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Parallel-Parking an Aircraft Carrier: *Revising the Calculus-Based Introductory Physics Sequence at Illinois*[1]‡

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Why Change?

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. Consider, for instance, the national impact of our own UIUC University physics—approximately 1 in 40 practicing engineers in the United States was trained at the UIUC,(1) and most of them took these courses. 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,(2) 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.(3) Second, as also documented by physics education research, 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 an increasingly technological society, failing to "stalk the second

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tier"[4] can be damaging, not only to physics' well-being, but also to our nation's scientific literacy and global competitiveness.

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—the need to promote collaborative learning and teamwork and communication skills, the need to motivate research faculty to employ new instructional methods and to train graduate teaching assistants to be effective teachers, and the need to standardize 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 stakeholders—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[5] and driving this revision, 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,[4] and (3) to make the students active participants in each path.[2,6] It has been an exhilarating and exhausting experience. The ensuing comments may be viewed as both a captain's log of our on-going efforts and, we hope, a useful operations manual for others who may consider undertaking their own challenging *carrier* maneuvers.

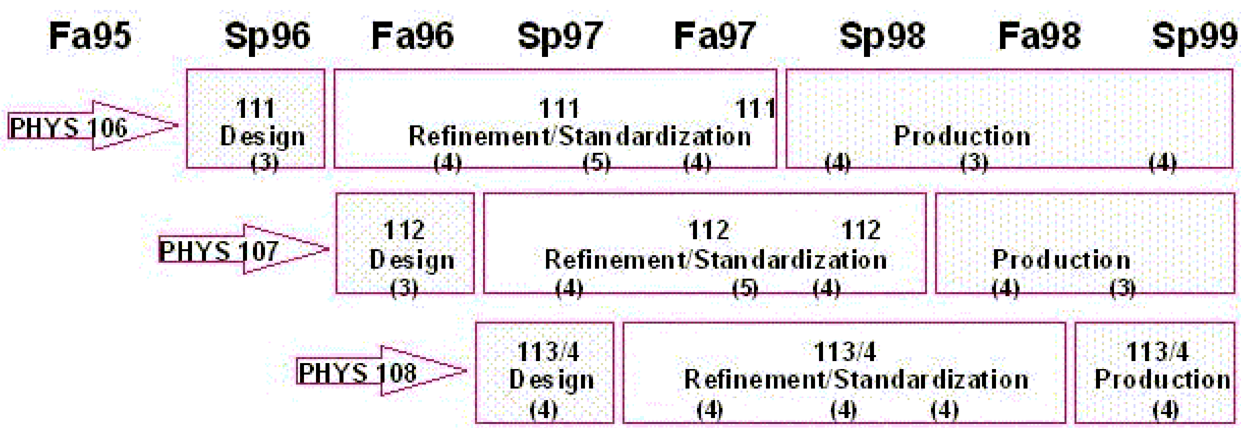

Fig. 1. The three bars illustrate the four-year transition (Fall 1995 to Spring 1999) from the former three-course University physics sequence at UIUC to the revised four-course sequence. The numerals in parentheses below each course name denote the number of faculty assigned. Note that one semester's worth of faculty time is devoted to the initial design of each new course during the last semester that the old course is taught, and that the new courses are initiated immediately thereafter. The three-semester *Refinement/Standardization* stage allows for adjustments in response to testing and evaluation, before the standardized courses go into the *Production* phase.

Designing the Changes: 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.[7,8,9]
- Utilizing state-of-the-art instructional media, including multimedia presentations, World Wide Web-based (Web) interactive course materials,[10] and laboratory computer data acquisition and analysis.
- Promoting student opportunities for collaborative learning and teamwork.[11]
- 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,[12] 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 our peer departments within 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.

To provide a bit more detail on the specific syllabi, Physics 111 replaces Physics 106, with the addition of a unit on transverse waves, which was 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; start at *http://webug.physics.uiuc.edu/courses/* and follow the links.

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—not 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 to the homework, and added 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.

Another area we are exploring is the optimal length and scope of the lecture presentations. In the first offerings of Physics 111 and 112, we took a conservative approach and extended the time allotted to lectures by 50 percent, in order to ensure adequate time for the ACTs while continuing to cover all of the lecture material presented in the former classes. This created scheduling difficulties for some of our students, and as we are testing the new curriculum, we are actively integrating the ACTs and tightening up the lecture demonstrations, with the goal of resuming the fifty-minute class hour.

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: Collective Ownership and Team Teaching

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 and does not have to “re-invent the wheel” each time he or she takes on a new course. 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 as well. 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 who have previously 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

(i) "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,[(2)] are patterned after the ConcepTests developed by Eric Mazur.[(6)] 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.

(ii) 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.[(13)] 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*[(14)] and the *Mechanics Baseline Test*[(15)] 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.

(iii) 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 [(16)] 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.

(iv) 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.[(17)] 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. [(10)] 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.

(v) 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.[(2)] 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.

Lessons Learned

Although we are still in the process of implementing the curriculum changes—Physics 113 and 114 will be taught for the first time in the Fall 1997 semester—we have already learned a number of important lessons, listed below with their light-hearted mnemonics:

"Just do it": Sweeping curriculum revision is one case where the bungee-jumping approach to change has its merits: it will ALWAYS be too painful to contemplate, and there will always be compelling reasons why *now* is not an opportune time. We in the community simply must "just do it!"

"The Few, the Proud, the . . . TEAM": We have been very fortunate to have a committed team of creative, visionary faculty guiding our curriculum revision. While it is essential to have administrative support for any reform effort, the success of such an undertaking cannot be mandated from the top down—it must have passionate leaders at the grass roots level, and it must be a group effort. Identifying a real "first team" of committed faculty is critical; in our case, we looked to individuals from subdisciplines where working in groups is a strong tradition.

"Equal Opportunity Thievery": There is now a considerable body of excellent materials derived from prior physics education research, and we have freely adapted many of them to our own circumstances. We hope that we can begin to repay our debts to the community by sharing our experiences.

"Bet the Farm": Departments wanting to undertake such a major revision effort must be prepared to spend their own dollars and resources on planning and development—for faculty release time, for instructional hardware, for faculty professional development, and for TA training. We hope that we will receive the necessary external support to share our materials and our experience with our peer departments, thus sparing them some of this expense. We are always glad to share our success—and horror—stories.

"Abe Lincoln's Axe": Of the many Lincoln stories told in Illinois, the one most relevant to the present situation may be the story of Abe Lincoln's axe—to be sure, the handle may have been replaced five times and the blade three since last Abe swung it, but it is *still* Abe Lincoln's axe! Thus should it be with the revised courses, which must be designed to remain "revised." Our approach—team teaching—appears to be successful, providing for essential individual creativity and flexibility for faculty while maintaining consistency of content and methodology.

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,"[18] 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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1. William R. Schowalter, Dean, UIUC College of Engineering, Commencement Address (17 May 1997).

2. L.C. McDermott, "How we teach and how students learn—a mismatch?" Am. J. Phys. **61**, 295-298 (1993); and L.C. McDermott, "What we teach and what is learned—Closing the gap," Am. J. Phys. **59**, 301-315 (1991).

3. Ibrahim Abou Halloun and David Hestenes, "The initial knowledge state of college physics students," Am. J. Phys. **53**, 1043-1055 (1985); Ibrahim Abou Halloun and David Hestenes, "Commonsense concepts about motion," Am. J. Phys. **53**, 1056-1065 (1985).

4. Sheila Tobias, *They're Not Dumb, They're Different: Stalking the Second Tier,* (Tucson, AZ, The Research Corporation, 1990).

5. Arnold Arons, *Homework and Test Questions for Introductory Physics Teaching* (New York, J. Wiley, 1994); Edward F. Redish, "Implications of cognitive studies for teaching physics," Am. J. Phys. **62**, 796-803 (1994); Jose Mestre and Jerold Touger, "Cognitive Research—What's in it for Physics Teachers?" Phys. Teach. **27**, 447-456 (1989).

6. E. Mazur, *Peer Instruction: A User's Manual*, Prentice Hall, Upper Saddle River, NJ (1997); Sheila Tobias, *Revitalizing Undergraduate Science: Why Some Things Work and Most Don't,* (Tucson, AZ, Research Corporation, 1992).

7. Edward F. Redish, "New Models of Physics Instruction Based on Physics Education Research," invited talk presented at the 60th meeting of the *Deutschen Physikalischen Gesellschaft*, Jena, Germany (14 March 1996).

8. Alan Van Heuvelen, "Learning to think like a physicist: A review of research-based instructional strategies," Am. J. Phys. **59**, 891-897 (1991).

9. William J. Leonard, Robert J. Dufresne, and Jose P. Mestre, "Using qualitative problem-solving strategies to highlight the role of conceptual knowledge in solving problems," Am. J. Phys. **64**, 1495-1503 (1996).

10. A.W. Hübler, "CyberProf: A New Way of Teaching and Learning," keynote speech presented at the National Science Foundation *LACEPT: Teaching Mathematics and Science at the Undergraduate Level*, Baton Rouge, LA (26-27 January 1996); see also Alfred W. Hübler and Andrew M. Assad, "CyberProf: An Intelligent Human-Computer Interface for Asynchronous Wide-Area Training and Teaching," invited talk presented at the *Fourth International World Wide Web Conference*, Boston, MA (12-13 December 1995).

11. Patricia Heller, Ronald Keith, and Scott Anderson, "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving," Am. J. Phys. **60**, 627-636 (1992); Patricia Heller and Mark Hollabaugh, "Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups," Am. J. Phys. **60**, 637-641 (1992).

12. J.W. Harrell, “Freshman Physics in the NSF Foundation Coalition,” *Forum on Education of the Am. Phys. Soc.*, 6-7 (Spring 1997).

13. Kenneth Heller, Patricia Heller, and Mark Hollabaugh, *Cooperative Group Problem-Solving in Physics*, (Minneapolis, MN, University of Minnesota, January 1994).

14. David Hestenes, Malcolm Wells, and Gregg Swackhamer, “Force Concept Inventory,” Phys. Teach. **30**, 141-151 (1992); and Douglas Huffman and Patricia Heller, “What Does the Force Concept Inventory Actually Measure?” Phys. Teach. **33**, 138-143 (1995).

15. David Hestenes and Malcolm Wells, “A Mechanics Baseline Test,” Phys. Teach. **30**, 159-166 (1992).

16. D.R. Sokoloff, R.K. Thornton, *Motion and Force Laboratory Curriculum and Teachers’ Guide*, Vernier Software (1992); D.R. Sokoloff, P.W. Laws, R.K. Thornton, *Real Time Physics: Active Learning Laboratories, Electricity* (1993); R.K. Thornton and D.R. Sokoloff, “Learning motion concepts using real-time microcomputer-based laboratory tools,” Am. J. Phys. **58**, 858-867 (1990).

17. L.M. Jones and D.J. Kane, “Student evaluation of computer-based instruction in a large university mechanics course,” Am. J. Phys. **62**, 832-836 (1994).

18. Joseph M. Pimbley, “Physicists in Finance,” Phys. Today **50** (2), 42-46 (1997).