

Paradigms in Physics: Restructuring the Upper Level

Eight years ago, Oregon State University's physics faculty reshaped their curriculum into one focusing on themes and concepts that cut across a variety of subjects. Students, faculty, and teaching assistants discuss the changes.

Corinne A. Manogue and Kenneth S. Krane

Before the early 1990s, Oregon State University followed a traditional approach to teaching upper-level college physics and presented to its students a steady diet of essential courses that make up the field: classical mechanics, electromagnetism, thermal physics, quantum mechanics, and math methods. Other aspects of the program were equally traditional for a “research 1” school like OSU—much of the faculty focused on research and the graduate program. With 1200 students per term enrolled in introductory courses, the bulk of our effort as faculty members went toward improving the courses that served the most students. The upper-level curriculum seemed to be supporting the much smaller third- and fourth-year classes well enough: OSU students were winning acceptance to leading graduate schools and securing jobs with leading companies in technical fields. The department was awarding an average of 15 baccalaureate degrees per year, which put us above the national average for PhD-granting physics departments. What possible motivation could there be for undertaking a major curriculum reform project that would eventually involve about three-fourths of the faculty and would reorganize the content in virtually every junior- and senior-level physics course?

Despite the department's success, not everyone was happy with the teaching of our upper-level courses. Many students had trouble moving from the relatively low level of mathematical and intellectual rigor of the introductory courses in the sophomore year to the much more demanding courses that began in the junior year. About one-third of our upper-level majors are transfer students from two-year colleges, and many of them had particular difficulty making the transition. And faculty members who taught the advanced undergraduate courses reported that even some of the better students were not acquiring the command of the subject matter that we expected them to achieve. But departmental efforts at improvement were fragmentary or incomplete.

The catalyst that finally prompted comprehensive change eight years ago was the participation of many of our engineering-physics students in a five-year internship-based degree program that required their absence from

campus during the spring quarter of their third and fourth years. Discussions of ways to eliminate all required courses from the spring quarter eventually snowballed into a complete review of all topics covered in the traditional core junior–senior courses: classical mechanics, electromagnetism, and so forth. Topics from each course were written on index cards

and laid out in parallel rows on a table. For the next several months, faculty members would individually move cards around to address curricular concerns. From the resulting array, we noticed that certain common physical and mathematical themes—solving the wave equation, for example, or transforming between frames of reference—appeared in several locations. We called these common themes or concepts “paradigms in physics.”

After identifying the set of themes that could form the basis for a redesigned curriculum, the faculty discussed the issues and voted unanimously to adopt a complete overhaul of the content and pedagogy. An NSF grant kick-started the development process and we introduced the revised curriculum to our junior class two years later in the fall of 1997. We have now been through five complete cycles of the program.

Pedagogy and curriculum

Insights gleaned from physics-education research (PER)¹ explain part of our rationale in restructuring the curriculum. Focused on introductory courses, PER results have proven robust, replicable, and applicable at all types of institutions, public and private, from two-year colleges to research institutions. In brief, PER has taught us that a number of factors will improve student learning: active participation (as opposed to passive note-taking) in exploring the material; a spiral approach that returns to common themes with an increasing level of sophistication or complexity; exploring examples before discussing the general theory; group activities and peer instruction, in which students work with one another during class time in response to problems or exercises posed by the instructor; and a clear focus on content objectives, which forces instructors to trim or repackage bloated courses to accommodate what they reasonably expect students to master in the allotted time—sometimes called the “less is more” approach. We believe that the need for these teaching strategies does not somehow vanish between the sophomore and junior years, so our paradigms courses reflect these proven pedagogical approaches.

The paradigms curriculum (see the table on page 54) consists of a set of nine intense three-week modules, each an individual course designed to explore themes and concepts, such as periodic potentials, energy and entropy, or central forces, that are common to a variety of fields in physics. Taken in sequence during the students' junior

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Paradigms in Physics Curriculum

Paradigms courses (junior year)	Capstone courses (senior year)
Symmetries and Idealizations (optional)	
Static Vector Fields	Electromagnetism
Oscillations	
One-Dimensional Waves	Classical Mechanics
Spin and Quantum Measurements	
Central Forces	Mathematical Methods
Energy and Entropy	
Periodic Potentials	Quantum Mechanics
Rigid Bodies	
Reference Frames	Thermal Physics

year, the courses transcend the traditional divisions in the advanced curriculum by encouraging students to draw connections between subdisciplines. Each course carries a unique catalog number and students receive a separate grade in each course. In our ten-week academic quarter system, we use the additional week as a preface (to introduce new skills, such as symbolic manipulation techniques) or postscript (to assist students in making the necessary synthesis). The schedule is intense, with courses meeting five days per week in one- and two-hour sessions.

During the senior year, students resume a more traditional program, a series of capstone classes in five traditional areas. Because topics from the five areas are scattered throughout the paradigms, however, the capstones can present a more advanced and synthesized approach to each of the critical areas. For example, we offer only a 10-week capstone in quantum mechanics because students have already seen many of the topics of our previous one-year quantum course at various times during the paradigms. And because such topics as orthogonal functions, eigenvalue equations, measurement theory, bra-ket notation, angular momentum eigenfunctions, density matrices, band structure, and coordinate rotations are included in the paradigms, the quantum mechanics capstone can

move quickly into more sophisticated applications, including fine structure, angular momentum coupling, and scattering theory. Another difference involves the dynamics of the discussion in the senior-year courses. Prior exposure in the paradigms courses to so wide a variety of examples affects the level of discussion in the capstones classes: Students appear more engaged and keen to discuss the extent, breadth, and limitations of the examples they studied the year before.

Additional breadth in the curriculum comes from required courses in electronics, optics, an elective specialty course—solid state, for instance—and a senior thesis.

In our current program, the total number of classroom hours remains roughly the same compared with the previous traditional curriculum; only the content organization has changed.

The details of the curriculum can be found in reference 2 and in the Web pages of the OSU physics department.³ Our focus in this article is the effect of the paradigms curriculum on our students as learners, ourselves as teachers, and, to some extent, the institution as a whole.

The student experience

It is apparent to faculty and students alike that the reforms in both content and pedagogy have changed the learning experience. Students have a distinct view of how the paradigms have affected their education—box 1 on page 55 offers a sampling of comments. As faculty, we have our own perspective.

► **Satisfaction is high.** Faculty who have taught upper-division courses before and after the introduction of the new curriculum are certainly aware of an improvement in student satisfaction and attitude. Top students reported feeling more excited and weak students reported feeling more supported. That satisfaction may account for an increase in the number of physics majors and graduates over the past few years; the increase is noteworthy be-

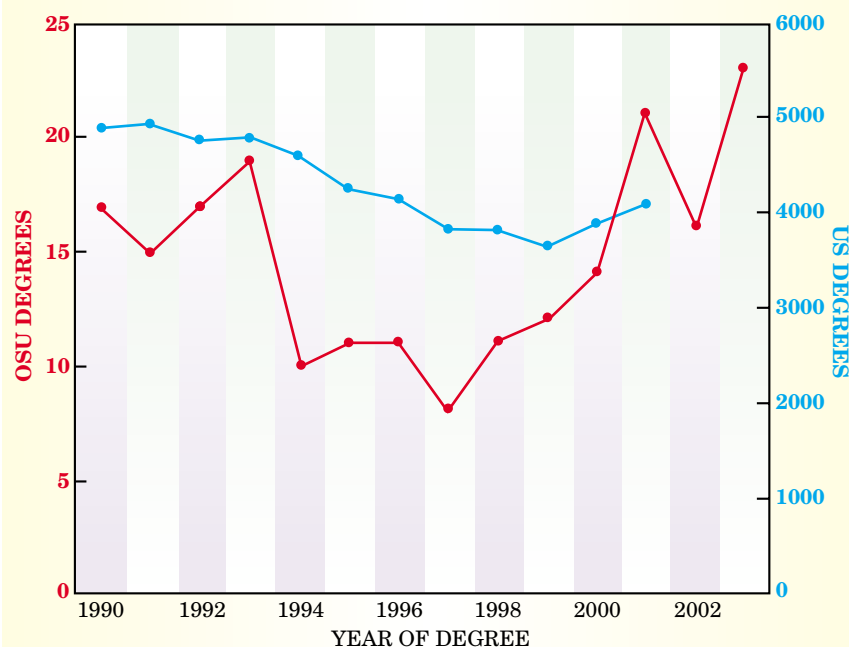


Figure 1. Oregon State University's physics department followed the national trend in the mid- to late 1990s, graduating progressively fewer majors. Red and blue data points indicate, respectively, the yearly number of OSU undergraduate physics degrees and the total number of US undergraduate physics degrees. OSU's graduate numbers have recovered to the point where they now exceed our early 1990s average of about 15 per year. Based on current class sizes, the department expects to award 25–30 degrees each year for the next two years. (US data adapted from ref. 6.)

Box 1. The Student Experience

The paradigms helped me understand the material better through visual aids and computer simulations. When you see it graphically, the physics of the problem becomes clear and gives life to the derived mathematical expressions. The project also helped students learn how to teach one another. Due to the rapid pace, everyone at some point in the program found themselves lost in the material. This provided multiple opportunities for fellow students to teach concepts.

—Tyson Olheiser, 2001, graduate student in physics at the University of Illinois at Urbana-Champaign

The paradigms program was very good about teaching me to use my resources, whether it be professors, texts, or journal articles. The program overall built my confidence because it was challenging. In retrospect, having the shortened, more intensive classes kept us on the ball more. Subjects were fresh and there were those elements of excitement and uncertainty going directly from finishing a difficult paradigm to starting a new one with a new professor.

—Megan Kalstad, 2000, graduate student in bioengineering at Arizona State University, Tempe

Prior to these classes, my only physics had been a first-year calculus-based intro course. The experience in paradigms was a complete departure from this. There wasn't much in the way of plugging things into formulas, but rather a focus on how to attack problems as a physicist would attack the problem. There was one other thing about the paradigm courses that really impressed me, and that was the way it drew all the majors together to work on things. There is nothing like this in mathematics.

—Sam Cook, graduate student in mathematics at Oregon State University, Corvallis

One of the best things about organizing the classes by paradigm rather than by application was that each concept was applied to different areas of physics in rapid succession. This encouraged me to see each concept as a useful tool rather than as a math trick specialized to a narrow set of

problems. Learning this way was extremely exciting and I remember toying with the application of basis functions, vector fields, and canonical ensembles to diverse things like taste, color, economics, and evolution. I learned faster in paradigms than at any other time in college.

—Ethan Bernard, 2000, graduate student at Cornell University, Ithaca, New York

The paradigms program exposed us to the necessity of time management and prioritization. We always had something due, and we needed time every day for something that was due or to simply catch up. This is immensely useful now that I am in grad school. As we had the class every day, it was generally easy to follow from one day to the next. When I have three to five days between classes, I have almost no recollection of the specifics from the previous discussion.

—Rachel Bartlett, 2002, graduate student in medical physics at the University of Wisconsin–Madison

Coming from the paradigms background, I immediately felt comfortable working in a team atmosphere: sharing ideas, problem-solving, double-checking your work with others. The other benefit of the paradigms program I have found was becoming accustomed to the quick turnaround between projects. Since the classes were only three weeks long, you got used to concentrating heavily on one area, then switching focus to another concentration. This, I have found, is exactly what the production environment is like.

—Mike Joyer, 2002, engineer at aerospace company

The paradigms curriculum constructed my knowledge from a fundamental level, with each paradigm building on the last. The emphasis on big-picture learning and universal problem-solving carries over in my graduate studies today. Additionally, I feel the pace and difficulty prepared me for the challenge of graduate school.

—Loren Linden-Levy, 2001, graduate student in physics at the University of Illinois at Urbana-Champaign

cause, as shown in figure 1, it came at a time when the number of physics majors throughout the US was showing a prolonged decline (see the article by Robert Hilborn and Ruth Howes on page 38).

Other factors may also explain the rising numbers of physics majors and graduates. The buzz on campus and throughout the local physics community has prompted some students to transfer into physics from other majors and some physics majors at nearby colleges to matriculate into OSU's program. The paradigms are no less rigorous than the standard curriculum, but provide a gentler introduction to topics. Moreover, the group activities provide faculty with more opportunity to offer students individual guidance and attention. Such a supportive classroom environment appears to retain the students who might otherwise transfer to less challenging majors if taught physics using the traditional approach. At the same time, the superior students find opportunities to explore the material at an even higher level.

► **The curriculum needs to be split.** Breaking the curriculum into smaller pieces promotes mastery and self-confidence. Who could ever hope to master a subject called “electromagnetism” or “classical mechanics?” The very names can intimidate students. We believe the simple division of the curriculum into three-week subjects having

less encompassing names, like “central forces” or “one-dimensional waves,” encourages focus by students and their instructors. The enthusiasm and high levels of concentration that students often bring to the start of a course are easier to sustain over short three-week segments.

► **Paradigms break the “tyranny of the textbook.”** In the absence of an existing textbook that follows our departure from the traditional approach, the paradigms curriculum does use a set of standard textbooks.⁴ But where our courses diverge from the traditional approach, we have developed unique materials; these range from short, transitional handouts (that cite traditional texts) to complete sets of notes. Our materials also include worksheets for group activities, computer projects, and homework assignments.

Initially, we were concerned with the difficulties that students would face without a comprehensive textbook to provide coherence. Because the paradigms often span several subdisciplines, students frequently will work from several different textbooks, each of which is likely to use a different voice or notation. We were surprised to discover that dealing with different textbook approaches forced students to examine concepts more closely and ask themselves the kind of questions that enhance the learning process.

Learning from several sources avoids the narrow focus

Figure 2. The paradigms classroom. Students are working on a project in the rigid-bodies paradigm to understand the rotational behavior of an asymmetric object. They are constructing such an object by attaching lumps of clay to various locations on a wire cage. When they have finished, quick swiveling of the chairs converts the classroom from lab to lecture. After class, students will reclaim the space as a study area and lounge.



that a single textbook provides. A textbook on classical mechanics, for example, cannot extensively develop the relationships of its fundamental concepts with those of electromagnetism or quantum physics, because the author cannot gauge the depth or breadth of student exposure to other subjects. Our curriculum can develop such connections precisely because we, not the textbook authors, manage the ordering and grouping of topics.

► **Paradigms promote a community of learners.** Small-group activities are woven into the fabric of the paradigms. Many of these are in-class projects that promote active engagement, and they generally do not count toward any student's grade. The emphasis is more on learning the concepts than simply getting the right answer. That spirit carries over into study sessions outside of class and persists into the senior year.

A critical element of this process was the creation of a dedicated classroom exclusively for the paradigms classes (see figure 2). Students sit at rectangular tables arranged in rows, with two or three to a table. Students face forward for lectures, but a quick move of some chairs transforms the class into working groups. Students can brainstorm on large whiteboards mounted on the wall next to each group or scratch notes and calculations on smaller portable whiteboards.

Junior-year students at OSU develop a sense of ownership for the paradigms room: They drop their books and coats in the room first thing each morning, have weekend or after-hours access, and use the room almost constantly as a group study area between classes. (A separate undergraduate study lounge exists, but is now seldom used by the juniors.)

► **The TA experience.** From the beginning, graduate students have played a significant role in the development and implementation of the paradigms program; they write and test many of the interactive projects and symbolic ma-

nipulation activities. Some, in fact, used the curriculum reform as the basis for thesis research in physics education. Others were teaching assistants assigned to the courses or were employed under an NSF grant.

Usually, a single graduate TA is assigned to the paradigms courses, and that person's assistance and expertise are essential ingredients of a successful program. Box 2 on page 57 offers the perspective of two graduate students who have been an integral part of the program.

The faculty experience

Such a coherent and tightly interconnected course structure involving 14 individual courses could not exist without mutual agreement and frequent communication among the 8–10 members of the faculty who teach the paradigms and capstone courses at any given time. We meet as a group about once a month to exchange ideas, share new developments, and apprise each other of any difficulties that arise. To ensure seamless course transitions, it is essential for faculty to know what has already been taught. The meetings let faculty coordinate content (and, in some ways, pedagogy), integrate new instructors into the program, and discuss mid-course corrections or ideas. Aided by the close collaboration, course development and improvement have become continuous and dynamic processes.

Some curriculum reform projects are carried out by a relatively small number of department “heroes” who are treated with benign neglect by other faculty. And, in the initial stages of our reform program, the paradigms courses were taught exclusively by their developers. But to fully integrate the program into the department, it was critical at an early stage to have the endorsement of all faculty, especially those who were not active participants in the program. Prior to its adoption at OSU, the curriculum was presented and discussed at numerous meetings of our

Box 2. The TA Experience

With many talented people working together to design and teach an entire upper-division physics curriculum at Oregon State University, the paradigms in physics program has provided a unique opportunity for the graduate teaching assistants involved. We have taken on a diversity of roles as paradigms teaching assistants; each role has fundamentally shaped how we understand teaching and learning physics. We were given responsibility and real opportunities to design and teach course materials. Our experience as TAs has been hallmarked by the fact that, throughout the development of the paradigms, we have worked closely with professors who have thought deeply and broadly about some piece of physics—what are the most important aspects of the topic, what are their implications to physics and the real world, and how can these be conveyed to students.

Working as teaching assistants in the paradigms has dramatically changed our thoughts about teaching physics as well as our understanding of how students learn physics. The paradigms curriculum development project has provided an excellent example for how to think about teaching. It clearly emphasizes the central position of the student in the classroom. Rather than focusing exclusively on what they were going to say, the professors spent a lot of time thinking about and observing how students interact with their course materials. Through pedagogical discussions and personal example, the paradigms instructors conveyed the value of listening to, observing, and engaging students, rather than merely lecturing at and testing them. While these experiences were instructive for us, the occasions when we were given the power to practice curriculum development ourselves affected us even more. The trial-and-error process of developing and teaching integrated labs and group activities convinced us of the value of actively engaging students. By observing students' behavior as they grappled with the physics and the curriculum, we developed a better understanding of how they interact with a curriculum to construct their own understanding of the material.

While the teaching methods and structure of the curriculum were a central part of our focus, we also benefited from our exposure to the content of the curriculum. The old adage is that to really learn a subject, one must first teach it. The paradigms gave us just such an opportunity to experience teaching upper-division physics with the guidance of expert teachers who were focused on developing and improving their courses. As a result, we came to a much deeper and broader understanding of the material. By working with so many thoughtful instructors, we learned to draw connections between the different branches of physics as well as to look for connections outside of physics. Among the paradigms TAs, it was said that there was no better preparation for the Graduate Comprehensive Exams than being a teaching assistant for the paradigms.

—Kerry Browne and Emily Townsend, TAs

entire faculty, and the program eventually received unanimous endorsement.

Faculty involvement and department-wide integration continue to be crucial for institutionalizing the reforms, especially at the stage when the initial developers hand off courses to new or previously uninvolved faculty. At the same time, the additional diversity has added new perspective on the courses, advanced their development, demonstrated their robustness, and confirmed the dynamic nature of this curriculum development project.

It is often said that active engagement helps students learn; it also helps faculty teach. The changing classroom

dynamic and our role as faculty has been a surprise. Paradigms instructors no longer judge a class to be successful if it goes smoothly. Rather, we embrace confusion in the classroom as a sign that students are constructing their own knowledge. On the other hand, the curriculum reform has forced us to examine which student problems are worth the huge time investment of small group activities and which can be handled efficiently with lectures.

The animated discussions sometimes reveal counter-intuitive insights. Often, students have trouble with what instructors think are the easy concepts and are quite comfortable with the sophisticated parts. In response to our new understanding of some of these difficulties, we have begun a new spin-off project, Bridging the Vector Calculus Gap, which examines how students transfer their mathematics knowledge of vector calculus to their upper-division physics courses.⁵

Because we are no longer bound to a textbook's approach, we find it easier to give the curriculum a particular focus. And the three-week time allowance enforces the focus automatically. Teachers lose the right to wander off on a lengthy tangent; but because we trust our colleagues to do their part at the appropriate time, we have less desire to digress.

Institution-wide effects

Support from the OSU administration has been critical to the paradigm project's success. To start the project, the university provided seed money during the initial phase in the form of summer salary for the three project leaders. Institutional matching funds also permitted hiring another instructor to pick up some of the teaching assignments for faculty members who were devoting time to curriculum development. The department provided funds for remodeling one of our rooms into a dedicated paradigms classroom—the traditional lecture hall works poorly for the paradigms style of student learning. In addition, the OSU president often referred positively to the paradigms project in his speeches. That recognition provided no small measure of moral and emotional support to the developers.

The debate over the role of major curriculum reform efforts in the mission of the institution is playing out at several levels. The small upper-level student numbers (compared to huge introductory course numbers) disqualified the paradigms project from receiving the funding ordinarily granted to classroom remodeling. And despite external funding, the project was also disqualified from receiving remodeling money earmarked for research laboratories. On another level, the inclusion of a faculty member from mathematics on the paradigms team proved a challenge: Teaching roles at OSU are assigned on a departmental level, which limits the latitude for inter-departmental cooperation. At the administrative level, there is still debate on the classification of curricular reform as appropriate scholarly activity. Its recognition through work assignments, merit salary raises, and promotion and tenure decisions continues to be a topic of departmental and institution-wide discussion.

Reaching out

At the start of the project, we set out to restructure an already successful traditional upper-division physics curriculum into a more modern, more flexible, and more inclusive program. At the time, we had only the vaguest notions—if any—that the end result would go well beyond mere course reform and encompass significant transformations in the faculty as teachers, in our students as learners, and in the department as an agent of change. The process has been exhilarating and exhausting, collaborative

The Development Team

Faculty members Philip Siemens, Janet Tate, and one of us (Manogue) led the curriculum reform effort. The article's coauthor (Krane) served as department chair during development of the program. It eventually took the significant efforts of roughly three-fourths of Oregon State University's physics faculty and a number of graduate students to develop and implement the paradigms courses. Listed here are members of the development team, which included teaching assistants (TAs), experimentalists, theorists, phenomenologists, and a mathematician from outside the department.

Kerry Browne (TA)*	Katherine Meyer (TA)
Jeremy Danielson (TA)	Tyson Olheiser (TA)
Tevian Dray	Steve Sahyun (TA)
William M. Hetherington	Paul Schmelzenbach (TA)
Jason Janesky (TA)	Philip J. Siemens
Henri J. F. Jansen	Albert W. Stetz
Cheryl Klipp (TA)	Janet Tate
Kenneth S. Krane	Emily Townsend (TA)
Jeff Loats (TA)	William W. Warren Jr
Corinne A. Manogue	Allen L. Wasserman
David H. McIntyre	

* Browne is now an assistant professor at Dickinson College.

and occasionally contentious, and the results rewarding and satisfying.

After these eight years of developing, testing, modifying, and sharing ideas, the OSU faculty are confident that the program has matured to an extent that it is ready to be used at other institutions. Schools could either subsume paradigms-like courses into an appropriately rearranged curriculum, for example, or add paradigms activities such as small-group interactions or computer exercises within a somewhat modified program. The OSU physics department has recently been awarded a second NSF grant to conduct workshops that help and encourage faculty at other colleges to consider just such an adoption. Information about these workshops is available on the department's Web site.³

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