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Parallel Parking an Aircraft Carrier: Revising the Calculus-Based Introductory Physics Sequence at Illinois

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For many decades, calculus-based introductory physics course sequences - henceforth, "University physics" -have provided the foundation of the outstanding science and engineering programs at many of our nation's large research universities, including the University of Illinois at Urbana-Champaign (UIUC). These courses, many substantially unchanged since the post-Sputnik science education initiatives of the late 1950s to early 1960s, have allowed most of our students to master the necessary skills to succeed in careers in science and engineering, as well as in law, medicine, and education. Given this apparent success and the immutable nature of most of the core concepts of basic physics - Newton's laws of mechanics, electricity and magnetism, geometrical optics -the obvious question is, "Why *change?*"

This question becomes even more telling when the costs of changing are considered, especially for a research university. First, the sheer scale of the project is daunting -at the UIUC, we teach nearly 2000 students per semester, 70 percent of them engineering students. Second, as at other research universities, all our faculty, postdocs, and graduate assistants must maintain active, ongoing research programs, and these responsibilities must be balanced with their teaching assignments. Finally, to provide the necessary continuity for the students who take University physics each year, we must implement these changes on the fly, without the luxury of phasing them in gradually. This means that each new course must be introduced immediately after the old course ends. Overall, the process of fundamentally recreating University physics seems a very challenging (and perhaps unnecessary?) exercise - akin to "parallel-parking an aircraft carrier".

Nonetheless, despite the very real difficulties and expense inherent in undertaking major curriculum reform, we have elected to go ahead and rock the boat. (Or in our case, the aircraft carrier.) Why? First, as recent physics education research has made painfully clear, traditional physics pedagogy has often been surprisingly ineffective in conveying fundamental conceptual understanding,[1] as distinct from rote learning and formulae manipulation. While successful students are able to solve problems by the "tyranny of technique", recent studies have shown that even they frequently misunderstand the most fundamental concepts, partly because they maintain deeply entrenched misconceptions about basic physics that conventional pedagogy has failed to dislodge.[2] Second, there are many individuals for whom traditional pedagogy has proven to be woefully counterproductive, leading neither to conceptual understanding nor to calculational dexterity, but rather to an utter disenchantment with physics.

In addition to these well-documented shortcomings in traditional instructional methods, the motivation for change comes from other needs that are also often unmet by traditional

University physics - promoting collaborative learning, teamwork and communication skills, motivating research faculty to employ new instructional methods, training graduate teaching assistants to be effective teachers, and standardizing effective pedagogy so that successful learning is independent of the efforts of one inspired teacher.

For all these reasons, over the past two years our Department has completely restructured University physics at the UIUC. A timeline for this project is presented in Fig. 1. Importantly, this effort arose simultaneously from the convictions of an energetic group of faculty dedicated to instructional change, and the vision of a departmental leadership committed to innovation to meet the explicit needs of our students and faculty, our client departments in the College of Engineering, and the organizations and institutions that employ our graduates. Our guiding philosophy, deriving from the strong theoretical base of recent physics research[3] has been: (1) to stress conceptual understanding as well as problem-solving skills, (2) to provide many paths to this understanding in order to accommodate diverse student learning styles, and (3) to make the students active participants in each path.[1,4] It has been an exhilarating and exhausting experience.

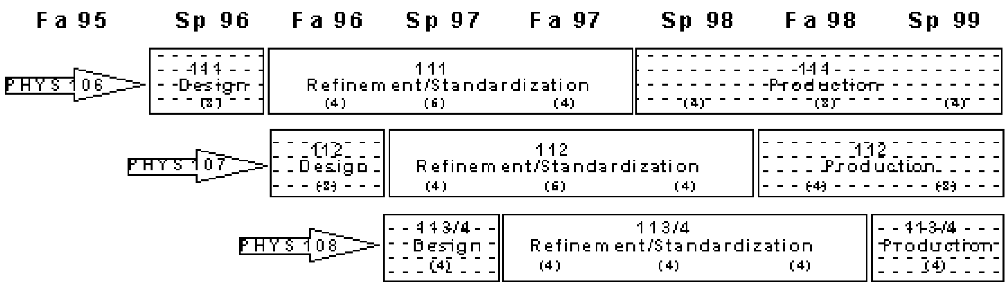

Figure 1: The three bars illustrate the four-year transition from the former three-course University physics sequence to the revised four-course sequence. The numbers in parentheses below each course name denote the number of faculty assigned. One semester's worth of faculty time is devoted to the initial design of each new course during the last semester the old course is taught, and the new courses are initiated immediately thereafter. The three-semester refinement/standardization stage allows for adjustments in response to testing and evaluation before the courses go into the production phase.

Objectives for our Curriculum Revision

In planning our curriculum revision, we first developed a set of objectives, which included:

- Adopting new "best-practice" instructional techniques, based on physics education research, that emphasize conceptual understanding.[5,6,7]
- Utilizing state-of-the-art instructional media, including multimedia presentations, World Wide Web-based interactive course materials,[8] and laboratory computer data acquisition and analysis.
- Promoting student opportunities for collaborative learning and teamwork.[9]
- Standardizing meaningful course content and effective pedagogical methods, so that good teaching is not dependent on a single inspired instructor but is integral to all sections of all classes,[10] while allowing room for faculty creativity and continuous improvement.
- Building an administrative/management infrastructure to support and sustain continued curriculum development as new methodologies evolve.

A significant consideration in redesigning the courses was to develop a comprehensive curriculum in modular units that could be combined in different ways by departments in the College of Engineering, according to their students' perceived needs. We have thus taken the earlier four-credit-hour courses - Physics 106 (Mechanics), 107 (Electricity and Magnetism plus Thermodynamics), and 108 (Geometrical Optics, Waves, and "Modern Physics") - and reworked them into Physics 111 (Mechanics) and 112 (Electricity and Magnetism) - still four-hour courses - and Physics 113 (Fluids and Thermal Physics) and 114 (Waves and Quantum Physics), which are now two-hour courses. Thus, the courses can be flexibly combined to form one 12-hour or two 10-hour sequences.

Physics 111 replaces Physics 106, with the addition of a unit on transverse waves (previously presented in Physics 108). With the deletion of the thermodynamics section of Physics 107, Physics 112 now provides a unified topical coverage of electricity and magnetism. Practical treatments of electromagnetic waves, polarization, and geometrical optics (previously in Physics 108) now round out Physics 112. Physics 113 presents an introduction to fluid mechanics and augments the coverage of thermodynamics (previously in Physics 107) with some ideas of the microscopic origins of the basic concepts. Physics 114 contains a practical treatment of wave interference and an introduction to quantum physics, topics that were previously covered in Physics 108. We invite you to examine our new course outlines and materials at http://webug.physics.uiuc.edu/courses/

Fine-Tuning the Changes: Refinement and Standardization

As shown in Fig. 1, after the initial one-semester design phase, we plunge immediately into teaching the course. We have planned a three-semester "shakedown cruise", when the curriculum and instructional changes can be tested and refined. The goal of this phase of development is to arrive at a basic core curriculum that is both meaningful and effective -ot dependent for success on the heroic efforts of one inspired and inspiring teacher - while at the same time offering the flexibility to accommodate individual faculty creativity and continuing improvement.

For example, in response to student mid-term and end-of-term evaluations in Physics 111, we have added more "conceptual" problems to the discussion sections and hourly exams, added some true/false and 3-part multiple-choice problems and some "optional" problems to the homework, in order to provide increased practice with these types of questions. We have reduced the number of activities in several of the new labs, having initially underestimated the time it would take students to complete them.

We are also using this time to develop, test, and refine a large bank of problems for discussion sections, homework sets, quizzes, and exams. We track student scores problem by problem and then use the results to either eliminate a problem or assign it to a better usage. For example, some questions clearly are not amenable to true/false or multiple choice solutions, but are well-suited for discussion sections. Other problems that appear to require considerable pondering might not be appropriate for time-limited exams but would offer good exercise for extra-credit homework questions.

It is important to note that we maintain a distinction between "standardization" and "fossilization". While our goal is to develop uniform, tested, effective curriculum modules, we also must support faculty innovation and creativity. Thus, faculty teaching the courses for the first time are encouraged to develop their own problems, design their own ACTs, and create their own lecture presentation materials. We are then able to test the effectiveness of this new material in our 2000-student "laboratory" keeping the best of it and thus incorporating incrementally improved material each semester.

"Institutionalizing" the Changes

Before discussing the five components of each of the new courses, we should emphasize our view that the long-term success of any curriculum revitalization can only be guaranteed if the changes can be institutionalized, i.e. can be designed to remain in place after faculty members initially involved in the revised courses move on to other endeavors, and new faculty take over.

Our Department has a tradition of instructional collective ownership: that is, our faculty do not have property rights to specific courses, but rotate to new teaching assignments every three to four semesters - reducing faculty burnout by distributing the burden of the more time-consuming and difficult courses. We find this approach increases interactions among the faculty in our large and broad department, promotes departmental collegiality, and improves overall instruction, while allowing us to maintain some "quality assurance" over the course content. We thus maintain a prescribed core curriculum and comprehensive files of instructor's notes, lesson plans, homework assignments, special projects, and exam questions for each course, so that a first-time instructor has a substantial set of pre-tested material to begin from. Despite these efforts, the elementary courses, in which many students view themselves as unwilling conscripts, have remained the most demanding and least satisfying teaching experiences. Not surprisingly, faculty have accepted their assignments to these courses stoically but not enthusiastically and were very glad when their tours of duty were complete. Clearly, unless teaching

University physics were to become more rewarding for the faculty, the prospects for institutionalizing the improvements that curriculum reform offered were dim.

Our solution for Physics 111-114 has been to employ team teaching, in which a group of faculty divides up the responsibilities for the various course components - i.e. each course has main and back-up lecturers, labmaster(s), and homework master(s) - and the team members are also rotated through these courses, such that each new instructor is matched with experienced faculty who have either participated in the initial course design or taught the revised course. This shared responsibility ensures that faculty assigned to these 700+ student courses regard this as an ordinary teaching assignment, not one requiring superhuman effort, and enhances institutionalization of content and methodology by providing on-going contact between experienced faculty and new team members.

From the faculty perspective, we have already noted two indicators of faculty satisfaction: (1) the original Physics 111 developers have chosen to remain in the course (having already served their original commitment of three semesters) but have exchanged course responsibilities, a practice we would like to encourage, and (2) seven new faculty members, in addition to the six original developers, have successfully and enjoyably taught on Physics 111 and 112 teams. Given that research faculty have historically disliked teaching traditional University physics courses nearly as much as students have hated taking them, we think this is remarkable.

Course Components

Lectures: We have altered the traditional lecturing format substantially, using interactive, multimedia lecture presentations that incorporate active learning segments (ACTs), typically three per presentation. These ACTs, which are motivated by research that has shown that students must be intellectually active in order to develop "functional" understanding,1 are patterned after the ConcepTests developed by Eric Mazur.[4] Importantly, many ACTs involve demonstrations to illustrate correct physics intuition and to reinforce the basic concepts being presented. In addition to the instructor, two "stairmasters" (typically senior graduate teaching assistants [TAs] or faculty who will be teaching the following semester) are assigned to each session; their job is to circulate through the auditorium and provide guidance and facilitate discussion during the ACTs. The interactivity promoted by the ACTs, both among the students, between the students and the presenter, and between the students and the stairmasters, results in classroom dynamics that are quite different from conventional large-audience lectures, and substantial increases in student attendance under the new format, compared to historic norms, have been observed.

Discussion Sections: The two-hour discussion sections for these courses feature group work on problems emphasizing conceptual understanding that have been created by senior faculty, not TAs. Our original intention was to create "context-rich" problems patterned after those of the U. Minnesota group.11 We have found that this approach works quite well for the Physics 111 (Mechanics) course, but we have thus far had to abandon it in Physics 112 (Electricity & Magnetism), because of its more abstract content.

While we are hopeful of eventually altering this situation, our experience mirrors that of the physics education community, where the well-tested Force Concept Inventory[12] and the Mechanics Baseline Test[13] provide accepted standards for assessing the knowledge of mechanics, but no similarly broad tools currently exist for testing knowledge of electricity and magnetism.

The format of the new discussion sections has required significantly increased attention to the training of our TAs. Instead of merely working calculational problems as the students watch passively, the TAs are now expected to act as facilitators for group learning and to emphasize conceptual knowledge-based problem solving, i.e. to guide students to the solution instead of telling them the answer. Increased emphasis has necessarily been placed on effective instructional methods, and we now separately train discussion TAs and lab TAs.

Laboratory Sections: Our former University physics labs - like those at many peer institutions - were "observe and measure" only, often with too much emphasis on the details of measurement (e.g., error analysis). The new two-hour labs feature experiments based on the "predict-observe-explain" approach of Thornton & Sokoloff [14] to more actively engage students in the learning process and to promote mastery of concepts by manipulation of experimental apparatus. We have also adopted the use of pre-lab assignments, consisting of several questions designed to prepare the students for the concepts and exercises presented in each lab. Scripted lab reports, which can be finished within the class time, are employed.

Homework Assignments: Our Department's more than twenty-five years' experience with computer-aided physics education provides considerable evidence of the effectiveness of requiring students to interact with a set of carefully constructed, incremental homework exercises, which progressively build both the student's sum of factual knowledge and his or her abilities to synthesize and apply this knowledge in practical problem-solving.[15] Homework sets developed for the new curriculum consist of problems that the students solve using CyberProf™ (CP), an interactive Web-based learning environment created by one of our faculty as an outgrowth of his complex systems research. CyberProf™ offers a number of advantages over conventional computer-assisted homework sets because of its Web-based implementation, platform independence, and comprehensive feedback. In its current version, CP is able to recognize even a mathematically ambiguous or partially correct answer and, using an interactive series of Hints and Helps, to guide the student to the correct answer. A drawing tool records and analyzes graphical input, and a what-if feature is planned that would allow a student to change a problem's variables to generate additional related questions, thus promoting self-testing.

Exams: Student attention inevitably focuses on the exams, since their performance on exams is the dominant factor in their final grades. Consequently, "conceptual" questions must be included on exams, if we wish to convey the importance of functional understanding.1 When only traditional calculational problems are given on exams (as in our previous Physics 106-108 sequence), students develop problem-solving "routines" that are often based on shortcuts, learned through repetition, and applied unthinkingly, rather than being derived from the concepts the problems were designed to test. We have thus adopted an exam format that includes approximately 25 percent conceptual questions.

In order to grade answers fairly and uniformly for the large number of students taking these classes, we have adopted a machine-gradeable, true/false and multiple-choice question format, which we believe tests conceptual understanding. Our initial experiences with this exam format have been quite positive, but we plan to undertake rigorous professional assessment of this method to validate it as an accurate tool for assessing a student's conceptual understanding.

The Last Word(s)

Has it been easy? No! Would we do it again? YES!! We believe that physics is the "liberal arts education for a technological society" and that excellence in physics is critical to maintaining scientific, technological, and economic vitality in a world where U.S. leadership can no longer be taken for granted. Thus, we must do a better job for our students in conveying conceptual understanding, in promoting teamwork and communication skills, and in recapturing the interest and enthusiasm of those who have too often before been disillusioned and left behind. Our preliminary assessment of the University physics revision undertaken at UIUC is strongly favorable. We have glowing testimonials from students and faculty that express great enthusiasm for the changes, and evaluation surveys that show statistically significant improvements in student satisfaction with the new courses, compared to their forerunners. In the years to come, we will continue to work to achieve our final objective - to support and sustain continued curriculum development as new insights emerge and methodologies evolve.

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