Forum on Education

of the American Physical Society
Spring 2004

Message from the Chair: How involved are you in the Forum?

Wolfgang Christian

How involved are you in the Forum? The APS Forum on Education provides a number of opportunities for APS members to become involved in activities related to physics and education.

- Apply for a FEd Education and Outreach mini-grant to engage your Unit in physics education and to address issues concerning the preparation of K-12 teachers. The first mini-grant was awarded to support the Four Corners Section for a high school student essay contest on Einstein in the 21st Century during the 2005 World Year of Physics.
- Honor an APS member who has made a significant contribution to the inter-relation of physics, physicists, and education by submitting a nomination for APS Fellow. The Forum will recognize this year's eight new APS Fellows at the Education Open House at the 2004 April meeting in Denver.
- Write an article for the FEd Newsletter.
- Organize or contribute to a FEd-sponsored Focus session at an APS meeting. The Forum is sponsoring its first Focus sessions at the 2004 April meeting on Physics Education Research (PER). The session organizer can include one invited paper.
- Work within your Unit to sponsor a session at an AAPT Meeting. The Forum will help subsidize one APS Unit a year. The first two such sessions are being organized by Ernie Malamud and Carl Wieman for DPB and DAMOP, respectively.

There are, of course, many other opportunities to contribute to physics education through the APS. The Joint AAPT-APS Task Force on Graduate Education in Physics is just starting its job and seeks your input. The SPIN/UP program is developing guidelines for self study and external evaluation of physics programs. And the comPADRE digital library is seeking content for its various collections, including Undergraduate Education and Quantum Mechanics. An email to wochristian@davidson.edu is all that it takes to become involved.

Wolfgang Christian is Chair of the Forum on Education and also a member of the Committee on Education. He is Brown Professor of Physics at Davidson College where his primary job is teaching. His research interests are in computational physics, educational software design and curriculum development.

Breaking News

FEd Mini-Grants

The APS Forum on Education Executive Board has made available a limited amount of financial support to encourage APS Units and Sections to actively engage in physics education and to address issues concerning the preparation of K-12 teachers. Joint activities with AAPT sections encouraged.

It is not the Forum's intention to propose an agenda for such discussions. The agenda should reflect the priorities and issues of importance to the individual APS Units and Sections and to the members they serve.

The APS Forum on Education is prepared to receive brief (approximately one page) proposals from APS members for Unit-sponsored activities to be held at Unit and Section meetings and at National APS meetings. The proposal should identify the topic and rationale for the activity, the meeting at which it will be offered, and the name of the person responsible for organizing the activity. The proposal should also include a statement of support from a Unit officer sponsoring the activity.

In response to such proposals, the APS Forum on Education will provide grants of up to $500 to support the efforts of Sections for activities consistent with these general objectives. The proposals should be sent to the Chair of the APS Forum on Education. The Forum's Chair, Program Committee Chair, and Treasurer will determine which proposals will be funded. While there is no deadline for proposals, currently available funds will support about 8 such proposals per year.

In order to share their experiences, award recipients are asked to provide a brief summary of their activity for the Forum's newsletter.

Proposals and questions should be addressed to the APS Forum on Education Chair. The 2003-04 Chair is Wolfgang Christian, wochristian@davidson.edu. The 2004-05 Chair is Gay Stewart, gstewart@comp.uark.edu.

Mandelbrot and Lorentz

A Gordon conference on teaching classical mechanics will be held June 13-18 at Mount Holyoke College in western Massachusetts. This conference will bring together teachers of classical mechanics and nonlinear dynamics, forefront researchers in these areas, and physics education researchers. The goal is to identify ways to effectively teach relevant lecture, laboratory, and computational courses in classical mechanics and nonlinear dynamics (including fractals and classical chaos), primarily at the undergraduate level. Presenters include Benoit Mandelbrot and Edward Lorentz. As of May 1, 2004 space was still available. For more information see http://www.grc.uri.edu/programs/2004/physres.htm or contact one of the conference chairs, Harvey S. Leff (hsleff@csupomona.edu) and David P. Jackson (jacksond@dickinson.edu).

Thank You, Fred Stein for All Your Hard Work!

The American Physical Society (APS) is seeking applications and nominations for the position of Director of Education and Outreach Programs to replace Fred Stein, who plans to retire in September. The person selected will play the leadership role in all APS education programs, including a major program to improve the physics education of K-12 teachers (PhysTEC), and will work closely with the Committee on Education and the Forum on Education. In addition, he or she will work with the Committee on the Status of Women in Physics and the Committee on Minorities in Physics in efforts to increase the number of women and minorities with careers in physics. An excellent staff is available to help with these programs. Qualifications for the position include a Ph.D. in physics or a related field, familiarity with the physics research and education communities, experience in managing large projects, some experience in working with teacher education programs, and excellent interpersonal and communication skills. For consideration, send a cover letter, resume, and professional references to Judy Franz, APS Executive Officer, franz@aps.org, by June 15.

AJP Resource Letters

The AAPT Committee on Undergraduate Education wants to remind everyone of the valuable information contained in the "Resource Letters" published periodically in the American Journal of Physics (AJP). Over thirty have been published in the last 5 years. Topics range from teaching light and optics to gravity waves to an oft cited review of physics education research. Go to www. scitation.aip.org/ajp/ and do a key word search under "resource letter" for a complete list.

Physics Essays for Airline Travelers

Jim McGuire

Write a dozen creative essays on specified topics in physics of about 300 words each, suitable for publication in airline magazines. Most of your course grade will be based on the originality and content of your essays. Imaginative style shall be rewarded. If you think your essay deserves a better grade, substantial credit will be given when your essay is actually accepted for publication.

While it excites the imagination to think of the disasters that could literally occur if such assignments were given in a course for engineers, the mere image of such entertaining scenarios provides get-even grist for the inventive minds of frustrated liberal arts majors who are forced to take a science course. And while many of these poor, miserable souls have been deprived of a consuming thirst for much of anything technical, they do have a few seeds of self respect when it comes to writing. Who among these aspiring leaders of humanity would admit to being unable to meet the lowly standards of airline magazines? Snickering at the very thought is indeed common during the first days of class. The more obscure the topic, the greater the challenge. So a Faustian accommodation can be reached with these young miscreants, who are bound and determined to become our masters by following pathways to money and power, theater and writing, or business and merchandizing. Not that we scientific purists need any of that!

So what dire things happen when such a devilish deed is done? First the number of hours worked per week by students in the course goes up to 3 – 6 from 0 - 3 hours. An hour or two is a limit clearly apparent when the "joy of solving physics problems" is imposed on normal people not used to this particular form of torture. Be warned that there are a few thieves in the thicket, however. While assigning technical topics (write an original essay on vectors) tends to yield clear and imaginative results, adding specific detail (write an original essay on vectors for rowing at 45^o across the Amazon river, 100 km upstream from its mouth) somehow hinders creative flow. Regularly changing the assignments' details (easy), and avoiding topics easily copied from the internet (not quite so easy) are both preventively prudent.

Grading these marvels of mass manipulation isn't exactly an exercise in mathematical precision. But as with other forms of creative art, one usually recognizes excellence when one sees it. Even graders, who have come to our shores from other countries and other cultures, can do this reliably. It sure beats grading typical physics labs. Then from the students clamors a common chorus of "My grade wasn't fair.", with a particularly piercing vocal style emanating from the pre-law students. Unlike our own progeny of young scientists, engineers and pre-meds, this more vulgar choir can be redirected with a rousing stanza of "OK, sell it to the masses -- publish it.". And some will try. The sobering truth is, however, that compared to physics, airline companies prefer 300 word essays on sunny destinations that sell airline tickets: a hint of humility that might moderate some intemperate arrogance of ambition. In the end one may anticipate a crescendo in expanding numbers of voices, articulating songs of science in a variety and style that few scientists shall ever achieve, but to which a multitude of non-scientists may contentedly listen.

More details and some examples are given at http://jubilee.phy.tulane.edu/~mcguire/

Jim McGuire is Chair and Murchinson - Mallory Professor of Physics at Tulane University. In addition to his teaching and administrative responsibilities, Jim is an active researcher in the field of theoretical atomic physics. He can be reached at mcguire@tulane.edu

A Course in Matter & Interactions

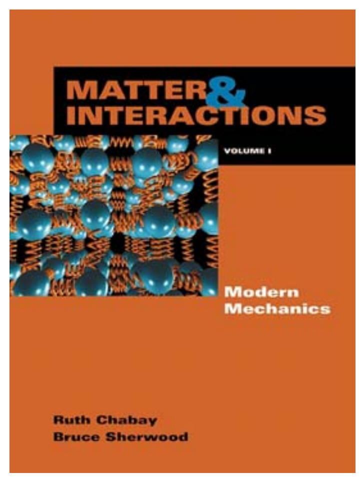
Ruth Chabay and Bruce Sherwood

"Matter and Interactions" is a calculus-based introductory physics course for engineering and science students that emphasizes the reductionist nature of physics. That is, from a small number of powerful fundamental principles one can explain a broad range of phenomena. The course emphasizes the atomic nature of matter throughout the mechanics and E&M semesters. Students are engaged in modeling the messy real world by making approximations, simplifying assumptions, idealizations, and estimates. They write computer programs which generate navigable 3D animations to model the motion of physical systems and to visualize fields (see http://vpython.org).

The emphasis on the atomic nature of matter allows us to unify mechanics and thermal physics throughout much of the mechanics semester, culminating with a statistical mechanics treatment of the Einstein solid. This emphasis also makes it possible to unify electrostatics and circuits, two subjects which are usually quite separate from each other.

Much educational research and development has gone into a thorough revision of the sequence of topics in both semesters, to make difficult concepts more accessible to students. For example, Gauss's law is usually treated far too early in the E&M semester for students to be able to understand it. We introduce it late in the semester, with greater success.

There is a two-volume Matter & Interactions textbook (Wiley 2002), a desktop experiment kit for E&M (Pasco), a comprehensive set of problems in WebAssign, and an extensive set of instructor support materials. See http://www4.ncsu.edu/~rwchabay/mi, for more information including PowerPoint presentations about the curriculum.



Ruth Chabay and Bruce Sherwood are members of the Physics Department at North Carolina State University. Ruth Chabay is a Professor of Physics and Bruce Sherwood is a Research Professor and Distinguished Educator in Residence . Both have research interests that rest within the field of Physics Education. Specifically they work to bring together research on learning and teaching, powerful computer tools and an understanding of contemporary physics in order to design curricular materials and courses that reflect the views of today's physicists.

Interactive Engagement in MIT Introductory Physics

John W. Belcher

Over the last three years, the MIT Physics Department has been introducing major changes in the way that Mechanics I, 8.01, and Electromagnetism I, 8.02, are taught. These cases are the result of the TEAL (Technology Enhanced Active Learning) Project. The TEAL format is centered on an "interactive engagement" approach, and merges lecture, recitations, and desktop laboratory experience. The format is similar to the Studio Physics format at Rensselaer Polytechnic Institute and to NCSU's Scale-Up format. We have expanded on the work of others by adding a large component centered on active and passive visualizations of electromagnetic phenomena. Most of these visualizations are on line and freely available at http://evangelion.mit.edu/802TEAL3D.

Why is MIT moving to this model for teaching introductory physics? First, the traditional lecture/recitation format for teaching 8.01 and 8.02 had a 40-50% attendance rate, even with spectacular lecturers, and a 10% or higher failure rate. Second, there have been a range of educational innovations in teaching freshman physics at universities other than MIT over the last few decades that demonstrate that any pedagogy using "interactive engagement" methods results in higher learning gains as compared to the traditional lecture format. This is usually accompanied by lower failure rates. Finally, the mainline introductory physics courses at MIT have not had a laboratory component for over 30 years, which is a major pedagogical disadvantage when teaching physics. The motivations for moving to the TEAL format were therefore to increase student engagement with the course by using teaching methods that have been successful at other institutions, and to re-introduce a laboratory component into the mainline physics courses after a 30-year absence.

In spring 2003 we taught 8.02 (Electromagnetism I) in the TEAL format for the first time in the mainline course with 550 students. In Fall 2001 and 2002 we taught a prototype to classes of about 150 students. In TEAL, students sit together at twelve round tables in a classroom especially designed for this purpose, the d'Arbeloff Studio Classroom. (See Figure at right). Each table accommodates nine students, with one laptop for every three students. Students are assigned to groups of three and remain in those groups for the entire term. Grades in the TEAL courses are not curved. Because collaboration is an element, it is important that the class not be graded on a curve, either in fact or in appearance, to encourage students with stronger backgrounds to help students with weaker backgrounds. Also, the cut-lines in the course are set in such a way that a student who consistently does not attend class cannot get an A. This is a deliberate policy to encourage attendance.

We have had an robust assessment and evaluation effort underway since the inception of the TEAL project, under the leadership of Professor Judy Yehudit Dori , a faculty member in the Department of Education in Technology and Science at the Technion in Hafia, Israel. We use a variety of assessment techniques, including the traditional in-class exams, focus groups, questionnaires (in addition to MIT's course evaluation questionnaire), and pre- and post-instruction conceptual testing. Based on the conceptual testing, the learning gains in TEAL spring 2003 were about twice those in the traditional lecture/recitation format (for detailed statistics, see http://web.mit.edu/jbelcher/www/802TEAL.pdf). These assessment results were consistent with the feeling of the physics faculty teaching the course that students were learning more with this method of instruction than they had in the traditional lecture/recitation format. The fact that interactive-engagement teaching methods produce about twice the average normalized learning gains when compared to traditional instruction replicates the results of many studies preformed at other universities. It is also consistent with the much lower failure rates for the Spring 2003 8.02 (a few percent) compared to 8.02 failure rates in recent years (from 7% to 13%).

In contrast to this overall increase in learning gains, student satisfaction with the spring 2003 course was mixed to negative. The MIT course evaluation *overall course score* for spring 2003 was 3.7/7.0, a low ranking. In hindsight, there were a number of missteps we made that contributed to this. For example, almost all of our students in the prototype courses had seen the material before at some level, and thus had some comfort level with it. This was not the case in spring 2003, when many students entering the course had never seen the material before. We use group work extensively in this class. Unfortunately, although we grouped according to background (that is, every group had a range of prior knowledge based on the pre test) in the prototype courses, in spring 2003 we simply assigned students to groups randomly. The result was that some of our groups consisted entirely of students who had never seen the material before. A frequent student complaint in our focus groups and in the course surveys was that "the blind can't lead the blind" in group work. We believe homogeneous grouping contributed to that reaction.

Another factor that may have impacted student reaction to the course was the low level of instructor knowledge in regard to the new methods and materials. We did train the six faculty members new to teaching the course in spring 2003 in regard to the teaching methods in the course. However, in hindsight, our training was not thorough enough to prepare them for the very new environment in the d'Arbeloff Classroom. This is true both in terms of the technology in the room and the teaching methods used in "interactive engagement." Moreover, we feel that we did not provide enough instruction to the student groups themselves in regard to collaborative work. Finally, many students said that they did not find the experiments useful. They were unsure of what they were supposed to learn from them, and the length of the experiments was such that frequently students did not have a chance to finish them.

We are teaching the mainline course again in spring 2004. The changes we are making this term in response to our experience in spring 2003 are: (1) heterogeneous grouping, and more training of students in collaborative methods; (2) more extensive training for course teaching staff, both section leaders, graduate student TAs and undergraduate TAs; (3) an increase in numbers of the course teaching staff (students felt we were understaffed during class); (4) fewer experiments that are better explained and better integrated into the course material; (5) better planning of individual classes to break our active learning sessions into smaller units that can be more closely overseen by the teaching staff.

The lessons of the TEAL experience thus far for educational innovation at MIT are many. First, any serious educational reform effort must be accompanied by a robust assessment effort. One needs some quantitative measure of the effectiveness of instruction to gauge whether the innovation is actually producing results that are superior to or equal to what it is replacing. Second, as is well known in educational circles, the most perilous part of any innovation is the attempt to move from small-scale innovation to large-scale implementation. With hindsight we feel that our major misstep in this transition was not training course personnel and students adequately to prepare them for this new method of teaching.

Acknowledgments: The TEAL Project is supported by the d'Arbeloff Fund for Excellence in MIT Education, the MIT/Microsoft iCampus Alliance, and NSF
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Increasing Student Engagement in Large Classes: A Departmental Case Study

Steve Pollock and Kathy Perkins

Over the last several years, the University of Colorado at Boulder's (CU) Physics Department has worked hard to improve student learning in the large-lecture introductory physics courses. Our main focus has been on increasing interactive engagement in lecture and on promoting collaborative learning. In addition, some courses have incorporated a variety of other practices based on Physics Education Research (PER) findings[1]. These include: emphasizing conceptual understanding, explicitly teaching metacognitive skills, incorporating conceptual and context-rich (real-world) problems in homework, using computer simulations[2], developing well-defined course learning goals, and measuring learning gains and student attitudes with validated assessment instruments. In this brief account, we discuss the range of approaches used in our introductory physics courses. We present measures of the extent to which these approaches have been adopted by the physics faculty and their impact on student learning and attitudes. Perhaps most interesting, though, is to reflect on the history which brings CU Physics to its current state. It is a department where the climate and practices encourage the use of research-based instructional methods. We conclude by discussing some key aspects which have been integral in initiating and nurturing the development of this culture within our department.

As a large state school, we are faced with the challenge of educating about 1800 students each semester in our introductory courses. The result is large lecture courses of up to 600 students held in theatre-style rooms. In 1997, several faculty members began promoting the use of interactive methods in the classroom. They cited the improved learning gains reported by others using Eric Mazur's Peer Instruction method[3] and began using such techniques. Each year since then additional faculty members have adopted this style of lecture. In fall 2002, we wired our large lecture halls for the H-iTT student response system[4]. Each student now votes anonymously using a personal IR transmitter, locally known as a "clicker". We have developed a local database of "clicker questions" with roughly 10 categories of questions used in the department. These include questions that 1) quiz on the reading, 2) elicit/reveal misconceptions, 3) test conceptual understanding, 4) require prediction of experimental outcomes or simulation response, 5) recall a lecture point, 6) require reasoning to apply concepts in different contexts, 7) relate different representations, 8) do a calculation, 9) draw on intuition from everyday life, and 10) survey students. The mix and types of questions used varies with course and instructor.

The manner in which active engagement methods are used varies with instructor. However, all implementations have included an increased emphasis on collaborative learning by encouraging peer discussions related to clicker questions. In some courses, this simply means that students discuss their ideas with neighbors. In other courses, groups of 3-4 students are formed and are required to come to a consensus before voting. Some instructors follow up clicker questions with teacher-led, full-class discussions. In addition to clicker questions, some faculty use interactive lecture demonstrations[5] which require each student to graph or otherwise predict the measured outcomes of an experiment.

This increased emphasis on collaborative learning exists outside the lecture hall as well. In 2000, the department created a public *Physics Help Room* for all introductory classes. Open 9 am to 5 pm and staffed by instructors and TAs, the "Help Room" is extremely popular. Typically thirty to ninety students are present in the room. Often they are working together in small groups. In addition, most of our introductory courses make use of CAPA, a computerized homework system[6] which personalizes problems. This further encourages a culture of student collaboration, since students can no longer simply copy answers. In fall 2003, traditional recitations in the calculus-based mechanics course were replaced with tutorials run by TAs and undergraduate learning assistants. These tutorials replicate the University of Washington Tutorials[7] as faithfully as possible, given local constraints.

Over the last 7 semesters, 28 out of 35 introductory physics courses included some degree of interactive engagement. Of the roughly 45 regular department faculty, 12 have now taught large lectures using these methods. Some faculty members are quite tentative, while others have designed their entire course around the interactive engagement methods. A smaller subset of faculty members have taken steps to assess the effectiveness of these methods. We have given the Force Concept Inventory (and other validated assessments) in a handful of classes. For comparison, traditional lectures generally result in normalized gains of about 25% on these tests[8]. In the mid-90's, one of our award winning lecturers measured a normalized gain of about this size in his popular but traditional course. Since shifting to peer-instruction style classes, we have measured gains of 33% in a more tentatively reformed class, 45% in an algebra-based course using clickers, 43% in a "pure concept test" style course, and 62% in our most recent calculus-based mechanics class using both the University of Washington style Tutorials and clickers.

Incorporating these new teaching methods has not had any adverse effects on course or instructor ratings. In fact, on average our interactive engagement-based courses rate higher than the traditional lecture-based courses on student evaluations. When asked to evaluate how the use of clickers in the classroom contributed to their learning, 96% of students in the most recent calculus-based course and 81% of students in the non-scientist course rated clickers as beneficial to their learning. Another value of using clickers has been higher attendance. When "clicker points" contribute to the grade, average attendance has exceeded 85%. When they are extra credit, average attendance has been above 75%.

It is interesting to reflect on the history which has led to a department where the climate and practices encourage the use of innovative, research-based teaching methods. The University of Colorado at Boulder has a legacy of dedicated and innovative teachers, including George Gamow, Frank Oppenheimer who developed freshman labs in a pre-Exploratorium style and Al Bartlett with his enormously popular classes that started in the 1960's. Nonetheless, our department was fairly conventional, with large teacher-centered lectures and graduate students lecturing in recitation. The shift towards an increasing awareness of physics education research and the use of active engagement methods started with the efforts of a modest number of energetic faculty. The growing interest and dedication of a highly respected senior research physicist to these efforts – evident through his local education initiatives and his vocal promotion of their value in improving education – drew the attention of the faculty. The Department Chair recognized and supported these fledgling efforts and contributed significantly himself. Among other things, he initiated a Preparing Future Faculty program (funded through AAPT) and modified the yearly teaching evaluation to include criteria that acknowledged the scholarship of teaching and learning.

The department now holds bi-weekly brown bag lunch meetings where interested faculty members can discuss educational issues. Physics education researchers are often invited to speak. Typical attendance at the "brown bag" meetings is up to 30% of the faculty. This is an informal but powerful forum for sharing interest and ideas, spreading pedagogical theories and practical approaches, and encouraging reflection on individual and departmental practices. The department also began inviting high-profile colloquia speakers, Lillian McDermott, Eric Mazur and Lorrie Shepard among others. These (and other) colloquia had a noticeable impact and were well attended by the faculty. Providing forums for dissemination of ideas – hallway discussions, colloquia, and lunch meetings – has certainly contributed to the spread of interest in and awareness of new teaching methods.

In addition to these bottom-up efforts, financial support from the administration, the department, and other university programs including the graduate school has been invaluable. The University of Colorado administration has a unique mandate to improve undergraduate education which provides both monetary support through student lab fees and top-down pressure on the department. The CU Faculty Teaching Excellence Program and Graduate Teacher Program are involved with our efforts, supporting faculty members individually and providing training and support for our graduate teaching assistants (TAs), including developing a lead TA program. An NSF Teacher Preparation grant[9] allowed us to hire undergraduate learning assistants to team up with graduate students as learning coaches in the Tutorial sessions. Increased collaboration with the School of Education provided learning assistant training, joint meetings on science education, and collaborative research activities in our classes.

More recently, our efforts gained momentum, with a hire this year of a junior faculty member whose research is in the field of physics education research (PER) , the development of research programs in PER by two tenured physics faculty members, and the ongoing interest of a senior instructor. We now have a rapidly growing PER group with internal and external funding, graduate students, and a post-doc. For more information on our group, please visit our web page at www.colorado.edu/physics/EducationIssues. We welcome feedback on efforts at other institutions to implement sustainable and effective change.

References:

(1) McDermott, L., Redish, E., American Journal of Physics, **67**(9), 755-767, 1999

(2) *www.colorado.edu/physics/phet,* supported by Kavli Foundation, NSF, and CU.

(3) Mazur, E., *Peer Instruction: A User's Manual.* Prentice-Hall, NJ 1997

(4) H-ITT: See *http://www.h-itt.com/*

(5) See e.g. Sokoloff, D., Thornton R., The Physics Teacher, vol. 35, pgs 340-346 (1997).

(6) CAPA: See www.lon-capa.org/

(7) McDermott, L., Shaffer, P., and the PEG, *Tutorials in Introductory Physics,* Prentice Hall, NJ 2002

(8) Hake, R., Conservation Ecology **5**(2):28, '02, *www.consecol.org/vol5/iss2/art28*

(9) Supported by a STEM-TP grant from the National Science Foundation

Steven Pollock is an Associate Professor of Physics at the University of Colorado at Boulder where he wears two hats. He does research in theoretical nuclear physics. He is also active in physics education research. Kathy Perkins is a Lecturer and Research Associate working with Carl Wieman and the physics education research group at CU Boulder.

Explorations in Physics: An Activity-Based Curriculum for Non-Science Students

David P. Jackson

Explorations in Physics (EiP) is a set of curricular materials developed by David P. Jackson, Priscilla Laws (developer of *Workshop Physics*) and Scott Franklin at Dickinson College. These materials have been created to increase the effectiveness of science education for non-science majors. By integrating guided-inquiry materials with student-directed projects, students are in a position to acquire a thorough understanding of what practicing scientists actually do. In addition, the use of computer-based data acquisition tools enables students to explore a wide range of physical phenomena.

The *Explorations in Physics* project began in 1994 with funding from the Charles A. Dana Foundation. Since then, we have received funding from the Department of Education's Fund for the Improvement of Post-Secondary Education (FIPSE) and the National Science Foundation (NSF). This has resulted in the completion of eight curricular units covering a wide range of topics including motion, pressure, buoyancy, light, heat, sound, magnets and charge. To enhance the flexibility of the curriculum, the units were designed so they can be taught in any order. This allows instructors to choose among the various units to customize a course to fit student needs and interests.

Since the beginning of this project, we have focused on treating the students as apprentice researchers. While this approach entails a reduction in content coverage, the resulting benefits are enormous. In addition to acquiring a deeper understanding of the concepts that are introduced, students gain hands-on experience with hypothesis formulation, mathematical model building, experimental design and the use of scientific measurement equipment. The course is taught using a "workshop" approach with no formal lectures and all work done in a laboratory setting. Active participation on the part of the students both in small groups and on their own permits ample opportunity for cooperative learning as well as independent accomplishments.

Some of the most important goals of *Explorations in Physics* are to:

- Enable students to master a diverse subset of important scientific concepts
- Enhance the ability and confidence of students to conduct basic scientific investigations and communicate their findings to others
- Allow students an opportunity to cope with ambiguity as it arises in science
- Help students develop a positive attitude toward science

To help accomplish these goals, the course is designed so that the entire class works through a unit of "core material" on a particular topic area. The core material for each unit consists of a student activity guide that is approximately 75 pages in length. The written activity guide for each unit contains explanatory material, student predictions and observations, experimental activities, problems, student reflections, and topics for class discussions. Each unit follows a "storyline" that culminates in a thorough understanding of a relatively common phenomenon, such as airplane flight or cloud formation. In addition, because there is no absolute set of topics that *must* be covered, any concept that is not essential to the storyline of a unit is eliminated. This helps students maintain a certain focus because superfluous concepts that might otherwise be distracting are absent.

Upon completion of the core material, students spend an equal amount of time working in small groups on a project of their own design. This involves writing a proposal, designing and carrying out experiments, taking and analyzing data, and presenting their results to the class. The emphasis on projects is a unique aspect of *Explorations in Physics*. When students pursue a topic of their own choosing, they become self motivated. Furthermore, because students are required to make a formal presentation of the project, they are placed in the role of an instructor. We are all familiar with how much better we understand a subject after having taught it, and the formal presentations contribute to student mastery of project topics. The projects give many students confidence that they really *can* do science. We feel this confidence is of tremendous value for this population.

Another unique aspect of *Explorations in Physics* is that many of the topics covered are not traditionally introduced in courses designed for non science students. In particular, many of the culminating activities in each unit are chosen because they are common real-world occurrences. In most cases, students learn these topics by completing a series of hands-on experiments in which they come face to face with the phenomenon under study. To give some examples, in one unit students measure the percentage of colored light that is transmitted through a simulated atmosphere (water with a little powdered cream). Their results allow them to understand why the sky is blue and why sunsets are orange. In another unit, students measure the temperature of wet and dry thermometers and then use these results to explain why people sweat and what it means for the weather to be "muggy".

Below is a *very* brief sampling of the topics in each of the units. The first four unit are available commercially and the others are available from our website. To access these materials or to obtain more information about the *Explorations in Physics* curriculum please visit the *EiP* website at http://physics.dickinson.edu/EiP.

Motion, Forces, and Scientific Theories—The most traditional of all the units, this unit begins with the vague question "how can we measure the motion of an object?" From there, position, velocity, and acceleration graphs are explored and the concept of force is introduced independent of any motion. Finally, the question of how a force will affect the motion of an object is explored and Newton's second law is "discovered". The unit ends by exploring the forces of gravity and friction.

Light, Sight, and Rainbows—This unit begins by exploring what it means to "see" an object. Students determine the necessity of light and then explore various aspects of light such as how it travels and how it interacts with objects. A model eye is constructed and refraction is explored to understand the role of the lens. Colored light and colored objects are explored using hand-held spectrometers and filters. The unit ends by exploring rainbows, sunsets and the blue sky.

Heat, Temperature, and Cloud Formation—This unit begins by mixing different amounts of water of different temperatures and trying to determine what the temperature of the final mixture will be. Students construct a thermometer and increase the temperature of water without "heating it up" thereby making a connection between "heat" and energy. Boiling, evaporation, condensation and humidity are then explored and the unit ends with students constructing their very own cloud in a bottle.

Buoyancy, Pressure, and Flight—This unit begins by exploring floating, sinking, and forces. Students weigh objects in air and in water and conclude that the effect of the water on the object is an upward "buoyant" force. The concept of pressure is then introduced using a hydraulic lift made of glass syringes (Pascal's principle). Hydrostatic pressure and the pressure of moving air are then explored and the unit ends by examining how barometers work and how airplanes fly.

Sound, Vibrations, and Musical Tones—This unit begins with students trying to classify various sounds. The generation, transmission, and detection of sound are all explored using a speaker and function generator. The relation between frequency and pitch is explored and the "frequency" graph using an FFT (Fast Fourier Transform) is introduced. Musical scales are introduced by determining which frequencies sound "nice" when played together. The unit ends by examining complex tones and musical instruments.

Magnets, Charge, and Electric Motors—This unit begins by playing with magnets and seeing how they interact with different materials. The ability to magnetize paperclips is explored and the relation to compasses is determined. The concept of charge is introduced with sticky-tape experiments. The students then construct a "lightning machine" which leads into how a current-carrying wire can affect a magnet. The unit ends with the students constructing a small working motor.

Population, Climate, and Mathematical Modeling—This unit begins by considering the factors that affect population growth. A population growth game is introduced with dice and beans and then a spreadsheet is introduced as a more sophisticated tool to model population dynamics. A connection is made between population dynamics and energy balance in a thermodynamic system and the unit ends by considering the temperature of the Earth in a global warming scenario.

Atoms, Crystals, and Snowflakes—This unit is under current developed and will explore the atomic nature of matter and culminate with students making their very own snowflakes.

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Hands-on Homework for Large Introductory Physics Courses

Chandralekha Singh

The "Physics Exploration Center" (PEC) at the University of Pittsburgh, modeled after similar centers at the University of California Santa Barbara and Rutgers University, provides concrete experiences with physical phenomena for students in our large, lecture-oriented introductory courses. In the PEC, physics lecture demonstrations illustrating various physical phenomena are transformed into fun, interactive displays. The central objective of the PEC is to provide students with an opportunity to do "hands-on homework problems". These problems can be assigned even in large classes because students do them at their own convenience and pace. The goal is to help students develop a robust conceptual understanding of the lecture material, challenge their preconceptions by providing contradictory experiences, and introduce them to the scientific method.

The most attractive feature of the PEC is its emphasis on hands-on, self-paced, guided-inquiry based learning. Vivid and memorable experiences in the PEC have both motivational and instructional advantages. The concrete experiences provided by the hands-on activities are very useful for building conceptual understanding of physical phenomena. Even if only one or two PEC homework problems are assigned per week, students will have performed approximately 15-30 by the end of the semester. These hands-on problems improve physical intuition. The interpretation of a problem is easier for novice problem solvers when they have apparatus they can directly view and manipulate as opposed to simply a two dimensional picture in a book. In addition, once a student has played with many demonstrations involving a given physical principle and answered related questions, we find he/she is more likely to be able to use physical reasoning in evaluating other problems involving the same concept. PEC problems also provide a closer look at lecture demonstrations. Due to time constraints, lecture demonstrations are often over before students have had an opportunity to interpret their significance. They can also be difficult to see in a large lecture hall. PEC problems provide students with an opportunity to personally engage in lecture demonstrations they see in class.

We find the Physics Exploration Center to be reasonably cost-effective since equipment can be borrowed from lecture-demonstration inventory. Most of the equipment and infrastructure needed for a PEC capable of serving up to a hundred students already exists in most physics departments. All that typically needs to be found is a space where students can perform the hands-on homework problems. The commitment from physics departments to provide space and cover the extra wear and tear on demonstration equipment is worthwhile since Physics Exploration Center experiences are so beneficial to students. Furthermore, instructors are supportive of the approach since it requires little additional effort on their part and does not require them to change their teaching styles.

The model of Physics Exploration Center that we have developed is suitable for most colleges and universities. The center is open 9am-6pm, Monday through Friday. It is integrated into our "Physics Tutoring Room" for undergraduate students seeking help related to physics courses. During regular PEC hours, the center is staffed by two teaching assistants. The directions for operating the equipment and an explanation of the phenomena involved in each PEC activity is provided with the PEC setup. We have found that providing such written directions and explanations with each setup allows students to carry out the PEC activities with minimal help from the staff. The University has provided permanent space (approximately 600 sq. ft. including the tutoring area) for the PEC. The demonstration equipment used in the PEC is maintained by the Physics Demonstration Resource Center (PDRC) staff.

In order to facilitate integration of PEC hands-on homework into our introductory physics courses, a library of well thought out problems has been compiled and made available to professors. We have also established a website http://www.phyast.pitt.edu/~cls/PEC, which contains an expanding database of PEC problems. Currently there are enough for both semesters of the introductory algebra and calculus-based courses. One factor that is taken into account when designing all our PEC problems is that the equipment must be safe for student use without supervision. In addition, we realize that the equipment must withstand handling by several hundred students. Fortunately, much of the lecture demonstration equipment in use is fairly sturdy. After all, it must survive handling by faculty members!

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Activity-Centered General Science Course Concerning Light and Optics

Jeff Marx, Shabbir Mian, Vasilis Pagonis

Each year in the United States hundreds of thousands of undergraduates enroll in introductory science courses geared towards non-science majors.[1] As is the case at McDaniel College, these general science courses may be one of, perhaps, only two college-level courses in science or mathematics in which these students will participate. Unfortunately, we notice many students have poor math and science backgrounds, as well as a weak set of epistemological beliefs. We believe these weaknesses can negatively impact students' capacity to comprehend fundamental physical concepts and basic relations.

Faced with these concerns, we created a general science course covering light in which non-science majors engage in simple activities designed to help them understand basic light phenomena, while gaining a sense of their own capacity to investigate and logically postulate about the physical world. To accomplish this, we fused together several successful pedagogical techniques and environments introduced by the physics education research community over the past decade. Specifically, we coupled the Prediction-Experiment-Result routine of Interactive Lecture Demonstrations[2] with the more intimate settings of Tutorials[3] and the hands-on Workshop Physics.[4]

In our course, *A World of Light and Color*, students regularly face their individual notions of various optical phenomena by making intellectual commitments to their ideas by predicting, sometimes publicly, conceivable outcomes for a particular activity. Students then observe the phenomena and acknowledge any discrepancies between their ideas and the outcome by articulating and recording their observations. Finally, the class tries to establish the natural rules governing the phenomena under investigation.

Population

McDaniel College is a selective, four-year, residential, liberal arts college, with an undergraduate population of about 1600 students. McDaniel's curriculum has a core set of Basic Liberal Arts Requirements. One of those requirements dictates that students pass two courses relating to the natural sciences and mathematics. For several years the Physics Department delivered *A World of Light and Color*, a single-semester, general science course at the 1000-level. Looking to improve the quality of this course, we remodeled its structure into the form described in this paper. We offered the improved version for the last two years in eight different sections. Enrollment varied from eleven to twenty-four students, and 75% to 100% of the students in any given class were non-science majors.

Classroom Environment and Course Structure

The classroom has six large, low, rectangular tables with ample room to accommodate four students and equipment and materials used for any particular day. Students work in groups for nearly every step of each activity.

Whenever the class begins a new topic (roughly every other class meeting) the students must arrive at class with a completed Preparatory Sheet. Preparatory Sheets have the reading assignment for the day, as well as questions about basic properties of light germane to that topic. The answers to the questions are not in the text; rather, the students must rely on their own understanding (including what they gleaned from the reading) of the phenomena in question to arrive at their conclusions. We collect, grade, and return the Preparatory Sheets by the next class. The grading scheme is a scale from 0 (no work) to 3 (serious effort and coherent, but not necessarily correct, set of answers). The main function of the Preparatory Sheets is to force students to consider the material before coming to class.

As class gets under way, the students read the opening remarks on the Procedure and Results Sheet (PRS). Each PRS begins with a checklist of materials the students will use for that set of activities, as well as remarks concerning how to use any equipment safely and properly.

Next, the PRS directs students to their Prediction Sheet (PS) to begin the three segments of the Prediction Phase. The PS describes the activity the students will conduct; however, *before* they perform that activity, the students enter the first segment of the Prediction Phase by making a personal prediction as to the outcome of the activity by writing (or, more typically, drawing) their thoughts on the PS. We encourage students to make predictions on their own before they move on to the next segment when they discuss and debate their predictions with their partner(s) and table mates. Students are free to update their predictions based on the discussions. During the first two segments of the Prediction Phase the instructor moves around the room to look at various predictions and hold dialogues with individual students regarding their predictions. When the discussions subside, the instructor moves the class into the last segment of the Prediction Phase by eliciting several predictions from the class. These public predictions are voluntary or brought forth by calling on students. (Varying classroom dynamics and levels of difficulty require both techniques.) To encourage students to offer predictions, we do not require them to necessarily present their own predictions; rather, they can say what someone else at their table thought was reasonable. If feasible, the instructor draws, or writes, predications on the whiteboard at the front of the classroom so the students can appreciate the, sometimes wide, range of notions. Usually the students will engage in some discussion and non-confrontational criticism of the various predictions.

Once the Prediction Phase winds down, the class moves to the Observation Phase. At this point pairs of students perform the short activity described on the PRS to find out what really happens. Then the instructor carefully outlines the results on the whiteboard or demonstrates the phenomena to the entire class. Short discussions often follow while the students describe and/or illustrate their observations on their PRS.

After a few cycles of Prediction and Observation we enter the Discussion Phase. Questions or ideas for discussion are on the PRS. These discussion questions give the students the chance to bring the last few observations together under one physical principle. We have students discuss the observations and possible overarching explanations with their table mates, first. Then the instructor holds a short class-wide discussion to get the various opinions and explanations out in the open. Hopefully, the class will come to some correct consensus about the broader physical idea. If they do, then the instructor simply restates the consensus, sometimes with more compact verbiage, so everyone has a chance to write down the major ideas on their PRS. If the class can not see the broad concept, then the instructor faces the challenge of bringing the class around to the correct idea while avoiding simply telling them what to think. Since we have carefully chosen our topics and observations, the latter situation rarely arises.

The entire class hour is filled with this cycle of Prediction-Observation-Discussion. Several topics span more than one class meeting to help ensure the students have a firm grasp of the material. (Classes meet three times per week.) The students do not take notes as they would in a more typical class. The information they compile on their PRS serve as the notes for the class. Other aspects of the course are more traditional. The students complete ten homework assignments (with short-answer questions and numerical problems), three short quizzes and three hour-long exams, and a comprehensive final.

Topics and Activity Examples

The outline of topics we cover in our class is located in Table 1. The reader familiar with this type of course will recognize the topics as part of the standard set for such a course.

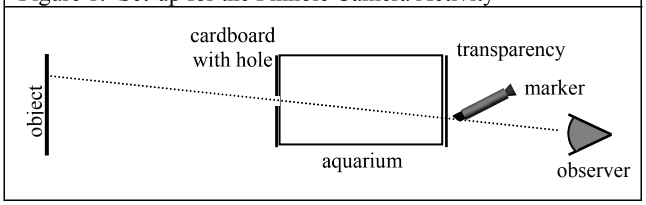
Table 1: Topics covered in *A World of Light and Color*

Topic	*classes devoted*
Basic Properties of Light	
Relationship Between Color and Wavelength	2
Light Beyond the Visible: IR and UV	2
Reflection, Absorption, and Transmission	1
Relationship Between Intensity and Distance	1
Color Mixing: Addition and Subtraction	2
Geometrical Optics	
Shadows	2
Ray Reflection from a Plane Mirror	1
Image Formation by a Planar Mirror	1
Ray Reflection from a Curved Mirror	2
Image Formation by Curved Mirrors	3
Refraction	1
Total Internal Reflection	1
Fiber Optics	1
Ray Refraction by a Lens	1
Image Formation by Lenses	3
Telescopes and Cameras	1
Pinhole Camera	1
Physical Optics and Polarization	
Reflection and Superposition of Waves	3
Water Waves in the Ripple Tank	1
Diffraction	2
Two-slit Interference	2
Polarization	1
Miscellaneous Topics	
Eye, Mineral Identification, Relativity.	3 or 4

To expose the students to the various topics, we developed a diverse set of activities. For example, to understand shadows, the students use a floodlight to cast the shadow of a small cylindrical object on a white screen. The students discuss and develop models for the light ray paths for various source-object configurations and develop an understanding of the various shadows' shades and shapes. Building on this, the students think about the details of the object's shadow when the source shines through a small hole in an opaque screen and when the source is behind a sheet of white paper. They also observe shadows cast by multiple sources, paying close attention to the varying shades of gray for each shadow. Finally, the students combine what they learned about color addition in previous activities and their new knowledge about shadows and multiple sources to predict and observe colored shadows.

To help students understand how a pinhole camera functions, we developed an activity in which the student plays the role of the film in a pinhole camera. The students place the object (paper with bold symbols printed on it) about 50 cm from a piece of cardboard with a small hole punched in it, which is fixed to one side of a 10-gallon aquarium. At the other side of the tank, the students attach a transparency sheet. (See Figure 1.) Students carefully line up a marker with the tiny part of the object they see through the hole and then mark a dot on the transparency. By repeating this for many locations, a pattern emerges on the transparency that resembles the object. By looking at the transparency from the inside of the tank, the students see what the pinhole image looks like. This activity reveals how the pinhole enforces a particular one-to-one relationship between locations on the object and on the image. It also prepares students to make predictions regarding the relationship between the object distance and the size of the image. And, it helps them understand why the pinhole image is inverted and reasonably sharp nearly independent of the object distance, which differs from the image created by a lens.

Figure 1: Set-up for the Pinhole Camera Activity



Reflections and Suggestions

Teaching a learner-centered course can be a challenge, as instructors must carefully balance their level of involvement. Too much intervention ruins the pedagogical intent; too little, and the class collapses into a frustrated heap. Along with aligning our course with the inspiring curricular materials we mentioned earlier, we worked hard to create activities in which the instructors can easily assume an engaging, but not overbearing, position. Along those lines, we present several observations we trust instructors may find useful when implementing this or similar courses.

First, we strive to keep a safe and open intellectual environment. If students sense the potential for ridicule, they will certainly not offer their predictions and ideas and may look to by-pass the critical Prediction Phase altogether. The instructor must carefully mediate interactions so there are thoughtful and polite evaluations of predictions and discussions. Since many ideas will be incorrect, in one form or another, it is important to highlight the fact that the entire class learns together and that even incorrect notions help everyone. All of this begins with the instructor who must serve as a model of how to deal with multiple notions of the physical world by rewarding honesty and openness.

Second, when students make and record observations, it is often important to discuss the ideal result from the actual result. For example, the color addition and subtraction experiments often yield results that differ from what one would predict using an ideal filter model. This mismatch can frustrate students, but we turn that around and use the discrepancy to point out that models have limitations and once one understands those limits, useful predications are still possible. Also, we make sure every student correctly records observations on their PRS. Frequently, all the students are looking same thing, but a few may interpret what they see differently than everyone else. For example, when students view colors projected onto a white screen, they sometimes mistake colors they observe as a result of the influences of nearby colors on the same screen.

Third, we feel preparatory work is an essential part of the type of learning environment we are attempting to create. Unfortunately, we have found it difficult to craft effective Preparatory Sheets for all of the topics. Because we want to encourage students, we tended to err on the side of caution and write relatively easy Preparatory Sheets. However, a bolder approach may be appropriate.

Also, we tried to make certain that each cycle of prediction, observation, and discussion focused on one concept. Moreover, we focused each class on one or two robust optical principles. We wanted students to come away from each class with broad concepts, not a bunch of notes on specific and seemingly disconnected examples. This serves to reinforce the idea that scientists often look for "Big Thoughts" that tie hosts of observations together.

Finally, for the vast majority of activities we intentionally avoided observations and experimental set-ups that require electronic interfaces. We recognize the important role technology plays in science, and we certainly would like our students to appreciate that, too. However, we felt it was more important for our students to feel a strong sense of ownership of their observations. Our population lacks both an understanding of physical phenomena and experience using computers and electronic equipment as experimental apparatus. We felt this presented too many pedagogical barriers, so we cleaved to a low-tech approach.

Conclusions

We have developed materials for our optics course, *A World of Light and Color*. We based the course's curriculum on techniques previously established to help students come to a full understanding of basic physical concepts. In particular, students proceed through a cycle of prediction, observation, and discussion to help them relate to fundamental ideas concerning light. We encourage instructors to contact us for more information.

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Investigative Science Learning Environment

Eugenia Etkina and Alan Van Heuvelen

Investigative Science Learning Environment (*ISLE*) is an introductory physics learning system that makes a conscious attempt to mirror the processes that physicists use in their real-world practice while constructing knowledge and applying it for useful purposes.[1] One of the major goals of *ISLE* is to help students master the inductive and deductive elements of scientific discovery.

ISLE students start each conceptual unit by observing carefully selected physical phenomena. They collect data with an open mind. Students construct ideas and rules to explain their experimental observations. They are encouraged to suggest multiple explanations for the same experiment. The fact that all explanations have equal weights before they are tested allows students to express their ideas, often based on every-day experience, freely without waiting for authority for validation. Students can use their contextual and epistemological resources to help in constructing explanations.[2] Students then evaluate their explanations and rules using hypothetic-deductive reasoning to predict the outcomes of new "testing experiments". After performing the testing experiments, they revise their explanations when necessary. Sometimes testing experiments reveal new features of the phenomenon that students try to explain, and the cycle starts again. They then use tested explanations and rules to explain every-day experiences and to solve problems. Students follow similar cycles for each conceptual unit and continuously reflect on "how they know what they know." (An example of a *ISLE* cycle is following the references at the end of this article.) At each stage students work collaboratively (in groups), sharing ideas and trying to convince each other. This approach resembles the processes that the scientific community uses to acquire knowledge.

This aspect of *ISLE* instruction differs from traditional and some reformed approaches to physics instruction in several ways. The instructor does not provide students with ready-made physics concepts to discuss nor shows experiments to illustrate concepts or rules that were presented earlier. *ISLE* students do not read the textbook before coming to class. The instructor *does not elicit predictions* before the observational experiments. Students' alternative ideas are addressed naturally at the concept construction or concept testing stages of the cycle.

Another feature of *ISLE* is that students master the concepts that they devised using various thinking and learning strategies. Students are active participants in all parts of their learning. They learn to represent physical phenomena in multiple ways.[3] These include sketches, concrete physical representations (motion diagrams, energy bar charts, free-body diagrams, ray diagrams, and so forth), graphs, and algebraic expressions. They learn to convert one type of representation for a process to other types. The concrete representations are used to help construct accurate mathematical descriptions of processes.

After concepts have been constructed and tested, students use the different representations to reason qualitatively and quantitatively about physical processes – a strategy commonly used by scientists. Students learn to take a more complex situation apart, solve the parts, and reassemble the parts to answer a bigger question. They learn to design experiments, for example experiments to solve practical problems.

Students are assessed for conceptual understanding, for problem-solving ability, and, most importantly, for their use of various scientific abilities. We have and are developing activities that help students acquire some of the abilities used by scientists in their work: experiment design, model building, use of multiple-representations, and evaluation. Similar tasks are used for formative assessment activities to determine the degree to which the students have acquired these abilities and to simultaneously provide feedback to the students.[4]

The *ISLE* system has been used in large (over 500 students) classes and in smaller classes. The format for the instruction depends on the number of lecture, recitation and lab classes each week. For example in one large class, a two-week unit starts with students observing phenomena in the first lecture. They work in groups of two/three to record their observations, look for patterns in these observations, analyze the experiments in various ways to help produce qualitative explanations that account for their observations. They use the different explanations to make predictions about a testing experiment proposed by the professor or suggest their own testing experiments. This is done through interactions with representatives of the groups, voting, or an electronic response system. The testing experiments are used to discriminate among the different explanations. In this lecture or in a second one, students identify relevant physical quantities. Students look for patterns in experimental data that relate these quantities—to devise a relationship between them – a physical rule or a law. These rules are then subjected to experimental testing again. Then students use the qualitative explanations and the rules to reason about new processes, to represent them in multiple ways, and to solve problems of easy to moderate difficulty. All this happens in an interactive format using a peer instruction approach.

During one or more recitations in this first week or early in the second week, students work in groups on problems—qualitative problems, multiple representation activities, and often on more complex multi-part problems. They also evaluate solutions to the problems devised by other students. The lab related to this conceptual area occurs during the second week and involves more complex quantitative testing experiments and experiment problems. Students are sometimes responsible for designing an experiment to test a concept or an experiment to solve a problem. They practice hypothetico-deductive reasoning (if, then, but, therefore)[5] to make predictions and to assess the results of the experiment. In lectures during this second week, a new cycle starts. As stated earlier, different formats are used depending on the size of the class and the class time available for each part of the course—lecture, recitation, and laboratory.

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An example ISLE cycle for projectile motion

The unit on projectile motion is done after kinematics and dynamics. At the beginning of the unit students in lecture observe a moving cart shooting a metal ball upward. They repeat the experiment several times for different speeds of the cart and record the patterns in their observations (the ball always returns to the cart). Then they work in groups to construct explanations based on the patterns in their observations. The instructor encourages them to think of different possibilities (the ball is somehow attracted to the cart, may be it is a metal ball and there is a magnet in the cart; the ball continues moving horizontally the same way as the cart – horizontal motion is independent from the vertical, etc). After the groups share their explanations, they then design testing experiments to determine if the explanations work. For example to test the magnet explanation, students suggested shooting the ball and then stopping the cart – if the cart attracts the ball, it will come back to the cart. To test the independence of the horizontal motion of the vertical motion they suggested holding the ball and then dropping it while walking at a steady pace – if the vertical motion is independent of the horizontal, the ball should land by the feet. The next step is to identify physical quantities and find relationships between them empirically or by derivations using prior knowledge (students combine familiar ideas of motion with constant speed and with constant acceleration). Then students design experiments to test the relationships – for example predict where a projectile will land in a laboratory. Finally students apply these concepts and relationships to explain their relevant life experiences (for example, real-life experiences related to sports) and to solve traditional and more complex problems in recitations.

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BRIDGING THE GAP BETWEEN MATHEMATICS AND PHYSICS

Tevian Dray and Corinne A. Manogue

Ask physicists to write down the magnetic field around a current-carrying wire, and the response may well be

$$\vec{B} = \frac{\mu_0}{2\pi}\frac{I}{r}\hat{\theta}.$$

Ask them where they learned about $\hat{\theta}$, and they'll most likely say, "In a math class." Yet most mathematicians have never heard of $\hat{\theta}$! So ask your mathematician colleagues, "Don't you teach students about spherical coordinates?" "Yes," they'll respond. But watch out; to a mathematician, working in spherical coordinates means just that—using the coordinates r, θ, and ϕ (which are called ρ, ϕ, and θ), but still using rectangular basis vectors $\hat{\imath}$, $\hat{\jmath}$, and $\hat{k}$.

Here's another example of the disconnect between the language of a mathematician and that of a physicist. Suppose that

$$T(x, y) = k(x^2 + y^2).$$

What is $T(r,\theta)$? Most physicists say $T(r,\theta)=kr^2$; many mathematicians would argue instead that $T(r,\theta)=k(r^2+\theta^2)$. Physicists are thinking of some physical quantity T, perhaps the temperature on a tabletop. Writing $T=T(x,y)$ refers to this temperature in rectangular coordinates, whereas $T=T(r,\theta)$ is the temperature in polar coordinates. Mathematicians have great difficulty taking this seriously, since T is being used as the name for two different functions. Instead, they would write $T=f(x, y)$, but $T=g(r,\theta)$, which physicists have great difficulty taking seriously, since it's the same temperature.

These two examples illustrate some of the pitfalls involved when mathematicians and physicists try to communicate. We speak different languages—but the basic vocabulary is the same! The first step in learning to communicate is for both sides to acknowledge that the languages are indeed different. The mathematician's claim that physicists are sloppy is no more true than the physicist's claim that mathematicians split hairs. Mathematical precision is important, especially in the absence of a physical context, but physics always has such a context.

At Oregon State University, the mathematics and physics departments are working to bridge this gap. Our first goal has been to revise the vector calculus course taught by the mathematics department. The material in this course is important for physicists, yet the math language is so different from that used in the standard physics applications that students are often unable to make the connection.

With support from the National Science Foundation, we have developed a series of guided group activities emphasizing the geometry of vector calculus, and an instructors' guide to accompany them. The materials discussed here have been used primarily in second-year calculus courses, at Oregon State University and elsewhere. We are actively developing similar materials for use in appropriate physics courses, especially mathematical methods courses or upper-division electricity and magnetism courses—look for an update!

In the process of developing these materials, we have concluded that there are two essential differences between mathematicians and physicists:

- Physics is about things;
- Physicists can't change the problem.

We discuss each of these in turn.

Physics is About Things

We like to ask students, "What sort of a beast is it?" Vector or scalar? Large or small? What are the units? This is not only a good way to quickly check the reasonableness of an equation, but also emphasizes the context. Mathematicians tend to ignore things like the "obvious" units; you can't equate a length to a squared length. Similarly, the argument of a trigonometric or exponential function, and the parameter in a power series expansion, must all be dimensionless. Putting in some extra constants is a small price to pay to get this idea across to students.

The question of units shows up again when dealing with graphs. Graphs are about the relationships between physical quantities. This means that hills are not the best examples of functions of two variables, since in this case the units for the domain and range are, atypically, the same. More importantly, physics is three-dimensional. It's hard to apply the intuition developed by graphing functions of two variables to a problem involving, say, the temperature in a room. Hence, we believe that more time should be spent on alternative ways of conveying the same information, such as the use of color, or contour diagrams, both of which do generalize to three dimensions.

Furthermore, few physics problems come neatly packaged with a coordinate system, since the physical world is independent of coordinates. It is therefore crucial to treat vectors as arrows in space, not just triples of numbers, and equally important to emphasize the geometric interpretation of the dot and cross products, not just how to compute them. In addition, physics tends to be highly symmetric. Paraboloids are the favorite surface in a vector calculus class, but how many paraboloids are there in physics? Interesting physics problems often involve elementary math. It is at least as important to understand the simple examples as it is to know how to generalize them. It is the desire to exploit symmetry that leads physicists to use adapted basis vectors such as $\hat{\theta}$, a skill mathematicians neglect in favor of more generality—those paraboloids again. In fact, we have found that the paraboloid is better handled in cylindrical coordinates!

Physicists Can't Change the Problem

Mathematics tries to chop learning up into neat packages, identifying each skill and refining it as far as possible. Physics involves the creative synthesis of multiple ideas. The problem drives the methods, not vice versa. In short, physics problems don't fit templates, so skill at solving template problems is not enough.

This can make it hard to get started. Physics problems are not usually as well-defined as math problems. There may be no preferred coordinates or independent variables, and certainly no parameterization of curves or surfaces. Unknowns don't have names. Getting to a well-defined math problem is often the hardest part of a physics problem.

Rather than a plethora of formulas for different cases, physicists need a few key ideas that will be remembered later on. The traditional vector calculus course is crammed full of formulas, most usually forgotten after the exam. We have instead built the entire course around a single idea, that of the infinitesimal vector displacement between points. By emphasizing the unity of the subject, we provide students something they may actually remember years later. Our favorite student complaint is that there doesn't seem to be enough material for an exam—we've made things too easy.

Here is a problem that illustrates some of these ideas. A helix with 17 turns has height H and radius R. Charge is distributed on the helix so that the linear charge density increases like the square of the distance up the helix. At the bottom of the helix the linear charge density is 0 Coulombs/meter. At the top of the helix, the linear charge density is 13 Coulombs/meter. What is the total charge on the helix?

We give this problem to students who have just learned about line integrals. They hate it. First of all, they don't know what "increases like" means. Second, they don't see the linear relationship between the polar angle and the height. And third, they're not comfortable finding arclength in cylindrical coordinates. None of these issues would arise in a traditional math class—the first two, because they're associated with setting up the problem, not solving it, and the last one because cylindrical coordinates are not emphasized in mathematics courses so the students are unlikely to see the problem at all.

The bottom line is that physicists tend to think geometrically, but lower-division mathematics classes have become increasingly algebraic. Perhaps the single most important goal of our work is to improve students' geometric visualization skills, thus helping to bridge the gap.

We offer workshops using materials inspired by these ideas. As of May 5, 2004, space was still available for summer workshops in Corvallis, Oregon for both the Bridge and Paradigms projects. Further information about the projects and workshops, including copies of papers and talks, can be found at http://www.math.oregonstate.edu/bridge and http://www.physics.oregonstate.edu/paradigms, respectively. These projects are supported by NSF grants DUE-0231032 and DUE-0231194.

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