human and moss life cycles and revised the active learning around angiosperm life cycles. Kendi and Brett have continued to express appreciation for Sarah’s feedback.

## **2. *Ecology (EBIO 2040)***

AMH developed and taught a case-based course in ecology (EBIO 2040), a one-time enrollment relief for the department. The course was developed as a student-centered, case-based course, with cooperative learning built into the course structure. In addition to teaching a section of this course, this activity was also designed to 1) create a course outline and structure that was consistent with department learning goals developed in the previous year, and 2) assemble course components in support of a future student-centered course in ecology that could be rapidly adopted by any faculty member. Consistent with the SEI goals, all aspects of the course were documented: learning goals derived from last year’s discussions among ecology faculty (NB, BM, KD, BB, AM, and AMH) with assessments derived from those goals; daily plans and debriefs (similar to Pollock’s classical mechanics notes), course learning materials, and full case documentation.

Together with NB and AM, we initiated a student poster session as the capstone product in our respective courses (ecology, evolution, and plant ecology) at the conclusion of fall 2012. We continue our work on authentic assessments that capture both content and skill knowledge with J. Harrison Carpenter, an instructor of writing and communication in EBIO, and will offer a second poster session at the conclusion of the spring semester 2013. Our intention is to prepare a manuscript that advocates for using poster sessions as authentic assessments and describes to our colleagues how to set up and scaffold this assessment within the framework of a biology course.

### ***3. Evolutionary Biology (EBIO 3080)***

Andy Martin continued to advance the development of EBIO 3080, Evolutionary Biology. As a consequence, there are now:

- clicker questions catalogs for a large number of formative assessment questions that include the question and the clicker scores
- exam catalogs
- science process skill questions that are useful for implementing pre- and post-teaching exams and estimating learning gains
- content questions that are useful for implementing pre- and post-teaching exams and estimating learning gains
- data from several iterations of pre- and post-assessments
- an archive of case studies and active learning activities aligned with course learning goals and published science-process skill learning goals (i.e. Vision and Change core skills)
- a catalog of powerpoint images

By the end of the summer, the whole course will be available on-line for adoption by other instructors.

## **C. Departmental Support Activities**

### ***1. Faculty Retreat***

Andy Martin and Anne-Marie Hoskinson planned and implemented an EBIO SEI faculty retreat....Sarah attended with infant Iris. Over two days (August 22 and 23), Andy, Nichole Barger, Sarah Wise, and Anne-Marie led workshops and discussions on topics including Bloom's taxonomy (constructing higher-level exam questions), following a backward-design cycle from learning objectives-learning outcomes-assessments-learning activities, formative and summative assessments, and metacognition/reflection in our classrooms. AMH and SW provided one-on-one and small-group working sessions.

### ***2. Ecology Concept Inventory***

Bill Bowman, NB, and AMH finished the first prototype of the ecology concept inventory, which was deployed in their three classes during fall semester 2012.

### **3. *Parasitology***

AMH worked with Valerie McKenzie during Spring 2013 to introduce active-learning techniques in her parasitology classroom. VM is now using clicker questions and infrequent minute papers. AMH also worked with VM to “Bloom” her existing exam and provided suggestions for increasing the cognitive richness of VM’s assessments.

### **4. *Mathematical Models in Ecology and Evolution***

AMH is teaching a section of an upper-division critical thinking course, Mathematical Models in Ecology and Evolution. This is based on a course she developed at Georgia Tech using the Modeling Instruction approach. This course was offered because the department currently does not have, but is seeking ways to enrich our students’ quantitative and computational modeling skills. As with fall ecology, the course objectives, assessments, teaching materials, and structure are being made available to the department, should a future faculty member choose to teach such a course.

### **5. *Faculty Meeting***

Sarah, John Basey, Andy Martin, Becca Safran and Nichole Barger presented an update on SEI activities during the EBIO faculty meeting Feb. 28, 2013. Andy Martin led faculty discussion of the upcoming EBIO Major Science Process Skills Assessment during the EBIO faculty meeting March 7, 2013.

### **6. *Peer Reviews***

Andy Martin provide peer reviews of teaching based on multiple observations of classrooms for Piet Johnson, Rebecca Safran, Kendi Davies, Nichole Barger, Christy McCain, Daniel Maderois, and Samuel Flaxman. The reviews included quantitative data on the timing and duration of events during lectures, a catalog of learning goals, and detailed observations of student engagement during the lectures. The data were also used to provide a peer review letter for the faculty member's permanent file.

## **D. Research and Scholarly Activities**

### **1. *Group Sign-Up Experiment.***

Analysis of student attitude survey, clicker survey, CQ performance, post-test performance, and exam performance data is scheduled for the week of April 15, 2013. Sarah, Brett Melbourne, and Kendi Davies will divide this analytic work and collaborate during this time. Sarah worked with Anne-Marie and Cesar Nufio to arrange to cover Brett and Kendi’s teaching during this week, to give them the time to complete this work.

## ***2. NSF TUES Clicker Discussion Experiment.***

Sarah, Jenny Knight, and Erin Furtak were awarded \$150,000 in June 2012 to carry out “Investigating Instructional Influences on Clicker Discussions”. While on maternity leave, Sarah worked with Angel Hoekstra to order and assemble the audiorecording equipment for this project. Then, during October and November 2012 Sarah worked with undergraduate research assistants Erika Lai (EL) and Sarah Zimmerman (SZ) to test the audiorecording equipment, recruit volunteers, and collect data in the General Biology I class. Sarah also collaborated with Barbara Demmig-Adams and William Adams during this time on the design and implementation of the experimental treatment, which involved specific introductory statements encouraging students’ use of reasoning during clicker discussions, and video models of good and not-so-good clicker discussions.

Data analysis is ongoing. During the second quarter of fall 2013, Sarah developed the databases in which clicker discussions are being transcribed from the audiorecordings by EL and SZ, and has advised these students in their work. Additionally, during spring 2013 Sarah collaborated with Jenny Knight to train a graduate research assistant, Tanya Swarts, to analyze student survey data. As transcripts have become complete, Sarah, Jenny, and their co-PI Erin Furtak collaborated on coding the transcripts for characteristics of argumentation, social cooperation and conflict. Initial data indicate that the treatment positively affected student attitudes toward group work and discussion, and may have stimulated students to engage in higher quality discussion.

## ***3. At-Risk Student Intervention Experiment.***

In May 2013, Sarah was awarded a \$10,000 Chancellor’s Award for STEM Excellence proposal with Barbara Demmig-Adams (BDA) and William Adams (WA). Entitled “Assessing the Impact of Early, Individualized Faculty and TA Interventions for At-Risk Students,” the experiment will invite students who score below a C on the first exam of General Biology I to a one-on-one exam review with BDA, WA, or a postdoctoral instructor (or engage in a placebo one-on-one meeting). Outcomes will be assessed for both identified at-risk (McNeill Academic Program) and nonidentified at-risk students.

## ***4. Student attitudes in case-based courses.***

In fall 2012, Anne-Marie initiated a project using the Bio-CLASS survey developed at CU and designed to explore differences between students in case-based vs. students in traditionally-taught courses. Students in course sections from evolution, plant ecology, and general ecology (traditional and case-based) courses were invited to take the C-LASS before and after their courses. We have collected data from one semester’s courses, and while data analysis isn’t complete, it appears that this instrument does not capture differences in student attitudes between the two instructional method treatments.

## ***5. Developing a deployable metacognitive tool.***

Beginning in Spring 2013, Anne-Marie worked with Nichole on metacognition in science courses. One activity centered on finding, creating, and/or modifying a functional tool to

quantify observed student metacognition in the classroom; this is being developed by mining the hundreds of written metacognitive reflections our students have submitted. The ultimate goal of this project is to discern how students' metacognitive skills develop over the course of a semester (and longer), and how best to scaffold this development with them. This project will be ongoing over the summer and next academic year.

#### ***6. Documenting and submitting case studies.***

AMH is writing two case studies developed for two courses: chytridiomycosis in amphibians (from KD's general biology course) and crazy ants on Christmas Island (trophic cascade case from fall 2012 ecology). These will be submitted to the National Center for Case Study Teaching in Science, a peer-reviewed collection at SUNY Buffalo, this summer. APM developed 6 case studies for evolutionary biology that are not ready for prime time. The case studies will, however, be posted on the department and SEI dropbox sites for general use, especially for new professors that will be coming on board in EBIO and will teach evolution.

#### ***7. Poster sessions as authentic assessments.***

Together with NB, AM, and senior instructor J. Harrison Carpenter, AMH initiated and leads a team exploring the use of poster sessions as authentic assessments in process-focused, upper-division courses. In fall 2012, we hosted the department's first course research symposium among ecology, evolution, and plant ecology courses. Over 200 students collaborated on course research projects that culminated in a poster session with over 50 entries. JHC joined us with his spring course, Writing in the Discipline. We continue to develop a common set of guiding documents to support a research project culminating in a poster session and plan a publication (targeted toward science-rhetoric and BER journals) after the spring poster session. The poster approach as an authentic assessment will be presented as a poster in the upcoming International Society for the Study of Evolution meeting in Snowbird UT, June 2013 (APM, AMH, and NB as co-authors).

#### ***8. Development of a Science Process Skills Assessment.***

APM, SW and John Basey worked towards developing a science process skills assessment tool that can be used to measure learning gains for EBIO majors. We completed the first test for a small sample of students that involved free-responses to 7 questions followed by interviews to gauge student perceptions of the questions and thoughts about their answers. The free-responses and interviews were recorded digitally. This process will be repeated for a larger number of questions using a larger sample of students in the summer of 2013. Our hope is that we can pilot the assessment in the 2013-2014 academic year.

## V. SEI in MCDB

### A. Departmental structure of the SEI program

<u>Current staff</u>	<u>Position</u>	
Dr. Jennifer Knight	Coordinator	
Dr. Bill Wood	Director	
Dr. Brian Couch	Science Teaching Fellow (full-time, Jan 2012-present)	
<u>Previous STFs</u>	<u>Current Position</u>	
Dr. Sarah Wise	STF in Ecology & Evolutionary Biology (EBio)	Dr.
Jia Shi	Academic Advisor in Integrative Physiology (IPhy)	
Dr. Michelle Smith	Assistant Professor (UMaine)	

### B. Course-related efforts

#### 1. General

Previous SEI-facilitated efforts have resulted in the core MCDB courses, as well as some additional electives having:

- 1) Course- and topic-level learning goals. The learning goals for each core course are shared with the students (usually via the course website) and frame the teaching of each course.
- 2) Interactive learning approaches, including in-class concept questions (clickers), small group activities, co-seminars designed to give students a small group environment to practice solving problems, homework activities, and formative assessments.
- 3) Two published concept inventories: the Genetics Concept Assessment (GCA) (Smith et al. 2008) and the Intro Molecular and Cell Biology Concept Assessment (IMCA) (Shi et al. 2010).

We continue to publish our findings in peer-reviewed journals. A complete list of publications since the onset of the SEI is at the end of the report.

#### 2. Courses previously modified

As mentioned above, the SEI has worked with the MCDB faculty to implement research-based teaching approaches across the curriculum. Below is a list of courses and faculty that the MCDB has partnered with in past years. Please refer to previous reports for course modification details.

- a) MCDB 1041 Fundamentals of Human Genetics (Jenny Knight)
- b) MCDB 1150 Intro to Cell & Molecular Biology (Nancy Guild and Jennifer Martin).
- c) MCDB 1152 Intro Co-seminar (Nancy Guild and Jennifer Martin)

- d) MCDB 2150 Principles of Genetics (Ken Krauter, Tin Tin Su; Mark Winey)
- e) MCDB 2152 Genetics Co-seminar (Nancy Guild, Christy Fillman)
- f) MCDB 3140 Cell Biology Laboratory Course (Joy Power)
- g) MCDB 3135 Molecular Cell Biology 1 (Cell Biology) (Greg Odorizzi, Gia Voeltz, Jingshi Shen)
- h) MCDB 3150 Molecular Cell Biology II (Molecular Biology) (Greg Odorizzi, Mike Stowell, Ravinder Singh)
- i) MCDB 4330 Immunology (Corrie Detweiler)
- j) MCDB 4650 Developmental Biology (Jenny Knight)
- k) MCDB 4777 Molecular Neurobiology (Kevin Jones)
- l) MCDB 4790 Experimental Embryology (Tin Tin Su)

### ***3. Sustainability***

Over the past year, we have visited many of the above courses to determine the degree to which they have maintained the modifications implemented with the SEI. From these observations and informal discussions with faculty, we are pleased to report that most of the changes implemented under the SEI have been maintained and many have been improved.

Faculty continue to use and renovate the extensive learning goals written for courses in our core series. Most faculty routinely use in-class clicker questions and problem-solving exercises, and the IMCA and GCA concept inventories are administered each semester on a pre-post basis to their respective classes. Overall, undergraduate education has gained an increasingly prominent position within departmental dialogue, and we are optimistic that our future work will continue to expand and enhance this dialogue.

## **C. Development of a Capstone Assessment tool for MCDB majors**

Previous discussions with MCDB faculty and the departmental Undergraduate Committee (UGCOM) led to an agreement that the best way to sustain and improve research-based teaching in our core courses would be to develop an assessment tool to monitor if our students are graduating with the knowledge and skills that the department values as essential. Administered each year to seniors and intended to measure students' ability to integrate and apply their knowledge, this "capstone" assessment would direct the attention of the faculty toward specific areas of difficulty and help shape our curriculum and teaching. Coupled with instituting a process for periodic review and updating of core course learning goals, this should ensure that core courses are adequately addressing the overall learning goals of the program.

The assessment is aimed at probing higher-level cognitive understanding of central concepts in biology, and consists of 18 multiple true/false questions. The assessment was designed through the following steps:

*Step 1:* Identify major concepts in biology and draft a set of related learning goals. Our learning goals are the product of roughly 20 faculty interviews, extensive textbook review, and student group discussions. Our final learning goals are framed within the core competencies recommended by the Vision & Change in Biology national report.

*Step 2:* Collect student thinking related to learning goals. For each concept, we drafted an open-ended question to probe student thinking and conducted interviews with 7-12 students per question.

*Step 3:* Draft forced-response questions based on student thinking. We elected to use the multiple T/F question format because it provides a much richer portrait of student thinking than simple multiple choice. We proceeded with validation efforts for 18 of these questions.

*Step 4:* Iteratively revise questions based on student and faculty interviews. For each question, we have conducted think-aloud interviews with 6-19 students and collected feedback from 7 faculty. We are presently working to conduct more student and faculty interviews and to bring questions into their final versions.

*Step 5:* Determine validity of final version through student interviews and faculty feedback. Once we have arrived at the final versions of each question, we will conduct a final set of student interviews to measure how well our items capture student reasoning. We will also send a survey to diverse faculty asking them to evaluate the content and appropriateness of each item.

*Step 6:* Administer pilot test to a large number of students and perform statistical analyses to determine evidence of validity and reliability.

In the Fall 2012 semester, we administered a complete draft of the Capstone to 337 advanced students at four institutions, including CU-Boulder. We used the results of this administration to revise the questions one last time before administering a final version of the assessment in Spring 2013 to 276 students at four institutions, including CU-Boulder. We are in the process of analyzing the resulting data, and we plan to begin drafting a manuscript summarizing this work in the coming weeks.

The final MBCA consists of 18 questions and 72 statements. Scored at the individual statement level, this assessment produces a wide range of student scores and statement difficulties, with advanced students achieving a 60% overall average. An internal reliability measure provides evidence that the MBCA yields reliable scores for the given subjects ( $\alpha = 0.78$ ).

Data from the MBCA indicate that advanced students have only partial understandings of many areas within molecular biology, evidenced by the low (20%) rate at which students correctly answer all four statements associated with a question. Furthermore, these students display incorrect conceptions that have been previously documented in introductory students,

suggesting that certain ideas persist despite multiple years of instruction. For example, advanced students demonstrate incorrect ideas related to genetic variation and molecular diffusion, and they struggle to dissect certain mechanistic processes, such as meiosis and translation. Statement discrimination values further identify the degree to which concepts are understood by high performing and low performing students.

#### **D. Faculty Presentations/Synergistic activities. Fall 2012/Spring 2013**

Jenny and Brian co-taught MCDB 5650-Teaching & Learning Seminar in spring 2013. There were 26 participants in the class, including undergraduates, graduate students, and postdocs from several different departments.

Jenny, Brian and Bill attended the SABER conference in July. Jenny and Brian gave talks; an additional poster was presented by post-grad Tanya Swarts. Jenny is the head of the abstract review committee for SABER.

Jenny and Bill led the National Academies and HHMI Mountain West Summer Institute on Undergraduate Biology Education at CU-Boulder in late July. Brian was a facilitator

Jenny gave invited talks at the University of Maine, University of Wyoming, and University of Richmond. She was part of a workshop at St. Mary's College in Maryland, and ran an HHMI-sponsored 2-day workshop called Entering Biology Education Research in Minneapolis.

Bill co-organized and co-led a 3-day professional development workshop (modeled after the NAS Summer Institutes) for college level biology instructors in Pune, India, and presented an invited seminar and workshop at the U. of New Mexico in Albuquerque.

Bill served on an NSF-HHMI panel to choose PULSE Fellows for the Vision and Change project, and continued to serve as Co-Chair of the National Academies Summer Institute program and its new umbrella organization, the National Academies Scientific Teaching Alliance (NASTA) and as a member of the Howard Hughes Medical Institute Science Education Board.

Jenny and Bill attended the Vision and Change meeting in Washington D.C. (August 2013).

Bill received the Viktor Hamburger Outstanding Educator Award from the Society for Developmental Biology and addressed an international meeting of the Society in Cancun, Mexico on the topic of undergraduate education in biology.

Brian received a CU Chancellor's iSTEM Award to develop a Scientific Teaching taxonomy. A manuscript is currently in preparation for this work.

Brian presented a job talk at University of Nebraska-Lincoln. He will be an Assistant Professor at UNL starting Fall 2014.

## **E. External funding:**

*NSF TUES II, Navigating from Vision to Change with Bio-MAPS, DUE-1322364; 2014-2017*

Jenny and Brian are co-PIs of a TUES II NSF project to coordinate the development of an overarching set of biology assessments aimed at monitoring student progress throughout biology majors. This set of assessments will be modeled after the MCDB capstone, but will extend across all years and feature questions from ecology, evolutionary biology, and physiology, in addition to molecular and cellular biology.

Additional funding (not directly related to SEI):

*NSF TUES I, Investigating Instructional Influences on the Productivity of Clicker Discussions, DUE 1140789; 2012-2014.* Jennifer Knight PI, Sarah Wise co-PI, Erin Furtak co-PI.

*NSF TUES III, Collaborative Research: Expanding a National Network for Automated Analysis of Constructed Response Assessments to Reveal Student Thinking in STEM 2013-2018.* Jennifer Knight, UC Boulder PI

*NSF WIDER, Collaborative Research: A Community of Enhanced Assessment Facilitates Reformed Teaching; 2013-2016.* Jennifer Knight, UC Boulder PI

*NSF TUES III (Pending)*

This collaboration with Yale, Cornell, and UConn would evaluate the impact of the Summer Institutes and Scientific Teaching on student achievement. Jennifer Knight, UC Boulder PI, Brian Couch UC Boulder co-PI

## **F. Goals for 2013-2014**

- 1) publish MCDB capstone paper. Continue to administer at CU and elsewhere, collect data and bring to faculty, disseminate, discuss, etc.
- 2) Draft report of findings for MCDB faculty. Work to incorporate our findings into the ongoing faculty curriculum dialogue. Facilitate adoption of departmental structures addressing the particular deficits seen in our students.
- 3) Develop BioMAPS assessments in collaboration with U. Washington and U. Maine. Use these to sustain changes already in place and upcoming at CU.

## **G. Publications of SEI-related research by SEI team members, 2012-2013**

- Knight JK, Wise SB, Southard KM (2013). Understanding clicker discussions: student reasoning and the impact of instructional cues. *CBE Life Sci. Educ. In Press*
- Knight, JK, Wood, WB, Smith, MK. (2013). What's downstream? A set of classroom exercises to help students understand recessive epistasis. *Journal of Biology and Microbiology Education. In press.*
- Prevost, LB, Knight, JK, Smith, MK, Urban-Lurain, M (2013) Student writing reveals their heterogeneous thinking about the origin of genetic variation in populations. In Proceedings of the National Association for Research in Science Teaching (NARST) annual conference. Rio Grande, Puerto Rico.
- Hoskinson, A-M, Caballero, MD, Knight JK (2013). How Can We Improve Problem-solving in Undergraduate Biology? Applying Lessons From 30 Years of Physics Education Research. *CBE Life Sci. Educ. 12: 153-161.*
- Smith, MK and Knight, JK (2012). Using the Genetics Concept Assessment to Document Persistent Conceptual Difficulties in Undergraduate Genetics Courses. *Genetics 191, 21–32.*
- Wood, WB and Tanner, KD (2012) The role of the lecturer as tutor: doing what effective tutors do in a large lecture class. *CBE-Life Sci. Educ. 11: 3-9.*  
[\(<http://www.lifescied.org/content/11/1/3.full>\)](http://www.lifescied.org/content/11/1/3.full)

## **VI. SEI in Physics**

### **A. Departmental structure of the SEI program**

The Physics Department was funded by SEI in Spring 2007. The intent of the proposal is to try to extend physics education research-based teaching methods into upper division physics curriculum for majors. Three Science Teaching Fellows have been hired by the department to support this work. Dr. Stephanie Chasteen started Fall 2007 and has focused on Electricity and Magnetism 1 (PHYS3310), with additional work in outreach beginning in 2009 and continuing to the present (see section on Outreach). Dr. Steve Goldhaber started Summer 2008, and has focused on Quantum Mechanics 1 (PHYS 3220), completing his position in the SEI in Summer 2010. Dr. Rachel Pepper started in Summer 2009 and continued Dr. Chasteen's work in PHYS3310 and began work in Mechanics and Mathematical Methods (PHYS2210) in 2010. Dr.

Pepper left the SEI in August 2011. Paul Beale served as Departmental Director of the SEI efforts until 2011, and the current Departmental Director is Steven Pollock.

Three faculty working groups have formed focusing on the three upper-division courses that are the focus of the SEI (PHYS3310 – Electricity and Magnetism 1, PHYS 3220 – Quantum Mechanics 1, and PHYS2210 – Mechanics and Mathematical Methods). The feedback of these groups of faculty has provided crucial direction for the STFs.

## B. Course-related efforts

### 1. Overview

A rotating instructor schedule for E&M I and Quantum I is intended to promote sustainability of course transformations by involving a variety of Physics Education Research (PER) faculty in developing the transformations, as well as engaging non-PER faculty in those transformations at a deep level. Co-teaching allows transfer of skills between instructors, a collaborative environment conducive to creating new teaching ideas and materials, as well as a reduced time-load for each instructor. This increases the opportunities to develop and implement new materials. As such, the following instruction schedule was set:

Spring 2008	E&M I – Steven Pollock (PER) Quantum I – Michael Dubson (PER)
Fall 2008	E&M I – Michael Dubson (PER) and Edward Kinney (non-PER) Quantum I – Steven Pollock (PER) and Oliver DeWolfe (non-PER)
Spring 2009	E&M I – Edward Kinney (non-PER) Quantum I – Oliver DeWolfe (non-PER)
Fall 2009	E&M I – Thomas Schibli (non-PER) Quantum I – Andreas Becker (non-PER)
Spring 2010	E&M I – Oliver DeWolfe (non-PER) Quantum I – Murray Holland (non-PER)

The SEI's formal involvement in instructor selection ended in Spring 2009. After that time, the assistant chair of the department assigned the course under his own jurisdiction, but accepted input from the SEI as to which instructors would be most likely to sustain the current reforms.

### 2. Electricity & Magnetism I (PHYS 3310)

Electricity & Magnetism 1 (E&M I), PHYS 3310, is required for completion of the BA in Physics, Astrophysics and the BS in Engineering Physics – about 80% of the course is populated by these majors. The remaining students are comprised of mathematics majors (11%), other natural science majors (4%), and other miscellaneous and undeclared majors (7%). Typically, this course is taken by juniors and seniors, and the enrollment is 30-50 students. Several faculty have taught this course – in the past five years. Recent instructors have been Anna Hasenfratz (taught twice), John Bohn, Uriel Nauenberg, Mihaly Horanyi, Charles Rogers, and Scott Parker. In about half the cases, the same instructor teaches PHYS 3310 and the second semester course, PHYS 3320.

Activities in E&M I include:

- a. Changes in course instruction

The course run in Spring 2008 by Steven Pollock was transformed to incorporate many pedagogical approaches aligned with research on learning and informed by information on student thinking about E&M that was gathered through observations and interviews in Fall 2007. Interactive lecture techniques were used in class, including clicker questions, kinesthetic, and white-boarding activities. In addition, homeworks for the class were reformed to explicitly include and require students to make more connections to the real world, practice more physicists' "habits of mind" such as examining behavior at limits and doing estimations, and more explanation of reasoning. Outside of class, biweekly group problem solving sessions were organized to focus on homework. Weekly tutorial activities were developed in order to give students an opportunity to work on some of the underlying conceptual ideas in E&M in a group setting. An optional weekly session where students worked through these tutorial activities was added to the course. The tutorial sessions have since been institutionalized as optional one-credit co-seminar courses which do not count towards the major.

This course has served as a model for the E&M course offered by Dubson/Kinney in Fall 2008, Kinney in Spring 2009, Schibli in Fall 2009, and deWolfe in Spring 2010. All instructors made heavy use of the clicker questions, tutorials, lecture notes, homework, and other activities developed for the course. In addition, the lists of student difficulties developed during the course of Spring 2008 has served as a guide for instructors at CU and elsewhere. The course was taught by Parker in Fall 2010, who referred to our course materials but did not implement the pedagogical techniques such as clickers or tutorials. The course is currently being taught by Horanyi in Spring 2011, who also referred to our course materials, and used clicker questions, student difficulties, and study sessions, but no tutorials. Horanyi taught the course again in Fall of 2011 and continued to use the materials above and offered the optional tutorials run by PER graduate student Bethany Wilcox. Andreas Becker taught the course in Spring 2012 and reported referring consistently to the available course materials and used clickers, tutorials, study sessions, and some of the modified homework. The Fall of 2012 was taught by Uriel Nauenberg who did not use or refer to our materials or Griffith's but rather used his own notes.

In the Spring of 2013, Pollock again had the course and, in addition to using all of the available materials, including online pre-flights, he moved the tutorials into the class. To do this, the original tutorials were considerably abbreviated and often split into several shorter 10-20 minute activities given in lecture.

#### b. Course Materials

In Fall and Summer of 2008 a set of course materials were developed and organized by Steven Pollock and Stephanie Chasteen. All materials were based on detailed student interviews (Fall 2007 through Fall 2008) as well as detailed observations of lecture and group work. All later instructors (Dubson, Kinney, Schibli) improved upon and/or annotated these materials, resulting in a robust and diverse set of materials. These materials include:

- COURSE CALENDAR, including activities and covered material
- HANDOUTS AND POSTERS, such as a detailed "crib sheet" for the course and posters of Maxwell's Equations

- STUDENT DIFFICULTIES pertinent to each chapter of the textbook, as compiled by observations in student interviews, homework help sessions, written homework, and tutorials over the course of 2 semesters.
- LEARNING GOALS for the course overall, and for individual chapters, developed from meetings and interviews with the faculty working group
- CONCEPTTESTS\*\* (a.k.a. ‘clicker questions’) for individual chapters. Several hundred questions have been developed in all, annotated with class responses and instructor observations.
- LECTURE NOTES\*\*
- CLASS ACTIVITIES: Lists and descriptions of interactive activities for each topic area in the course, including lecture demos, kinesthetic activities, whiteboards, and group work.
- HOMEWORK ASSIGNMENTS\*\* and solutions, and detailed observations of student performance for assessment of the value of those homework questions
- HOMEWORK BANKS of other potentially valuable homework questions which were not used in the course.
- TUTORIALS\*\* developed by undergraduate Darren Tarshis, Stephanie Chasteen, and Steven Pollock, revised by Dubson and Kinney, and tutorials PRE-TESTS developed by Steven Pollock and Rachel Pepper.
- PUBLICATIONS on this work, including four posters and five papers.
- TRADITIONAL ASSESSMENTS including midterm and final exams
- CONCEPTUAL ASSESSMENT. The Colorado Upper-Division Electrostatics (CUE) diagnostic was developed and administered at several universities, see below.

The course archive materials were made available online on the website ([per.colorado.edu/Electrostatics](http://per.colorado.edu/Electrostatics)), on our website ([http://www.colorado.edu/sei/departments/physics\\_3310.htm](http://www.colorado.edu/sei/departments/physics_3310.htm)), at the Physical Science Resource Center for the AAPT (<http://www.compadre.org/psrc/items/detail.cfm?ID=7891>), and promoted at the AAPT and PERC meetings and met with considerable interest. A total of 53 external faculty have indicated an interest in using the materials, and to date we know of at least 17 who have done so. This enthusiastic response to our materials is a strong indicator of the need within the physics community for research-based materials for teaching upper-division E&M. We developed a preliminary survey of users of the materials, which indicates that most instructors became aware of our materials through research conferences and publications, though we are also aware of some who have located our work through internet search engines that directed them to our website. That survey suggests that most users are new instructors, seeking pedagogical guidance. Thus, these materials represent a valuable opportunity to impact the next generation of college instructors such that they develop interactive teaching strategies based on research.

Another important aspect to disseminating and sustaining the course transformations is providing an organizational structure that is easily navigated and lends itself to a-la carte use of individual resources, so that instructors may tailor their use of the materials to their particular class and teaching style. Overall reactions to the organization of the materials – by instructors at CU and outside -- was positive. The course archive system has recently been recommended for adoption among other SEI departments, and a document detailing the organizational structure and rationale was created to assist other departments in emulating it. The [per.colorado.edu/Electrostatics](http://per.colorado.edu/Electrostatics) site was put together in the Spring and Summer of 2012 to provide a comprehensive archive of our material. The interface helps to facilitate

browsing the materials quickly and easily by category or by topic. This makes it even easier for users to choose individual resources a-la carte. The new site is also monitored with Google Analytics allowing us to gather detailed information on the frequency and location of users as well as information on how they interact with the site.

The six CU instructors were interviewed individually for one hour, twice during the course of each semester of instruction up to 2011. This allowed us to assess the efficacy of our method of course transformation, sustainability of the reforms, and gather feedback on the organization of course materials.

### c. Colorado Upper-Division Electrostatics (CUE) Assessment

The CUE is a conceptual assessment that examines student learning in aspects of the course not typically tapped in traditional (exam) assessments. This exam enables CU and other institutions to assess the impact of different methods of instruction on student understanding in this course, providing an independent measure of student learning for comparison across courses and over time. It also provides a window into student thinking on topics of the course, by analysis of student answers and patterns of responses.

The CUE is an open-ended assessment developed based on faculty learning goals and common student difficulties. It is a 17-question test consisting of written explanations, conceptual reasoning, sketching, graphing, and a few multiple choice questions. A pre-test was developed based on a reasonable subset of the post-test. The pre-test takes 20 minutes of in-class time and the post-test takes 50 minutes of in-class time.

A detailed grading rubric was developed, along with classification of common student errors. Two independent graders used the rubric to score a set of 36 student exams. Inter-rater reliability was very high, with an average score difference of just 1.4%. Graders agree within 10% of the overall CUE score on about 10% of the exams. CUE score is significantly correlated with the student's overall score in the course based on traditional measures such as homework and exams. It shows good item discrimination, as indicated by high correlation of individual test items with the overall test score. Cronbach's  $\alpha$  for the items on the CUE is 0.82, indicating strong internal statistical reliability. The CUE has been validated through think-aloud interviews and faculty feedback – that work is ongoing, and a publication on the CUE is in development.

The CUE post-test was given to 10 semesters of E&M I students – Fall 2007 (taught traditionally: STND), and the 5-semesters of transformed (PER) courses: Spring 2008 (the first semester of transformations), Fall 2008, Spring 2009, Fall 2009, Spring 2010 (successive iterations of transformations), Spring 2011 (semi-transformed), Fall 2011(semi-transformed), Spring 2012 (transformed), and Fall 2012 (taught traditionally). The CUE post-test was also given in several external institutions, and graded for nine courses in six outside institutions. In Fall of 2011 and 2012, the CUE was also given to 16 graduate students from CU. All courses with CUE scores above the mean used interactive engagement techniques, such as clickers. The CUE post-test scores of students in courses using PER-based instructional techniques are statistically significantly higher than all the courses using a standard lecture format at CU and elsewhere (with the exception of Non-

CU-STND2, which matches the lower-scoring PER-based courses). Taking each student from the first 6 CU courses and the Non-CU courses as a data point, the average CUE score is higher in PER courses ( $57 \pm 1.3\%$ ) than in STND courses ( $44 \pm 1.6\% p < 0.001$ ). Taking each of the 10 CU courses and the Non-CU courses as a data point, the same result holds ( $56 \pm 4\%$  PER vs.  $45 \pm 4\%$  STND). If the CUE were a graded exam, this would be comparable to a gain of two letter grades. The graduate students averaged a  $69 \pm 4\%$ .

This provides some of the first evidence that interactive engagement techniques improve student learning, even at the upper division. Overall, these results suggest that the interactive techniques were consistently successful, over 8 semesters at CU and at three external institutions, in improving students' facility with the concepts and problem-solving methods of junior E&M. As the CUE was developed based on the learning goals (Figure 1), this suggests that we achieved some measure of success in our aim of supporting the cognitive skills of developing physicists. Examination of the demographics of individual courses shows that these results cannot be easily explained by factors related to the students or instructors, such as incoming GPA, incoming score on the introductory conceptual assessment (BEMA), or instructor experience. Indeed, some of the highest scores on the CUE occur in classes where the instructor had no prior experience teaching the course. The robustness of these results over time, across instructors, and across institution also suggests that the course transformation effects can be sustained from instructor to instructor and across institutions.

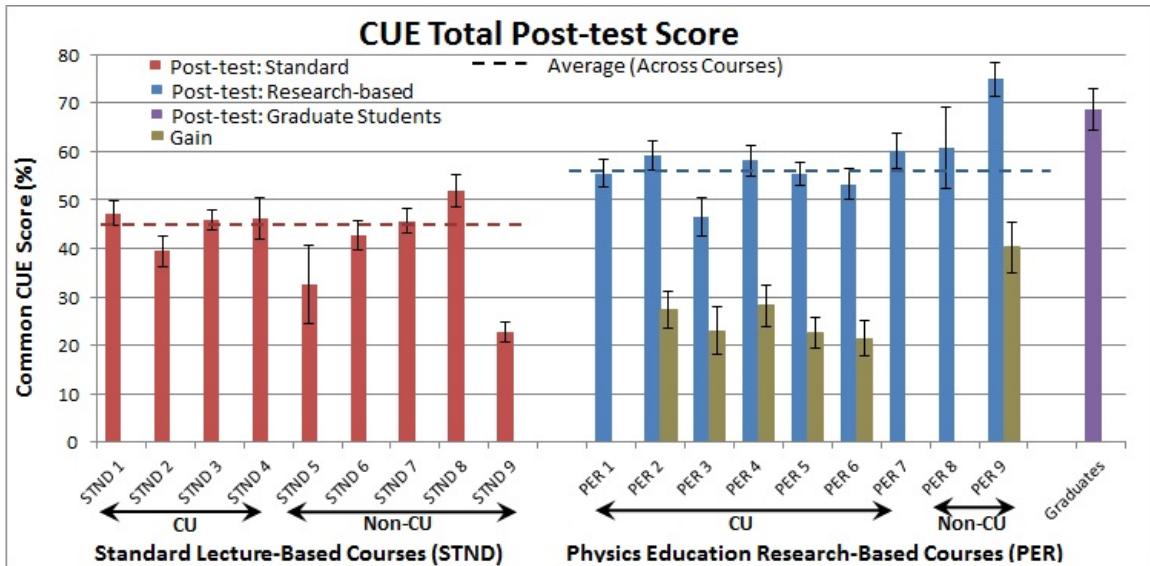


Figure 1. CUE scores across institutions for N=515 students. "Post-test" represents course average score (% correct) for the subset of CUE questions given in common across all exams (88 out of 118 possible points). "Gain" represents the course average (out of 100%) for the difference between the pre-test (60 points) and the matched subset of the post-test (i.e., 60 points). Number of respondents varies from 5 to 138 in a given course. PER courses are not listed sequentially (i.e., PER-1 is not the first semester of the transformation). Error bars represent 1 standard error of the mean.

Scores on the pre-test are consistently low (30%), except for the scores for student at a private liberal arts institution (C-IE in the figure above), who were taught using the materials developed in this project. Thus, the CUE can differentiate between students with different levels of preparation, and students using our materials experience similar levels of learning gains on the CUE from pre- to post-test, regardless of initial levels of preparation. The CUE is also capable of differentiating between different types of course instruction.

Beginning in Fall 2012 and responding to a call from faculty who attended a working group on E&M II transformations, Bethany Wilcox began working to produce a multiple-choice version of the CUE pre- and post-tests. The multiple-choice pre-test was given online to all students in the Spring 2013 semester. The post-test was given in class with half the students taking the multiple-choice version and half taking the open-ended version.

#### d. Course Data

The first 6 courses at CU were compared on several measures to assess the impact of the transformations. Students in these courses were, for the most part, similar in terms of incoming GPA, gender, and major. Complete comparisons across all courses are reported below.

	PER-A	PER-B	PER-C	PER-D	PER-E	STND
Pedagogy	Research-based transformations					Lecture
Instructor	PER1 + Non-PER1	Non-PER2	PER2	Non-PER2	Non-PER3	Non-PER4
Course N	48	37	22	56	46	41
Major (%)	PHYS EPEN	48 27	49 22	50 36	55 30	57 20
Females (% of class)	27	26	25	16	11	25
Ave lecture attendance (% of class)	86	77	94	77	76	73
Ave students attending a tutorial (% of class)	30	42	44	37	38	N/A
Ave students attending a help session (% of class)	30	Unknown	58	Unknown	Unknown	Unknown
FCQ	Instructor Course	85 80	97 90	98 92	95 87	97 85
<b>Demographics</b>						
Cumulative GPA	3.1	3.1	3.1	3.2	3.2	3.1
Physics GPA	3.0	3.1	3.0	3.2	2.9	2.9
BEMA	Post-102 Post-301	61 66	58 63	69 71	58 63	60 N/A

Table 1: Course demographics. Courses involved in this study, not in chronological order. PER 1 and 2 are different PER faculty. Non-PER 1-4 are different non-PER faculty. “EPEN” = Engineering Physics, and “PHYS” = Physics. Attendance is an average of the attendance on the days that the FCQ and CUE were administered, and the clicker attendance scores (where applicable). Students who missed two exams and/or did not take the final exam were excluded from study, and students who took the course more than once (without failing/dropping) were included only in the first enrollment. “FCQ” = Faculty Course Questionnaire given at the end of the semester, given out of 100%. “Instructor” = “Rate this instructor compared to all your other university instructors.” “Course” = “Rate this course compared to all your other university courses.” Cumulative and Physics GPA are calculated prior to the start of PHYS301. “BEMA” = Basic Electricity and Magnetism Assessment, given as a Post-test after introductory physics (PHYS 1120) and Junior E&M I (PHYS 3310).

We gave some exam problems in common among the courses. The course transformations did not hurt students’ ability to perform mathematical calculations (e.g., separation of variables, direct integration), but they did not particularly improve this skill, as measured by these traditional exam problems. However, the new course approach did appear to improve students’ skills in two key areas on exams: The ability to provide reasoning behind the answer, and to properly identify the most suitable method for solving a particular problem.

Overall, students liked the PER-based courses, as judged by end of term attitude surveys. Students engaged more fully in the PER-based courses, as judged by improved attendance at lecture, attendance at optional tutorial and homework help sessions, and time spent on homework. However, in one course (PER-A), student attitude data was less favorable. It appeared that this instructor may have paid less attention to student difficulties at the junior level, and students did not feel that lecture prepared them for challenging homework. So, these course materials are not turn-key, and implementing the pedagogical approach requires substantial instructor involvement and pedagogical sophistication.

Lecture, clicker questions, and tutorials were most popular among students. Students (with the exception of PER-1) felt that the lecture was well-connected to homework and provided adequate instruction in mathematical techniques. While whiteboards were poorly rated by students, we have reason to believe that this tool could be more valuable if implementation were optimized for effectiveness. No clear effect of clicker questions or lecture could be discerned. Tutorials – in addition to being favorably rated by students – also contribute positively to student learning (as measured by the conceptual assessment, the CUE), even when background variables are taken into account by multiple regression. Judging from student comments, we successfully provided students support in honing their problem-solving skills through carefully designed homework and additional opportunities to interact with one another and instructors in tutorials and help sessions.

Students are not the only participants positively affected by the course. Several aspects of the course – particularly clickers, tutorials, and homework help sessions – provide a valuable opportunity for instructors to gain insight into student thinking. These course elements provided opportunities for instructors to discuss with and listen to students, providing a window into student thinking. This formative assessment is not typically

available in a lecture-based course, and allows the instructor to better match the course to the students. One (non-PER) instructor who used the materials contrasted this approach with a traditional course: “What you tend to do teaching in the traditional way is, there are three or four students, maybe only one sometimes, who’s on top of everything, answers all the questions, is smiling, is happy, and you get a rapport with the students who talk to you and you feel like things are going great.” The developed materials (clicker questions, tutorials, and homework help sessions), he claimed, help him to “talk more directly to and hear, listen to, the average student.” These techniques also help to change the culture of the classroom. One instructor (teaching a similarly transformed quantum mechanics course) indicated that clickers helped to frame the class as an interactive environment, essentially breaking the ice so that it was easier to generate conversation in the class. One non-trivial outcome is that the instructors were very positive about the experience, which can result in dissemination and sustainability of the transformations: “I enjoyed it immensely,” reported one (non-PER) instructor. “Next time you need somebody else to do it, don’t hesitate to call.”

#### e. Physics graduate survey

In order to gather more information about student perceptions of our upper-division courses, over 250 alumni of the physics program were surveyed about their current careers as well as their impressions of the CU physics program. About 25% (67 respondents) completed the survey, most of whom had graduated between 2003 and 2007. Results from the survey are shown below:

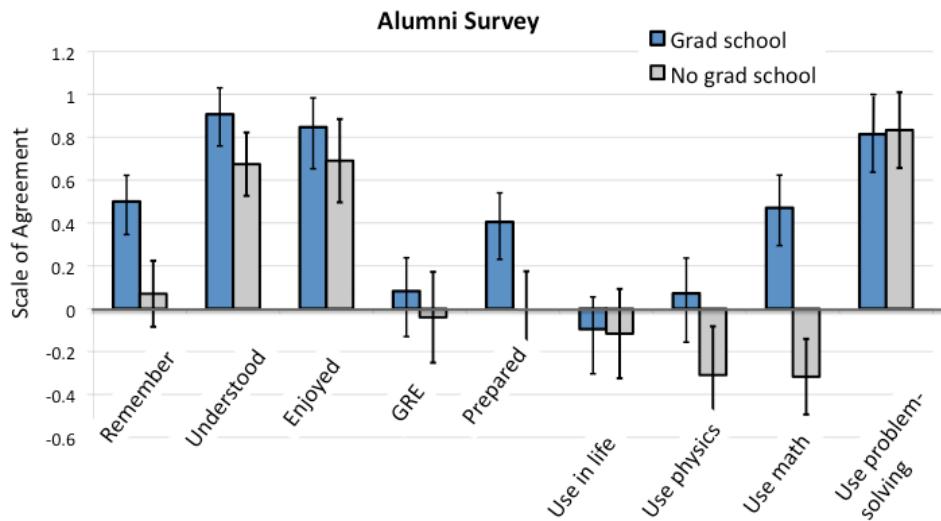


Figure 2. Alumni survey results. Alumni were asked to answer on the basis of their graduate degree program (if ever enrolled) or current job (if never enrolled in graduate school). Questions were rated on a scale of 1-5 (strongly disagree to strongly agree), and then converted to an scale of -2 (strongly disagree) to +2 (strongly agree) by subtracting 3 from the overall average. Questions were as follows: (1) I remember what I learned in PHYS301, (2) I understood the material in PHYS301, (3) I enjoyed PHYS301, (4) PHYS301 prepared me well to take the GRE (if applicable), (5) PHYS301 prepared me

well for my job or graduate school, (6) I use something I learned in PHYS301 in my life outside of my primary job or graduate research, (7), I use the physics I learned in PHYS301 in my primary job or graduate research, (8) I use the math I learned in PHYS301 in my primary job or graduate research, (9) I use the problem-solving techniques or approaches that I learned in PHYS301 in my primary job or graduate research.

Graduates were employed in a wide variety of jobs, especially in industry and finance. Fewer continued on to graduate school than had been expected, with a total of 35% never having attended graduate school. Many recurrent themes were noted with respect to upper-division E&M and Quantum, such as an appreciation of the intellectual challenge of the course, but a dissatisfaction with the focus on mathematics at the expense of conceptual understanding, and a disconnect from real-world examples. Alumni who continued on to graduate school found the material of both E&M and Quantum to be more relevant to their careers and lives. These results provided useful information about our graduates and how we might serve their needs through these course transformations. In particular, the following questions were posed to the undergraduate committee, based on these results: (1) Are we meeting the needs of those who do not attend graduate school? (2) Are we focused appropriately on problem-solving and critical thinking? (3) How do we increase continuity in two-semester courses? (4) How can we support supplemental activities from instructors? And (5) Can and should we increase the conceptual focus in upper-division?

### ***3. Quantum Mechanics I (PHYS 3220)***

Quantum Mechanics 1, PHYS 3220, is required for completion of the BA in Physics and Astrophysics as well as for the BS in Engineering Physics – about 72% of the course is populated by these majors. The remaining students are comprised of mathematics majors (10%), other natural science majors (2%), non-physics engineering majors (11%) and other miscellaneous and undeclared majors (5%). Typically, this course is taken by juniors and seniors, and the enrollment is 30-60 students. Several faculty have taught this course in the past six years. Recent instructors have been Eric Zimmerman, James Shepard, John Price, (twice), Tom DeGrand (twice), Kevin Stenson, Oliver DeWolfe, Steven Pollock, and Andreas Becker. For the Fall 2008 semester, the course was team taught by Steven Pollock and Oliver DeWolfe. In six of the last twelve semesters, the same instructor taught PHYS 3220 and the second semester course, PHYS 4410.

In Spring 2009 Oliver DeWolfe taught the course, using the reforms which were developed over the two previous semesters. In Fall 2009, the course was taught by Andreas Becker. While he took a different approach to the material, he used many of the reformed course materials and also developed new materials to support his curricular approach. The course is being taught in the Spring 2010 semester by Murray Holland who is using mainly the approach and the materials developed by Pollock and DeWolfe.

Activities in Quantum I include:

- a. The Quantum Mechanics Assessment Tool (QMAT)

With the assistance of several faculty members, Steve Goldhaber has developed a post-test assessment tool based on learning goals, and has performed preliminary validation of

the instrument through interviews with faculty and students. During development of the test, a total of 21 students were videotaped while they took versions of the test and explained their reasoning out loud. A total of 27 students took the test as an in-class diagnostic exam near the end of the Fall 2008 semester. As an incentive to take the test seriously, students were offered individual feedback on their strengths and weaknesses in areas such as quantum mechanics formalism and separation of variables. The test was revised and administered in both the Spring 2009 and Fall 2009 semesters. In all, a total of 89 CU quantum I students have taken the assessment. In addition, near the end of the Fall 2009 semester, the QMAT was administered at four outside institutions to a total of 113 students.

This instrument will not serve as a pre-test, since most students have not previously been exposed to much of the content of the course.

#### b. Course Materials

All materials generated for PHYS 3220 will be available to future faculty who teach the course. One resource many have requested is a bank of homework and exam problems that they can draw upon. These questions have been chosen and developed to align with the learning goals for the course, allowing faculty to provide students with assignments designed to develop a wider variety of student skills than those easily created by a single faculty member. Similarly, the concept/clicker questions developed for the course are provided as a ready-to-use resource for faculty. Steve Goldhaber has assembled a bank of exam questions given in PHYS 3220 over the last decade. Concept test questions developed by Mike Dubson, Steve Pollock, Oliver DeWolfe and Steve Goldhaber have been gathered and mostly organized by type of material. Currently, the course archive consists of:

- COURSE CALENDAR: sample course calendars
- STUDENT DIFFICULTIES organized by topic, as compiled from the literature and from observations in student interviews, homework help sessions, written homework, and tutorials over the course of 3 semesters.
- LEARNING GOALS: The faculty consensus goals developed from meetings and interviews with the faculty working group. These goals include overall course goals as well as goals for specific topics in quantum mechanics.
- CONCEPTTESTS (a.k.a. ‘clicker questions’) organized roughly by the chapters in Griffiths’ textbook. Several hundred questions have been developed in all, annotated with class responses and instructor observations.
- LECTURE NOTES written by Steven Pollock and Michael Dubson.
- HOMEWORK ASSIGNMENTS: Significant work has gone into homework questions which not only develop computational proficiency with the new material but which also require students to engage in conceptual thinking and to make sense of their answers. The archive contains the homework assignments and solutions along with detailed observations of student performance for assessment of the value of those homework questions.
- TUTORIALS : Eight quantum tutorials developed by Steve Goldhaber, and Steven Pollock.
- PUBLICATIONS on this work, including a poster and two papers.
- TRADITIONAL ASSESSMENTS including midterms and final exams.

- CONCEPTUAL ASSESSMENT. The Quantum Mechanics Assessment Tool (QMAT) diagnostic was developed and administered at several universities, see above.

The course archive materials were made available online and promoted at the AAPT and PERC meetings and met with considerable interest. A total of 23 faculty have indicated an interest in using the materials, and to date we know of at least 4 who have done so with more planning on using them in the near future. In addition, some of the materials are being incorporated into a senior physical chemistry class in the chemistry department at CU.

#### ***4. Classical Mechanics and Math Methods I (PHYS 2210)***

Classical Mechanics and Math Methods 1, PHYS 2210, is required for completion of the BA in Physics or Astrophysics and for the BS in Engineering Physics – these majors populate about 79% of the course. The remaining students are usually other natural science majors. Typically, sophomores take this course as their 4th course in the physics sequence, and the enrollment is 40-70 students. Several faculty have taught this course in the past six years. Recent instructors have been John Wahr, Shijie Zhong, Bill Ford, Meredith Betterton, and Anna Hazenfratz. In 2010, no intervention was made in the choice of faculty teaching PHYS 2210 – John Wahr, who has taught the course many time taught in the spring and Alysia Marino, a new faculty member taught in the fall.

Dr. Pepper sat in on both John Wahr and Alysia Marino's courses. In spring of 2010, though a transformed version of the course was not yet prepared, Professor Marino independently decided to implement a number of PER-based techniques with help from Dr. Pepper. These techniques included the clicker questions in class, Intermediate Mechanics Tutorials (available from the University of Maine) in class, homework help sessions, and some conceptual homework and exam questions. The official SEI course transformation of PHYS 2210 started in the spring of 2011 with Steve Pollock and Ana Maria Rey co-teaching the course. Transformation of the course has continued through the spring of 2013 with Dr. Marcos Caballero facilitating the development and refinement of course materials. Instructors teaching a transformed version of this course now include Steve Pollock, Alysia Marino, and John Bohn. Kyle McElroy is teaching a minimally transformed version of the course this semester (spring 2013) because enrollment swelled to 90+ students requiring the use of a temporary space. McElroy is the sole instructor for the course; Dr. Caballero observes the course weekly.

Activities in PHYS 2210 include:

- a. Creation of learning goals

A faculty working group facilitated by Dr. Pepper created both broad-scale and topical learning goals for PHYS 2210. The goals are listed online ([http://per.colorado.edu/ClassicalMechanics/learning\\_goals.html](http://per.colorado.edu/ClassicalMechanics/learning_goals.html))

- b. The Colorado Classical Mechanics/Math Methods Instrument (CCMI)

With the assistance of several faculty members, Dr. Pepper began development of both a pre and post-test assessment tool based on the most important learning goals selected by the faculty working group. Initially, the instrument contained 15 questions split into two exams with roughly 10 questions appearing on each version. Through discussions with faculty, Dr. Caballero culled the exam to 11 questions. The CCMI has been administered as a pre- and post-test each semester since the transformation began in spring 2011.

Dr. Caballero conducted interviews with 8 students who had recently completed PHYS 2210 to refine the wording of each of the 11 questions. Data from interviews also suggested why students answered question in particular ways. The locally validated instrument was then administered at CU and at 5 partner institutions (Table below) who are not presently using course materials developed at CU.

Institution	Type
1	Private, liberal arts college
2	Private, liberal arts college
3	Public, research university (BS granting)
4	Public, research university (PhD granting)
5	Prestigious, private, liberal arts college
6	Public, research university (PhD granting)

Feedback from instructors teaching outside of CU was overwhelmingly positive. Instructors found value in the instrument and how their students responded to it. Even instructors teaching a single-semester classical mechanics course believed the instrument was valuable. According to these instructors, the CCMI covers the core concepts they want students to leave their course knowing. However, 2 questions were deemed inappropriate for most partner institutions; most instructors do not teach a combined classical mechanics and math methods course. The 2 questions were moved to the end of the instrument and are now optional. The score that students earn on the questions does not contribute to official calculated score, and instructors may choose to neglect them completely. The finalized version of the instrument was first given in fall of 2012.

Scoring the assessment reliably has been the focus of this semester (spring 2013). Developing a rubric that instructors can use easily with no training has produced a simple rubric that evaluates mastery. Most questions are graded for correctness only with some partial credit assigned for very small mistakes. This reliability of this rubric is currently being established using student work from the fall 2012 version of the CCMI.

Capturing the nuances of student work is equally important, but is not the role of a grading rubric. A parallel coding rubric will be developed for researchers interested in capturing these nuances. Dr. Caballero plans to complete the development of the CCMI in the next year including establishing its reliability. Future work will use the CCMI to evaluate instructional methods at CU and elsewhere.

### b. Course Materials

Between spring 2011 and summer 2012, a set of course materials were developed and organized by Alycia Marino, Steven Pollock, and Marcos Caballero. All materials were based on detailed student interviews as well as detailed observations of lecture and group work. These materials include:

- COURSE CALENDAR, including activities and covered material
- STUDENT DIFFICULTIES pertinent to each chapter of the textbook, as compiled by observations in student interviews, homework help sessions, written homework, and tutorials over the course of 4 semesters.
- LEARNING GOALS for the course overall, and for individual chapters, developed from meetings and interviews with the faculty working group
- CONCEPTTESTS (a.k.a. ‘clicker questions’) for individual chapters. A few hundred questions have been developed in all, annotated with class responses and instructor observations.
- LECTURE NOTES
- CLASS ACTIVITIES: Lists and descriptions of interactive activities for each topic area in the course, including lecture demos, kinesthetic activities, whiteboards, and group work.
- HOMEWORK ASSIGNMENTS and solutions, and detailed observations of student performance for assessment of the value of those homework questions. Computational homework questions for which students use Mathematica are also included.
- HOMEWORK BANKS of other potentially valuable homework questions that were not used in the course.
- TUTORIALS developed by Rachel Pepper, Marcos Caballero, Alycia Marino and Steven Pollock.
- TRADITIONAL ASSESSMENTS including midterm and final exams
- CONCEPTUAL ASSESSMENT. The Colorado Classical Mechanics/Math Methods Instrument (CCMI) diagnostic was developed and administered at several universities, see below.

Dissemination of these materials is facilitated through course materials website (<http://per.colorado.edu/ClassicalMechanics/>) developed by Dr. Caballero and now used for E&M 1, E&M 2, and Quantum Mechanics. The website simplifies the navigation of course materials, allows incremental and full downloads, and tracks web traffic automatically. Since the launch of this website in summer 2012, it has had 839 unique visitors and 45 visitors have downloaded the entire archive.

## 5. *Optics and Modern Physics Laboratory (PHYS 3340/4430)*

The Optics and Modern Physics Laboratory, PHYS 3340/4430, is the last of four lab courses in the undergraduate physics curriculum. The course is usually taken by Juniors and Seniors. The course is an elective for Physics majors, and satisfies a required research experience for Engineering Physics majors. Typically about 25 students take the course per year. Typically about 70% are Engineering Physics, and about 30% are physics majors. The course covers experimental techniques in optics and modern physics.

In response to significant faculty interest, the course is being redesigned by Professor Heather Lewandowski (Physics/JILA) and a post-doctoral researcher, Ben Zwickl. The SEI has contributed support for the first stages of the course redesign. Two years of NSF support (Heather Lewandowski, PI) will begin in the summer of 2011. The grant is provided through the Transforming Undergraduate Education in STEM (TUES) program. The funding is for a research-based redesign of the CU upper-division physics lab courses.

Lab courses are under scrutiny because they require expensive equipment, have low student teacher ratios, take lots of time, and don't always have clear education value. This project has as major goals to establish clear learning objectives, assessments, new lab guides, and a better sense of the role of lab courses in the curriculum. Faculty, students, and industry employers will all provide input as we redesign the course.

Background research and preliminary work on learning goals took place in November and December of 2010. A list of activities and goals for 2011 are listed in the section on goals below.

### **C. Departmental faculty development and involvement in SEI efforts.**

#### **1. E&M I (PHYS 3310) working group**

The faculty working group for E&MI was convened twice this year, to present results from the alumni survey and the course transformations. The results of the alumni survey were also presented at the faculty meeting at large, and distributed to every faculty member. Some members of the faculty working group for 3310 were consulted individually as the CUE post-test was revised.

STF's met with the instructors for 3310 weekly, to provide ongoing course support and collectively reflect on observations and outcomes related to the course -- Dr. Chasteen with Dr. Kinney in Spring 2009, and Dr. Pepper and Dr. Chasteen with Professor Schibli in Fall 2009.

Dr. Chasteen, Dr. Goldhaber and Dr. Pepper interviewed the five faculty (DeWolfe, Pollock, Dubson, Kinney and Schibli) on the process of the course transformations. These results are in the process of being reviewed and compiled, potentially for publication.

Dr. Chasteen gathered some materials for the second semester of the course (E&M II: PHYS 3320), and discussed course pedagogy with Professor Charles Rogers. After that course, Dr. Chasteen discussed outcomes and pedagogy with Professor Rogers, and shared it with the next instructor, Professor Kinney.

Dr. Chasteen discussed the implementation of tutorials (developed at another university) in sophomore-level Mechanics with Professor Betterton – she and Dr. Pollock assisted Dr. Betterton in implementing two of those tutorials in class.

#### **2. Quantum Mechanics I (PHYS 3220) working group**

The faculty working group for quantum mechanics I meet in April to review the QMAT before the administration at the end of the semester. Based on feedback received at this meeting, several minor changes were made and the final set of questions was selected.

### 3. Classical Mechanics/Math Methods I (PHYS 2210) working group

Dr. Pepper recruited a faculty working group and facilitated 3 meetings over the summer of 2010 and 4 meetings in the fall of 2010. In the summer, the faculty agreed on what topics the 2210/3210 course sequence would cover, and in which semester each topic would fall. Broad course-scale learning goals were also determined. In the fall, topical learning goals were discussed and prioritized for inclusion in a conceptual post assessment. Some diagnostic questions were written and improved with help from the faculty working group. Nineteen faculty (4 of whom were PER faculty) participated in these working group meetings with an average attendance of 9 faculty members at each meeting. Each faculty member who participated attended on average about half of the meetings.

Prior to the creation of the faculty working group and its meetings, Dr. Pepper interviewed several previous instructors of PHYS 2210 and PHYS 3210, including some faculty members who did not later participate in the working group meetings.

### 4. Optics and Modern Physics Lab (PHYS 3340/4430) working group

Professor Heather Lewandowski (Physics/JILA) has been the driving force behind this project. She is motivated by personal experience teaching the lab class, and has a strong desire to create outstanding lab classes at CU. She has successfully applied for NSF funding through the TUES program and is collaborating with the Physics Education Research Group in addition to leading a lab in Atomic Molecular and Optical Physics.

Ben Zwickl, the post-doctoral researcher on the project, will involve faculty in the redesign of the Optics and Modern Physics Lab through individual interviews, and later through faculty working groups. It is expected about 15 individual interviews will be conducted and a faculty working group of about 6 will be established in the spring of 2011.

### 5. Faculty impact interviews

The four CU instructors from the Fall 2008 and Spring 2009 semesters were interviewed individually for one hour, twice during the course of each semester of instruction. This allowed us to assess the efficacy of our method of course transformation, sustainability of the reforms, and gather feedback on the organization of course materials. These interviews will be the subject of future analysis, but key results include:

- The STF's involvement in the course (through discussions and feedback) is cited as being very helpful, underlining the utility of a dedicated postdoc in course transformations
- The availability of transformed course materials appears to promote greater interactivity in instructors' pedagogy during the course, XXX
- Co-teaching with an experienced PER instructor appears to be transformative for non-PER instructors, who report learning a great deal from the experience. Instructors using the materials, without co-teaching, appear to receive less educational benefit from teaching the course.
- Both PER and non-PER co-teachers reported benefits from co-teaching and enjoyed it immensely as a professional experience. Non-PER co-teachers learned a great deal from the experience, such as learning to write clicker questions that were more integrated with lecture, and how to facilitate productive student conversation in the classroom.
- Instructors found course materials to be very useful (in particular student difficulties, the tutorials and clicker questions), and, for the most part, would not have had the time to

- develop these during course instruction. Overwhelmingly, they would use the course materials if teaching the course again.
- Various recommendations were given for organization of course materials to be user-friendly and easy to navigate
  - Course instruction with the materials appears to take more time (not less) due to the increase in the number of materials to reference prior to planning lecture, though opinions vary by instructor.

#### **D. Goals for 2013-2014**

1. Goals for work on 3310:
  - Continue to support and promote the use of these materials at CU and other institutions by maintaining the online interface.
  - Analyze the first semester of data on the multiple-choice CUE and write this up for the 2013 Physics Education Research Conference.
2. Goals for work on 3220:
  - Analyze results from three administrations of the QMAT at the University of Colorado as well as those from four outside institutions. Use these results along with results from exams, homework assignments and tutorial pre-and-post tests to summarize our findings about student learning difficulties in upper-division quantum mechanics.
  - Conduct inter-rater reliability testing in order to refine the rubric and to produce a QMAT instructor guide so that outside administrators can reliably assess the performance of their students.
3. Goals for work on 2010:

Should funding continue for this transformation project, the SEI should:

- Continue to run transformed versions of PHYS 2210, including creating new clicker questions, homework questions, in-class activities/tutorials, exam questions, and pre-class activities.
- Add materials to online archive and continually refine online format.
- Administer the CCMI at CU-Boulder and at other institutions.
- Investigate student difficulties through weekly homework help sessions, individual student interviews, and small-group student interviews.
  - Broaden investigations to include longitudinal studies of student difficulties.
- Write papers (PERC, AJP, and PRST-PER) about the results of this work including research into student difficulties, development of and results from the CCMI, and the transformation process.

4. Goals for 3340/4430 Optics and Modern Physics Lab:

- Establish consensus learning goal with faculty for the advanced lab course.
- Observe, interview, and survey students taking 3340/4430 during the spring of 2011.
- Review literature and practices at other colleges and universities for assessment in lab courses. Establish assessment methods for 3340/4430. It is essential we use assessments which provide evidence of learning in the lab, and provide feedback to students so they can improve their own scientific abilities.
- Create revised laboratory experiments. This could involve new lab equipment, rewritten lab guides, rubrics for student lab reports and lab notebooks, etc.
- Develop tutorials in experimental physics for the lecture part of the course. Tutorials could involve data analysis, plotting, computer control of experiments (LabVIEW), design of

experiments, scientific writing, and other topics relevant to laboratory work, but which are better suited to being taught in a classroom.

- Write up a PERC paper on the process of establishing learning goals at CU, and a review article on assessments in lab courses.