Paradigms in Physics: A new upper-division curriculum

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We describe a new curriculum for the final two years of a B.S. program in Physics. Case studies in the junior year provide concrete examples or Paradigms as pillars to support systematic Capstone lectures in the senior year. In each of nine three-week Paradigms, the junior progresses from a descriptive lower-division understanding to an advanced analysis of a topic defined by phenomenon rather than discipline. Students generally view the new format with favor. They are better at visualization and make important connections among physics disciplines. Independent assessment is ongoing.

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I. INTRODUCTION

In the fall of 1999 two dozen Physics and Engineering Physics majors at Oregon State University (OSU) plunged enthusiastically into their junior year, which was also the third year for faculty teaching a new curriculum of upper-division studies in physics. They participated in a series of nine three-week intensive case studies taught with a variety of classroom methods and topics that bear scant resemblance to the courses followed by OSU juniors a few years ago. Senior-year students, who became the second class to graduate from the new program, began a set of survey courses which rounded out and knit together the junior-year examples from several viewpoints. These senior courses correspond more closely to the traditional disciplines and methodology of upper-division physics courses, as do the laboratory-lecture courses in electronics and optics that run alongside through both years. A senior thesis or engineering project completes the undergraduate training of these aspiring scientists.

The experimental curriculum is structured to help students organize their own knowledge in ways that parallel the professional's organizing strategies. It is intended to remedy numerous drawbacks of the conventional approach by using a variety of pedagogical techniques, applying insights into the cognitive structures that are being constructed by advanced students. While some of these techniques are inspired by those which have been successful in lower-division and precollege physics instruction, many are new. Upper-division students must deal with problems of far greater complexity and must learn to see patterns which cross the boundaries of traditional physics subdivisions.

This narrative is primarily an account of the intentions, experiences, and observations of the faculty who planned and implemented the new curriculum. Many of our impressions are anecdotal, no doubt deserving the skepticism of a critical reader. However, our students' progress has been monitored by independent experts in the teaching of science, eager to observe how the newly adapted methods play out at a level of instruction for which little documented experience is available. A summary of the evaluation by these education researchers (MN and AW) is included as Sec. IV of this report.

A. Challenges for a new curriculum

The old upper-division physics curriculum at OSU was typical of most similar institutions. Each of several subdisciplines was taught separately as a sequence of courses two to three quarters in length. Two sequences (Electronics, Optics) were laboratory based, the others theoretical, applying abstract principles to deduce concrete examples. Some theoretical sequences (Electromagnetism, Classical Mechanics, and Mathematical Methods) were taken in the junior year and some (Quantum Mechanics and Thermal Physics) in the senior year. Students had to master each topic as it arose, since it arose only once. Individual faculty members typically taught an entire sequence independently, and there was little opportunity to bring out the underlying unity of the various subdisciplines. Because students had to take several sequences in parallel, they frequently struggled when they encountered difficult material simultaneously in several different sequences. The level of difficulty in the junior-year courses was similar to the level in the senior year, making the junior year a significant barrier; locally, it was referred to as the ''brick wall.'' We suspect that this basic scenario depicts a national problem.

B. Response to the challenges

Our solution has been to introduce a two-tiered upper-division course of study involving a nonstandard division of topics compared to the traditional subject areas. This allows students to consider the main topics twice: first emphasizing analytical skills and a multi-faceted approach to problems, then emphasizing deductive skills and disciplinary integration. The junior-year curriculum involves a sequence of case studies of paradigmatic physical situations and conceptual examples, some involving two or more subdisciplines. We thus equip students with concrete examples on which to base an abstract deductive framework. The senior year consists of more advanced courses, each of which consolidates an individual physics subdiscipline, in addition to electives offering introductions to some major areas of current research.

We aim to improve students' comprehension by cultivating their analytical and problem-solving skills, to provide bridges between the content of different subdisciplines, and to offer a more varied and flexible learning experience. Since we see our solution as rooted in fundamental aspects of the

Table I. Case studies offered in the junior year. Detailed syllabi for the nine Paradigms are available at our web site: http://www.physics.orst.edu/paradigms.

Fall quarter	Winter quarter	Spring quarter
Static Vector Fields	Waves in One Dimension	Periodic Systems
Oscillations	Quantum Measurements and Spin	Rotational Motion
Energy and Entropy	Central Forces	Reference Frames

learning experience, we may hope that our results and methods may also prove to be useful in other allied disciplines, e.g., mathematics or chemistry.

Our new curriculum for junior-year physics majors consists of a sequence of nine courses, each lasting about three weeks and meeting for seven hours per week. Each course is a case study involving a single physical situation or simple, conceptual principle. We call these case studies Paradigms.

The Paradigms serve a dual function. The topics, shown in Table I, were chosen to span many of the principal examples usually developed in the deductive subdisciplines, but without restriction to the ideas and strategies of a single subdiscipline. In addition, they emphasize the development of analytical and problem-solving skills, often involving integrated observational and/or computer laboratories. For example, in the unit on Waves in One Dimension, the students study traveling and standing waves in a coaxial wave guide. They make experimental observations and analyze them mathematically, testing the limits of an ideal model. After studying pulses and their resolution into normal modes in this nondispersive context, they compare the propagation of quantum Schrödinger waves in computer simulations.

The Paradigms are followed by six single-term Capstone courses that systematically present the usual deductive systems of physics. The topics and sequences are shown in Table II. The format is condensed compared to our previous year-long sequences in these disciplines, since the students are already familiar with many of the central examples. For example, the Capstone in Classical Mechanics uses topics from the Paradigms such as harmonic and anharmonic oscillations and central forces as illustrative examples when discussing the Lagrangian and Hamiltonian formulations. During the senior year we also offer a selection of specialty courses surveying the phenomena and methodology of modern research areas, such as solid state physics, nuclear and particle physics, advanced optics, and computational physics. These are topics for which there was insufficient time in our old curriculum.

The inherent flexibility of our curriculum is a significant asset. Students pursuing variations on the basic Physics degree, degrees in related fields, or interdisciplinary degrees can pick appropriate topics without being locked into year-long commitments. For example, our Engineering Physics majors choose a subset of the Paradigms and Capstones appropriate to their engineering specialization. In addition, a number of nonphysics majors and graduate students (chemists, mathematicians, geophysicists, oceanographers, and engineers) take some of our upper-division courses; the Paradigms can assist them by addressing specific needs they may have, or specific deficiencies in the background they need for a senior Capstone course. Students who have difficulty with a particular topic may be able to revisit or retake that Paradigm the following year without getting out of step with the whole program. And the one-quarter senior-year deductive Capstone courses make good entry-level courses for graduate students with isolated weaknesses in their background.

The two-tiered approach to the upper-division curriculum addresses the needs of physics students from the most basic to the most applied curricula. Because students experience the broad sweep of physics earlier, they can begin to formulate realistic career goals in time to apply for relevant summer internships or other jobs between their junior and senior years. In addition, they can tailor their experiences during the senior year to their particular career goals. Our graduate-school-bound students encounter basic quantum mechanics and thermal physics early enough to help on their Graduate Record Examinations. Our applied students are able to participate in the co-op program of off-campus internships while still maintaining a coherent academic program. Our courses may be particularly helpful for students who aim to use their B.S. in Physics as part of their pre-service training for careers as high school physics teachers. We believe our integrative, paradigmatic approach will improve the training of high school teachers and offer them an up-to-date model for instruction.

C. Context for implementation

Our institution, Oregon State University, is a typical medium-sized research university. Our introductory calculus-based physics sequence is primarily a service course for engineers and students from other sciences, but also provides the entrance to our undergraduate major programs in Physics and Engineering Physics. Many of our Physics majors transfer from community colleges as juniors with basic math courses and only a single year-long introductory physics sequence. As a result of these circumstances, most of the material in our curriculum for majors is crammed into the last two years. Few of our Physics majors have adequate opportunities to develop their analytical and problem-solving skills before they enter the upper division. Efforts to reform

Table II. Survey courses offered in 1999–2000. Detailed syllabi are available at our web site.

Fall quarter	Winter quarter	Spring quarter
Capstone Quantum Mechanics	Capstone Electromagnetic Theory	Capstone (junior year) Classical Mechanics
Capstone Mathematical Methods in Physics	Capstone Thermal and Statistical Physics	Specialty Nuclear and Particle Physics
Capstone Optics (with laboratory)	Specialty Optics 2 (with laboratory)	Specialty Optics 3 (with laboratory)
Specialty (graduate level) Advanced Mechanics including Chaos	Specialty Computational Physics	Specialty Solid State Physics

the introductory curriculum are under way here, as at other institutions including community colleges, but even under the best of circumstances it will be some time before such changes can be implemented by all the community colleges that prepare students for our program. Therefore, we have decided to focus on what we can do now with the upper-division curriculum.

The single most important requisite for success in a change of this magnitude was the unanimous support of the Physics Department. Those who were not directly involved in the project helped by providing release time, advice and suggestions, temporary postponement of some other department priorities, and a wide variety of other support for the project. We found an effective mechanism for obtaining productive input from the entire department in the early planning stages which helped to build consensus. As part of the process of determining an appropriate rearrangement of content for our new courses, experienced faculty recorded the subject matter of our old curriculum in small natural chunks on index cards color-coded by discipline. After these cards had been rearranged by the committee into a tentative plan, each faculty member in the department was invited, individually, to consider the proposed curriculum. Their suggestions for change were instantly converted into a rearrangement of the cards. Some rearrangements resulted in apparent improvement; others revealed disadvantages of the suggestion. Eventually this departmental game of Solitaire converged on an optimized curriculum that was acceptable to all.

Financial support has been essential to develop the new curriculum. External funding from the National Science Foundation supported the external evaluation activities as well as summer salary for faculty preparing instructional materials and experimenting with new pedagogical strategies. Such funding may not be necessary for institutions adopting our program after its development is completed.

Internal funding is another matter. Initially, we could see no way to phase in our new curriculum more slowly than we did—all the junior courses changed in the first year, the senior courses in the following year. Internal funding from the department and higher levels of the Oregon State administration have supported release time and acquisition of curricular materials. In particular, it was critical that faculty teaching the Paradigms for the first time did not have other simultaneous teaching duties. [All of the faculty directly involved in teaching are regular research faculty with the substantial load of commitments which that entails. One of us (CAM) is also a coordinator for the project.] It is our view that this amount of support will turn out to be a comfortable minimum for institutions that opt to make the change rapidly, as we did. Meanwhile we are looking for ways in which other institutions might be able to make the change more gradually and with fewer resources.

Our external budget also has included funding for a single teaching assistant for the Paradigms classes. During the initial years, the efforts of outstanding and dedicated physics graduate students working with us (on part-time appointments) have been critical to the program's function. While our own efforts were focused on the development and implementation of the new program, their attention centered on the students. One of the challenges we need to address is how to run the laboratory and small-group activities described below without support from teaching assistants.

II. CONTENT OF THE CURRICULUM

A course of studies can help a student become a physicist in many ways. Some of the student's needs are specific to the discipline of physics; others are common needs shared by all beginning scientific professionals.

A. Specific physics content

The basic principles guiding the choice of Paradigms topics are important to emphasize. First, we chose simple examples, with only enough complexity to adequately develop the needed concepts. Second, we chose central concepts and examples which lie at the heart of physics—concepts which professional physicists use often. Third, we chose examples and concepts common to more than one of the traditional subdisciplines of physics or to an important area of application or research. Finally, we sought to include enough subject matter from each subdiscipline to provide a sufficient basis for the senior courses.

All of the Paradigms build on a basic knowledge of classical physics acquired in a traditional introductory calculus-based physics course; some also presume an introductory course in modern physics, including elements of quantum physics and special relativity. Mathematics prerequisites include calculus through vector analysis and an introduction to ordinary differential equations. However, we have found that the majority of our students benefit when we revisit a number of these mathematics topics as part of the Paradigms sequence.

1. Content by discipline

An illuminating way of viewing our reorganization of the curriculum is to see how the main topics of the traditional courses are distributed among the Paradigms and Capstones, shown in Table III. First, compare the last row, topics not included in the new curriculum, with the last column, topics not included in the old curriculum. We see that nearly all the content of the previous curriculum is included in the new. Although there are certainly differences in relative weight assigned to individual topics, we might well have made these changes within the traditional curriculum to reflect the needs and prospects of our students. For example, we now approach Coriolis forces with extensive computer visualization;[1] spin is covered more thoroughly and collisions receive less emphasis. The additional professional skills and interdisciplinary training of the new curriculum have been accommodated without loss of traditional topics.

Table III does not show the additional specialty courses which now enrich the senior year. This year, for example, we offered ten-week surveys of subatomic and solid state physics, in addition to the courses in computational physics, lasers, and wave guides carried over from our previous catalog. Nor does it show the junior-year electronics laboratory and senior thesis, both continuations of previous successful components of our majors' curriculum.

2. Order of presentation

A second look at Table III shows how substantial material from each discipline appears in the Paradigms. By comparison, under the old system, our students had to wait until their senior year for basic quantum and statistical concepts. Another such change, not shown in the table, shifted most circuit theory from spring electromagnetism lectures to the preceding fall's electronics lab. Conversely, advanced topics

Table III. Principal topics of previous traditional curriculum (columns) and new curriculum (rows).

Course unit	Mathematical Methods	Classical Mechanics	Electromagnetism	Quantum Mechanics	Thermal Physics	Not included in old courses
Vector Fields	Vector calculus Visualization		Statics, 3D geometry Vector theorems	Delta functions		Computer Visualization
Oscillations	Fourier series, integrals Complex exponentials	Small oscillations Anharmonic pendulum	LRC circuit Resonance	Orthogonal expansions State space	State space	Lab component
Energy & Entropy					Probability Thermodynamic potentials	Statistical inference
Waves in 1 Dimension	Normal mode expansions	Vibrating string	Standing and traveling waves Coax cable	Eigenmodes Wave packets		Lab component
Quantum Measurements and Spin	Matrix algebra Representations Basis transforms	Hamiltonian		Eigenvalues, probabilities Repeated measurements Spinors, spin 1/2	Measuring probability	Bell inequalities
Central Forces	Legendre functions Separability	Angular momentum conservation Kepler, others		Angular momentum conservation Spherical harmonics		
Periodic Systems		Coupled oscillations		Band structure	Distribution functions	Phonons Bloch waves
Rotational Motion	Tensor notation	Rigid rotation Inertial tensors	Tensor notation	Basis rotations		Lab component
Reference Frames		Rotating frames Relativity	Relativity Lorentz transf.			Lab component
Math Methods Capstone	Partial differential equations Complex analysis		Green functions			
Mechanics Capstone		Formal Lagrange and Hamilton methods				
Electromagnetism Capstone			Dynamics, media Waves, radiation			
Optics Capstone	Boundary conditions		3D waves Coherence			
Quantum Capstone				Atoms, fine structure Angular momentum coupling Scattering		
Thermal Capstone					Statistical mechanics and applications	
Not included in new courses				Time dependent perturbation theory		

such as Lagrangian formalism, radiation, and Bessel functions no longer scourge the juniors, but now are reserved for the better prepared seniors.

The sequence in which the Paradigms are offered is influenced by constraints on our students' background and participation which may not apply to other institutions. First, our university accommodates many transfer students from local two-year community colleges, who have studied reasonable courses in classical physics but have little or no background in modern physics. Their mathematics background may also be weak. These late arrivals take our Introductory Modern Physics course and sometimes vector calculus and/or differential equations alongside their first term of Paradigms; we accommodate them by appropriate scheduling of the order in which the Paradigms courses are offered. Also, some of our Engineering Physics students participate in a five-year co-op program which takes them off campus in the spring of their third and fourth years; these students cannot take the spring courses until their fifth year, so we have scheduled advanced topics in that term. Most universities and colleges will have constraints of their own; the flexibility inherent in the Paradigms approach should allow other institutions to find a suitable sequence should they elect to adopt our approach. This flexibility should also make it easy to deploy our curriculum in a semester-based setting. We are exploring sequences which may be appropriate to the smallest schools which alternate upper-division courses on a two-year cycle.

Each Paradigm is offered as a separate course for two quarter-hours of credit (versus three quarter-hours for our traditional lecture classes), in order to give students flexibility in arranging their schedules and choice of experiences.

However, the order in which the courses are taken cannot be entirely arbitrary, since some of the units build on knowledge or skills acquired in others. For example, the Paradigm on Oscillations develops methods of Fourier analysis that are an essential background for the Paradigm on Waves in One Dimension.

We begin each of the first two quarters with a week-long Preface, discussed below. The last week of the spring term is the Postscript, a finale to the junior-year series involving presentations from senior scientists (in the first year, for example, we included an astrophysicist, a geophysicist, and a materials scientist) on how they use some of the Paradigms concepts in their own research.

B. Professional preparation

Progress from student to professional is marked by a series of changes in mindset regarding the individual's role in acquiring knowledge. The student must ultimately learn to address new and old knowledge directly, free of mediation by the teacher. The nascent scientist must learn how to record new results to preserve them and make them available to other researchers. And each inquirer must learn how to progress, not only by following experienced guidance, but by pooling insights with peers, and eventually by following one's own counsel.

Our Physics majors need to acquire several skills that are common to a range of related scientific professions. They need to know how to approach a problem and solve it. They need to access knowledge resources knowledgeably, to employ computers confidently, to analyze data quantitatively, to model and approximate appropriately. The Paradigms address all these needs.

1. Role definition and modeling

The student whose goal is to satisfy the teachers must become the scientist whose goal is to acquire knowledge. The intense involvement required by the Paradigms courses is meant to facilitate this transition. Drawing from multiple text sources—textbooks, MAPLE scripts, notes—the Paradigms direct the students' attention to comparable content in divergent notation, so that they quickly learn to adapt. One very successful outcome is that the Paradigms students take the multitude of different notations they encounter in stride, unlike their old-curriculum counterparts. This outcome is expected as the students turn their attention from the bearers of the information they are learning, to the information itself. It may indicate that they are internalizing their knowledge as they acquire it.

Another way the Paradigms help students take charge of their own learning is by providing enhanced opportunities to confront natural phenomena. In the laboratory exercises and other concretely visualized examples, each student gains a repertoire of immediate experiences. As these are analyzed, they become useful objects of analogy for future reasoning about unfamiliar or inaccessible phenomena. By insisting that each student draws conclusions from the experiences provided in each Paradigm, we begin a habit of exercising judgment in a professional context. Many students welcome this opportunity but, at least initially, some are hesitant to advocate their own interpretations. They often express anxiety about revealing their opinions, which evidently has not been encouraged in some previous situations.

2. Problem-solving approaches

The Paradigms are meant to form a link in an evolutionary chain as the students' way of solving problems adapts to their changing role. By the end of their introductory courses, students are accustomed to guided discovery: they follow a path indicated by an instructor to gain the prescribed perspective. They are beginning to learn peer-assisted discovery:[2] they discuss common problems with other students, for example by working together on homework. Lower-division students at a nearby university who are following the Inquiry Method have a head start on this process.[3] In the Paradigms, we encourage the further development of peer-assisted discovery with frequent group activities, including collaborating in the laboratory, sharing a computer screen in a visualization exercise, and gathering around a whiteboard in a classroom discussion of a theoretical problem. Facility in the peer-assisted mode of discovery, which dominates most scientific workplaces, is essential for professional success.

After the Paradigms, our Physics majors also have an opportunity to sample independent discovery as they do research for their senior theses. This last transition is often completed at the Ph.D. or postdoctoral level.

3. Scientific skills

By drawing information from a variety of sources in a single course, a Paradigm helps the students develop the practical tools of scientific literacy. They also learn to use computers, both for numerical and symbolic manipulation as well as for accessing and transferring information via computer networks.

In addition to accessing external resources, Paradigms students also develop reasoning skills they need in their professions. They learn to carry out quantitative confrontation of observational data with theoretical expectations. They are encouraged to analyze the conditions under which a model or approximation is appropriate, and to draw conclusions from their analysis. These abilities are a necessary part of every scientist's repertoire.

4. Documentation and communication

Another habit cultivated in the laboratory-based Paradigms is recording the students' experiences. They learn to document their observations, both quantitatively and qualitatively. They learn the value of this documentation when they return for more advanced analysis of earlier observations. They also learn to record their analyses, creating a paper trail of both intermediate numerical results and intermediate steps in the reasoning process. Finally they learn to sort out their results into an organized set of conclusions, which they record in analytical reports. These habits are needed by every professional.

In one of the later Paradigms, students are expected to report on at least one journal article related to the course material from the American Journal of Physics. Most students choose to make an oral presentation as well as the required written report. The oral presentation is a first step toward professional communication in science, and the research activity opens up a new resource for them. Most students are not readers of AJP, and they learn that it is accessible to them. They may also observe that it is very affordable for students.

III. METHODS OF TEACHING

Our curriculum incorporates new developments in pedagogy in many ways. We reorganize the order of presentation of topics and the way they are grouped. We incorporate a wide variety of activities both in the classroom and in the students' preparation. And we employ an array of devices for evaluating the students' performance.

A. Instructional organization

The most striking way in which our new curriculum differs from the previous one is that it fundamentally reorganizes how the content is presented. Two sweeps cover the upper-division material instead of one. The new, extra layer of case studies groups topics by affinity of the phenomena observed and concepts employed rather than the equations invoked. Mathematical sophistication is developed in a context of Physics applications. And many of the Paradigms are organized into learning cycles of hypothesis and observation.

1. Case study format

The Paradigms replace previous parallel-track lecture courses, each meeting three hours per week for a ten-week term.[4] Instead the Paradigms run serially, each Paradigm lasting three weeks at seven class hours per week. They meet for one hour on Monday, Wednesday, and Friday and two hours on Tuesday and Thursday. The students have the advantage of concentrating on one theory course at a time, instead of dividing their attention among the traditional two or three. Several have commented that, just as they tire of a topic, it changes. On the other hand, students must develop the flexibility to change topics frequently, with little elapsed time to become accustomed to new facts, methods, and concepts.

Each Paradigm typically draws subject matter from several traditional disciplines, as illustrated in Table III. The resulting cross-disciplinary connections, a characteristic strength of the case-study method, make it especially valuable in advanced studies to counter the fragmentation that so often accompanies specialization. In addition, we hope that the repeated example of assembling knowledge from varied sources can help students develop habits of resourceful problem solving.

2. Redistributed mathematical content

One of the perennial problems in designing any upper-division physics curriculum is the appropriate placement of mathematical methods (beyond the calculus sequence ordinarily taken from a mathematics department). If the math is taught separately, then students have trouble envisioning how they will use it. They focus on extraneous aspects and find the techniques difficult to remember when they need them, sometimes a year or more later. In contrast, when the math is offered in context, the primary focus on physics makes it difficult for students also to see the underlying patterns of the mathematics. They have trouble generalizing to similar mathematical situations when the physical contexts may appear radically different. Weaker students are often overwhelmed by having to learn the mathematics simultaneously with the physics.

Our double-tiered structure allows us to use both placements strategically. During the junior year, the math is taught primarily in context by incorporating it directly into relevant Paradigms; while at the beginning of the senior year, we teach a separate course in mathematical methods. By then, students have seen eigenfunction expansions in the context of classical oscillations as well as in the quantum hydrogen atom and they are eager to see what these two problems have to do with each other. They have considerable experience with simple examples of the methods, learned in context, and are ready to ask questions like: How do I know when I can use this technique and how do I recognize when it will fail?

There are a few basic mathematical methods common to many of the Paradigms which need to be highlighted before the senior year. To accommodate this need, we use the Prefaces, a week at the beginning of the term, before the Paradigms begin in earnest. In the fall term, the Preface is used to ensure that all of the students have accounts in the computer lab and to get them started using MAPLE, a computer algebra system that is used as an instructional tool in many of the classes. MAPLE labs are then used to help students visualize some basics of complex functions and power series needed for the first term's Paradigms. In the winter term, the Preface is used to explore rotations as preparation for the Paradigms on Spin and Central Forces.

3. Incorporating modern viewpoints

We have taken advantage of the restructuring of our curriculum to present some traditional topics from a modern viewpoint.

The winter quarter Paradigms begin our first formal presentation of quantum mechanics. In the Preface, we use the rotation matrices as a simple, finite-dimensional exercise for examining concepts such as eigenfunctions and eigenvalues; Dirac bra-ket notation is introduced. In the Paradigm on One-Dimensional Waves students solve explicitly for the eigenstates of the one-dimensional particle in a box. Then, in the Paradigm on Quantum Measurements, the students plunge immediately into a detailed study of the Stern–Gerlach experiment, where spin is used as a vehicle to teach the quantum postulates. The only mathematical manipulations required are small-dimensional matrix calculations, so that students can focus on basic concepts. Finally, in the Central Forces Paradigm, students engage in an investigation of the hydrogen atom, deriving and then solving problems with the eigenstates. The fact that students turn spontaneously to bra-ket notation in their problem solving shows us that our strategy of alternating between the matrix and wave function representations of quantum mechanics is a powerful one.

The Energy and Entropy Paradigm (thermal physics) begins with an explicit discussion—with numerous examples—of macroscopic thermodynamics, so that the meaning and usage of these time-honored quantities is clearly laid out. In this process thermodynamics is presented as the quantum mechanics of macroscopic systems in which thermodynamic state functions are defined as quantum average values and the required probabilities are quantum probabilities. But wave functions are not measurables and quantum probabilities are not immediately accessible. In lieu of this, a minimum bias (maximum entropy function) postulate is used to invert relevant macroscopic knowledge to infer the unknown probabilities. This Baysean process yields probabilities consistent with the few macroscopic constraints known about a given system. Partition functions are an immediate by-product. The circle is then closed when students are shown that the quantities and thermodynamic laws obtained in the inferential approach are identical to those of macroscopic thermodynamics introduced at the beginning of the course. In this way students see that statistical physics is the quantum mechanics of macroscopic systems. In a few examples, partition functions for simple microscopic models are constructed and the observable thermodynamics implied by them are studied in qualitative and quantitative lab experiments.

Standard approaches to electrostatics typically introduce the electric field first, use line integrals to obtain the potential at a particular point, and lastly employ gradients to arrive back at the vector field, completing the circle. We complete the same circle, but begin instead with the scalar potential familiar from voltmeters and oscilloscopes. Explicit attention must be paid to helping students visualize the scalar fields by exploiting the power of three-dimensional computer graphics (we employ color to represent the value of the field). The extra attention pays off as students come to view both the electrostatic potential and the electric field as fundamental properties of space.

4. New juxtapositions

In several other Paradigms, we have found that the unusual juxtaposition of topics has introduced a new synergy into our courses. For example, the Paradigm on Central Forces begins with a treatment of the classical case of orbits around a gravitational point source and then goes on to examine the hydrogen atom in the context of quantum mechanics. It is far easier to highlight the similarities and differences between the classical and quantum concepts of angular momentum when they follow each other by days rather than months. Students who have just seen the value of an effective potential in finding classical turning points are primed also to see its role in the radial equation for the hydrogen atom.

Inertial frames are at the heart of special relativity. Yet the use of Einstein-like thought experiments involving rocket ships leads to an intuitive notion of inertial frame which is really local—perfect for the extension to general relativity, but subtly different from the Newtonian concept taught in introductory physics. The juxtaposition of noninertial (rotating) frames and inertial frames (special relativity) in the last Paradigm forces students to confront these subtleties. Is the surface of a nonrotating earth an inertial frame? The answer depends on one's point of view. In many of the Paradigms, puzzles like these have invigorated our own conversations as well as those with students.

5. Exploiting learning cycles

A variety of studies of learning at the secondary and lower-division post-secondary levels have recognized a sequential pattern, the learning cycle.[5–7] It seems natural to inquire whether this pattern persists as the learner's understanding approaches the state of the art.

We utilize a schematic learning cycle in planning several of the Paradigms. In particular, two of the Paradigms have been designed to conform to a formal pattern based on a five-stage learning cycle: interest, experience, analysis, experiment, integration. In the Paradigm on Oscillations, the cycles form a nested structure which will be described elsewhere. In the Paradigm on Rotational Motion of Rigid Bodies, overlapping learning cycles are employed. Two parallel cycles span the three-week experience: a study of rotational dynamics, and a study of tensors. The first experience of the dynamics cycle is itself a cycle involving the construction and characterization of a rigid body and its small-amplitude oscillations about fixed axes; the second subcycle begins with the free rotations of the same body and concludes with gravity-driven precession of the rotor, introducing the Euler equations of motion in the analysis. The parallel cycle begins with a subcycle introducing inertial tensors and rotation matrices, and concludes with a subcycle treating their alternative characterizations and eigenrepresentations. This structure seems quite effective, with the math component providing tools for understanding the physical systems, and the laboratories providing motivation and examples for the math. The students show a surprising level of interest and enthusiasm for subject matter traditionally considered dry and arcane. An ongoing challenge is to improve the primitive experimental techniques.

6. Advanced courses

After the Paradigms, our curriculum returns to the deductive didactic with the Capstones' overview of the traditional disciplines. Each of these analytical courses gives its own interpretation of the examples forming the Paradigms, reflecting a way of thinking which is as characteristic of the discipline as it is of the teacher. The varying ''takes'' on the experiences of the junior year give the students a variety of patterns to incorporate into their own conceptual structures.

The alternation between the introductory and advanced survey courses, versus the case studies of the Paradigms and the specialized senior thesis, gives the student's undergraduate experience a rhythm reminiscent of a long-term learning cycle. The final interpretation of the experience takes place as each student chooses and plans a post-graduate career.

B. Instructional activities

Extensive research at the lower-division level has shown that, by and large, students are not learning what faculty think they are teaching.[2,8–11] Lower-division curricula that incorporate interactive experiments[3] or adopt the experimental method to the exclusion of the lecture[12] have demonstrated success in avoiding or clearing up misconceptions.

1. Classroom methods

To help address this issue at the upper-division level, the weekly schedule of the Paradigms has deliberately included multi-hour blocks of time to allow us to employ a variety of teaching methods. These methods include integrating laboratory investigations into the instruction—both computer simulation laboratories (e.g., CUPS[13] and SPINS[14]) in situations for which actual experiments are not possible, and also real experiments that allow students to discover new information or gain first-hand experience with concepts encountered in the classroom. Influenced by successes in the lower division,[2,15] we have tried several strategies for collaborative small group activities. Our main efforts involve both guided MAPLE worksheets[16] and interactive problem-solving in small groups.[17]

Direct laboratory observations are a mainstay integrated into most introductory physics courses. Expert-level instruction in advanced laboratory techniques often features an integrated theoretical component; for example our electronics course includes circuit theory and a phenomenological description of semiconductors, and our optics course reviews the propagation of electromagnetic waves at boundaries. But advanced theoretical courses usually rely on descriptions of observations with occasional lecture demonstrations. In several of the Paradigms, we have found it useful for the students to observe and interact with simple systems which exhibit the advanced physics concepts as well as the simple ones. For example, loaded dice give a starting point for a discussion of statistical inference and entropy. The anharmonic motion of a pendulum provides a concrete application of Fourier series, while a simple *LRC* circuit illustrates the treatment of damped motion by Fourier integrals. One-dimensional waves are palpably illustrated on an elastic rope, then electronically observed in a coaxial cable; these experiences prepare the students to appreciate computer simulations of quantum wave packets. And rigid rotors tacked together from simple materials allow students to gain a kinesthetic experience of an inertial tensor while marveling at the counterintuitive aspects of rotational motion.

An example from the Paradigm on One-Dimensional Waves illustrates our approach. Here the students encounter the classic problem of transverse waves propagating without dissipation in a rope under tension. An interactive lecture demonstration of standing waves in a rope is introduced, and the students locate the frequencies of the standing waves, measure the tension in the rope, and then predict the mass per unit length of the rope, which they later measure with the help of a scale and a ruler. This is a vehicle for a discussion of boundary conditions and superposition and the ideas of reflection and transmission. The students then work together in groups of three or four in the laboratory to measure the speed of propagation of an electromagnetic wave down a coaxial cable. During the course of this exercise, they naturally encounter the concept of attenuation from an experimental point of view, and the entire laboratory then focuses on measuring transmission and reflection coefficients with the added complication of damping. The students seek out the appropriate equation of motion that correctly describes the observed damping. They consider what ''weak'' damping means and investigate attenuation length. In this context, they must define ''short'' and ''long'' and are confronted with the fact that any physical quantity must be compared with another of the same dimension. Finally, they come full circle: they set up standing waves in this damped system and must model the expected behavior in MAPLE.

In a Physics Education Research Master's project,[17] Katherine Meyer found that effective small group activities at this upper-division level shared the following characteristics:

> they are short, containing approximately three questions,
>
> they require groups to apply the same techniques to different examples, allowing students to compare and contrast several cases expeditiously, and
>
> they are followed by a summary lecture/discussion with the instructor.

For example, in the activity which she ranked highest, Linear Transformations, each group is asked to calculate and then report to the class the effect of a two-dimensional linear transformation on a group of representative vectors. As the class discussion proceeds, someone inevitably asks if the vectors that are unchanged by the transformation have anything to do with eigenvectors. The class as a whole is astonished that the answer is yes. They have learned how to solve eigenvalue/eigenvector equations in mathematics classes, but the geometric meaning has never registered. After this short experience, it is much easier to convey the role of eigenfunctions in quantum mechanics.

Because collaborative activities require lots of classroom time, we have been obliged to limit their use to carefully chosen, critical topics. Interestingly, it is becoming apparent that the most valuable time for a collaborative activity may be when a new topic is being introduced, to ensure that the topic is set in context. If students fail to understand a simple idea (such as the physical meaning of an eigenvector in the example above) then their learning can come to a complete halt and subsequent activities are lost to them. A short activity (such as the worksheet on Linear Transformations) can make it possible for high-content presentations such as traditional lectures to carry meaning for more students.

Our experience has also uncovered a remarkable synergy obtained by juxtaposing the ideas of three-dimensional physics, especially electrostatics; the mathematical skills of vector calculus; and the visualization capabilities of modern technology. Using the impressive graphical and algebraic-manipulation capabilities which are available on MAPLE (and other similar computer algebra systems), we have written a number of guided worksheets which allow the students to explore the connection between spatial visualization and formulas. These worksheets are incorporated directly into lectures and class discussion sessions which take place in the computer lab. The approach is different from that of most current physics texts incorporating computer algebra which teach students to use technology to solve entire problems, in that we still rely heavily on solving equations by hand, reserving MAPLE to enhance students' visualization skills.

2. Out of class

Much of the time students devote to learning is spent outside the classroom. During this time they use many resources: pencils and paper, computers, books, notes, on-line information, and consultations with instructors and with each other.

Many students are eager to take advantage of the computer's facility not only at numerical computations and graphics, but also at algebra, calculus, and other symbolic manipulations. These early adopters soon begin turning in homework problems in computer format, with MAPLE doubling as a word processor! However many other students warm more slowly to computerization, often frustrated by the unintelligent machine's demands for arcane technical trivia. We encourage each student to develop an individual style integrating computer usage as part of a flexible problem-solving strategy. We try to insist that all students exercise basic skills of verbal reasoning and of pencil-and-paper computation as well as of key computer applications.

The fact that traditional textbooks are not structured along the same lines as our new courses posed an obvious problem. The syllabus of each Paradigm refers students to written expositions of the course content. A standard set of textbooks, adopted to serve both Paradigms and Capstones, is supplemented with varying quantities of notes prepared specifically for the Paradigms. We have chosen traditional textbooks which have a reasonably modular format, so that sections can be studied out of sequence. By the middle of the junior year, the students adapt to blending the contents of sources with varying notation. We consider it an advantage that students cultivate this indispensable skill at an early stage of their careers. An additional advantage is that the same books are familiar to the students when they reappear in the senior Capstone courses.

Up-to-date collections of course materials are available around the clock on the Web, although we are not making much use of the interactivity of that medium. We do take advantage of its speedy dynamics by posting solutions of assigned problems quickly after they have been collected (in hard copy) for grading.

The peer interactions modeled in the classroom continue intensely among the students as they prepare their assignments. The Physics Department encourages and facilitates these interactions by providing the students with a couple of large rooms where they can study together. Operated by the local chapter of the Society of Physics Students, this area houses a collection of useful textbooks, old course notes, problems and exams, computer terminals, whiteboards, tables, and sofas where the students can work together. Instructional faculty and graduate teaching assistants often stop by to join the discussion; equally often, a strongly interacting cluster of students erupts from the study area in search of an instructor who can help with their questions. During the first year of the Paradigms, the graduate teaching assistants found their time monopolized by the demanding curiosity of the undergrads; within a year they learned to share the chores—and fun—with the faculty instructors.

It has been a challenge to steer a balanced course between collaborative learning and individual development. We encourage working together because of its many advantages in the learning process and in later workplace situations. However some students experience the group effort as a temptation to become passive. (A cautionary note: students copy each others' MAPLE worksheets indiscriminately without understanding the implications.) One way to compensate for this tendency is to require individual essays interpreting the collaborative projects. This ensures that each student spends time reflecting on the experiences and integrating them into an organized view of the physical world.

C. Evaluation of student performance

Evaluation serves two main purposes: to give the participants feedback to use in managing activities during the course, and to record the students' achievements for their credit and the instructors' analysis. The distinction between these two roles of the evaluation process becomes especially prominent due to the brief duration of the Paradigms. Only the quickest students can consistently demonstrate mastery of early material before the end of the course. Ironically the early feedback is needed most by the students who are not yet ready to document their achievements.

1. Self-assessment

The frequency of class meetings makes it important for students to keep up, while making it hard to provide grading services in time for the next application of the learned material. We provide opportunities for our students to practice recurring mathematical manipulations on Web-posted examples with posted solutions. In this way we can reserve individual grading for more substantial homework exercises.

More importantly, an active classroom provides students with myriad opportunities to check their own understanding. Small group activities which require groups to report to the class as a whole can serve as valuable checkpoints for students' self-assessment. We have found that some of our most effective small group activities share a common structure:[17] Each group works with a slightly different example and the informal follow-up presentations help the students themselves to highlight the similarities and differences. Students are more responsive to Socratic teaching styles in the Paradigms environment. After just a few weeks, the simple demand ''*You* tell *me* what will be on the exam'' elicits a far more interesting discussion, and more accurate suggestions from the students, than in the past.

In the Quantum Measurements Paradigm, students are told from the first day of class that they will be expected to solve four basic types of problems: time-independent problems involving spin 1/2, generalizations of these (typically to spin 1), time-dependent problems involving spin 1/2, and generic time-dependent problems. Students have many opportunities to assess their progress toward these goals as these four types of problems are discussed in class, modeled in computer labs using a specialized program called SPINS,[14] and practiced on homework.

2. Formal feedback during courses

To encourage students with a variety of learning styles, we use a number of evaluative tools to mark progress in the Paradigms, ranging from homework problems, through reports on laboratory-related activities, to a cumulative method: the Inventory of Achievement. Based on the overall learning goals and strategies of each Paradigm, different courses use different methods.

Three of the Paradigms utilize laboratory reports as a way to evaluate the students' progress. A typical report would include a description of measurements together with a quantitative analysis. The students are asked to test hypotheses by confronting expectations with experience, and to draw conclusions from this comparison. Most are able to do so, when appropriately prompted. Students found overly prescriptive lab manuals as unsettling as those which were too open-ended; we are learning to find the right mixture.

Two of the Paradigms provide students with a list of about a dozen announced goals to be documented during the course. These goals are used to provide a running evaluation: an Inventory of Achievement. Corrected work is returned to the student with annotations, along with a sheet evaluating progress toward the goals. Eventual documentation of full accomplishment of all goals gives a top grade; goals not or only partially met translate to a lower course grade. In this evaluation scheme students are not penalized for being slow to catch on, since only their ultimate achievement is recorded. But they still get feedback that relates directly to their grades, which seems to be important to many of our students.

3. Rhythm of feedback

As faculty, we have years of experience (including our own schooling) with the traditional schedule, so that we spontaneously encourage a familiar rhythm of weekly homework, review, midterms, and exams. This is not so with the current mode of the Paradigms. A significant problem in the first year was to find and establish a natural rhythm for these intensive courses. Experience in succeeding years has been more favorable.

Originally, each faculty member set his/her own schedule for homework and integrated lab project due dates, often differing week by week within a single course. The results were devastating to the students, particularly to the large population of our students with outside work and/or family responsibilities. An important recommendation to anyone attempting a similar curriculum change is to develop a consistent weekly pattern which enables the students to be responsible about coordinating their academic lives with their other commitments.

We experimented with homework frequency within the context of our daily class meetings. Daily homework, even when assignments were short, was too incessant; weekly homework did not allow enough practice. In particular, some students came up short, by the end of the year, in their familiarity with simple algebra and calculus manipulations. Twice-weekly assignments proved a good compromise for most Paradigms the second time we taught them.

The first time we taught the Paradigms we experienced a stage, around the end of the second week of each, when the students were afraid they were not ‘‘getting it’’ and the faculty, in response, suffered a crisis of confidence. We now make sure that students (and faculty) know that this is a normal and expected stage in the intensive format. By the end of the three weeks, students and faculty generally report being more comfortable with the level of understanding attained.

By the end of the junior year, the format of the Paradigms courses is generally viewed with favor by the students. They frequently mention that classes every day assist their immersion in physics thinking and their understanding of the concepts. Many students feel that this immersion in physics helps them build on the topics in lecture, instead of losing concepts after a two-day layoff. The student dropout rate appears to be decreasing, although this trend is not yet statistically significant. Some at-risk students are blossoming.

4. Summative assessments of individual achievements

The students are encouraged to work collaboratively during the courses, so all instructors include homework and reports that have a collaborative component in their assessments. Students are also encouraged to understand that individual contributions are ultimately very important. Thus most of the Paradigms courses use an exam as part of the evaluation of student performance. This is always a final exam: no instructors deemed a midterm exam appropriate in a three-week course.

Timing of the exams has been a thorny issue. The first Paradigm’s final exam was given on a Wednesday evening, with negative consequences for the Monday start-up of the succeeding Paradigm. Subsequent exams have been administered on Monday evenings, with better success. Students appear satisfied with only two days of integration between the end of formal course work and the final exam. A related problem is that there is no natural time to go over the exam with the students after grading; we now provide an extra session to do so. In the first year we lost out on this important opportunity for consolidation.

An integrative experience can also be provided by requiring the student to prepare a summary of conclusions for submission together with the other work at the end of the course, in the format of a portfolio. Each of the two portfolio-based courses included two major laboratory experiences. Each student submitted a written report analyzing each experiment, which was evaluated and returned, so that the student could correct errors before drawing final conclusions. The portfolio consisted of the laboratory reports, a few technical exercises graded and returned during the course, and an essay summarizing the conclusions supported by the student’s experiences. Due the Monday after the course ended, most were handed in (almost) on time. The limited scope of each Paradigm helped keep the portfolios manageable. After the portfolios were evaluated and the course grade assigned, each student’s performance and experiences were debriefed in a 20-min exit interview with the instructor. In the most recent round of these courses, the portfolio was evaluated using the Inventory of Achievement described above. The Inventory requires about the same amount of faculty effort as the usual grading system, but the exit interviews add a significant effort, which might best be considered instructional rather than evaluatory time.

IV. EVALUATION OF CURRICULUM, INSTRUCTION, AND IMPACT ON STUDENTS

The process we have undertaken has been a complete reform of the structure, content, and instructional methodologies of our upper-division program. Of necessity, the reform involved a number of components: assembly of necessary resources, internal planning of flow of the content, and external review by an expert panel of advisors. Formative evaluation procedures guided the development over the three years while summative evaluation procedures provided a comprehensive look at the effects of the new implementation. A variety of data collection techniques included periodic term-by-term student feedback from e-mail questions, classroom observations, quantitative measures of student achievement including pre-upper division Grade Point Average (GPA), GPA during program, Graduate Record Examination in Physics (GRE) scores, and feedback from instructors and graduate assistants about achievement of students.

Preliminary course syllabi and related information were sent to a panel of eight faculty engaged in teaching upper-division Physics at a variety of other institutions. The comments of these reviewers were initially an important source of information for us on potential problems both in the individual courses and in the content and flow of the whole. Their responses indicated that they believed that the new curriculum would meet the needs of Physics majors; indeed, a number of them expressed interest in considering the new courses and structure for their own institutions.

In the Paradigms approach, students have exposure to several faculty members, each with unique perspectives to convey, and to a wide variety of textbooks and other instructional materials. These varied viewpoints can be significant strengths of the new approach, but only if special attention is paid to continuity. While we were first preparing the new junior-year courses, the faculty who would be teaching them held a number of meetings whose main focus was the flow of the ideas and content through the Paradigms. We have explicitly addressed the need to have a number of physical concepts and mathematical tools develop naturally over the course of several Paradigms. An example is the concept of basis states which builds gradually through all of the Paradigms, beginning with the Fourier analysis of Oscillations and Waves, is picked up again in Quantum Measurements and Central Forces, and culminates in the Capstones. Flow charts were developed to help us maintain this continuity. During the first year of implementation, at the end of each new course, we held meetings with faculty and teaching assistants where we were informed by the work of the reviewers and the evaluation team. These meetings focused on the effectiveness of our teaching strategies and the rhythm of the intensive implementation. Yet, near the middle of the year, we returned to the issue of content and continuity. These discussions of pedagogy were novel in our department and were one of the most valuable outcomes of our efforts. We were energized by the interaction and the curriculum benefited greatly from the coordination. (Of course, it should not have been necessary to revise the entire curriculum in order to get together to discuss pedagogy!)

As the program matured over three years of implementation, its impact has been verified with respect to student learning and the alternative instructional modular approach. For student learning, evidence from a comparison of the GRE (Physics) scores and pre-Physics GPA indicates that the Paradigms have improved the support for the learning of physics for average and below average students. In the previous program, students struggling early tended to withdraw, changing to other majors. However, these students were more often retained and supported in their continued work with physics at no apparent expense to the above average students. In the Paradigms students quickly recognized the importance of working together, both the strong and the weak students. And, their work was continuous over the term with courses changing every three weeks. This extensive group work appeared to contribute to a stronger support mechanism for average and below average students, students who typically need additional support to engage in the processes.

Throughout the junior year of the program, students were constantly involved in the application of mathematics to physical phenomenon. And, with courses changing every three weeks, they were involved in intense study of particular problems. The evidence of comparing the analytic problem-solving abilities of the students prior to the Paradigms program with those in the Paradigms indicates that the students' problem-solving skills and thinking skills were enhanced. When students were asked, ''What was the most important thing you have gained throughout the program?'' they indicated:

> ''I have more confidence to solve problems and feel that I have a bigger tool box to start problems.''
>
> ''I have gained a fairly decent physical intuition.''
>
> ''... not get frightened of anything that is asked, for example, find out how tall a tree will grow if it behaves a certain way, I know how to do that right now from a purely thermodynamic approach; or if I have to look at something in geophysics like seismic refraction, there are a lot of principles I understand that help to understand how the system will behave.''
>
> ''I have a bag of tricks, an arsenal for solving problems or weaponry for solving problems. If a problem comes your way of any sort, you know how to tackle it.''

Another important feature of the student growth in the program has been a stronger integration of mathematics and physics. Previously, the mathematics presented in the junior year was perceived as separate from the physics program. This finding suggests that students begin thinking as physicists where mathematics and physics are considered integrated. Students indicated that ''unifying across disciplines'' was a realization from the program. Students indicated an improved comfort level with applications of mathematical tools. In some students' minds, they ''gained experiences at applying math to various problems where math provides a different perspective in thinking about things.'' The extension of the mathematics to the physical system was also more clearly recognized by students in the Paradigms. In their words they developed a ''physical intuition ... to get from the physical situation to the math expression.''

One problem that plagued students in the traditional curriculum was the use of varied notations. However, this problem seemed to disappear in the Paradigms. While the students noted the ''difference in notation'' the fact that the mathematics was more integrated with the physics helped them make ''sense of math formulas'' such that they saw the math as ''words and not just symbols.'' In some cases, students noted ''a thread running through all the classes; the first time we saw a topic, half of us did not know what we were looking at but when we saw it the second time we could say, 'Hey, we know what we are looking at.' We could learn what was going on ... it was just written a different way and the more times you see something makes it less intimidating and you can deal with the multiple notations. You can read any book.'' One student added: ''I learned to use the index in books to look things up in more than one book.''

The Paradigms' modular approach (with a three-week focus for each module) required students to learn in a manner different than their traditional mode of instruction. This change was most problematic during the first term. Students had difficulty learning how to learn in the new mode. They had to adjust how they learned physics as well as how they wove that learning among their other concurrent traditional eleven-week courses. By the second term, students seemed to adjust by developing strategies for dealing with the differences. As one student indicated, ''I learned how to learn.''

Students consistently pointed to pace and intensity throughout the junior year as major obstacles for learning. As they recognized a repetition of major concepts from Paradigm to Paradigm, their stress over pace lessened, indicating recognition that they had not missed major concepts (a fear in the pacing issue). Reflecting over the year, however, students recognized how the courses complemented each other. ''They built on one another pretty well. Fourier analysis was learned in one course and used in the next Paradigm and then in others as well. They introduced a concept and then more in depth for the next use.'' It may be that this repetition, with each level developing more depth, helped the average and lower students remain in the Paradigms.

The modular approach with different instructors for each module resulted in various important side benefits of the program. Students were required to adjust to a new instructor every three weeks. This adjustment required additional student learning that was problematic for them until they had the instructors more than once. As they indicated one of the major obstacles in the program was ''getting used to the new system of three or four professors each quarter for each Paradigm. We did not know what they wanted and what they expected.'' Another student indicated that ''adjusting to the new system, four or five professors in the first term and half, [meant I had to adjust] the work load from previous years.'' With the different instructors, however, a variety of learning styles were met in one term. Where one student indicated ''I learn by lecture so the style is important,'' another expressed a request for ‘‘more demonstrations and labs.’’ Some instructors used projects while others used examinations to assess student understanding. ‘‘I like it being project-based not final-based.’’

The expertise of the instructors each term was maximized in the Paradigms. Students recognized the expertise in the specific Paradigms. However, the use of modules did require instructors to have an intense three-week assignment for one course. Thus, their work did not have a consistency throughout the term. Yet the students noted the availability of the instructors for assistance as a positive of the program. ‘‘The teachers, you can always find someone if you have a problem, even if he is not teaching the class; I asked Professor X something the other day that was for something totally different and he helped... in terms of people resources we are fine. We have awesome people, a really good department where you can always find someone.’’

Graduate teaching assistants (TAs) were assigned each term providing students a consistency of support through this learning process that was overwhelmingly indicated as important for student success. The students indicated that the ‘‘TA helped a lot in classes. It was great to have someone else to bounce ideas off of.’’ During the first year of the program, the TA was considered to be an essential feature for possible success. As the program progressed to the third year, the dependency on these assistants lessened, perhaps because the instructors were no longer in the ‘‘constant development’’ stage and thus had more time to work with students.

At the completion of one year in the program, students were asked to comment on the most important concepts learned. While students would indicate particular physics concepts, they also were able to reflect on the program as a whole: ‘‘I doubled my intelligence in one year. I learned more about physics and nature in the last year than in my entire life. I feel a confidence when confronted by a physics problem or situation that I can overcome it... the Paradigms prepared me to solve hard problems.’’

V. PROSPECTUS

Teaching students through the Paradigms and Capstones is a satisfying experience. The students’ response richly rewards the work. A graduate of the first class to complete the Paradigms and Capstones (with below-average grades!) wrote in an unsolicited e-mail from his job as a high-tech designer, ‘‘I can’t thank you enough for teaching me how to think. Your classes certainly did just that.’’

The strength of the curriculum derives not only from the choice and arrangement of topics, but also from the many different pedagogical strategies employed. Some Paradigms are heavier on lecture content than others, some involve labs, others are more focused on group problem solving. Students comment time and again that they really appreciate the many different experiences. Most students derive benefit from all the approaches, but a few students do not respond well to some methods. An important aspect of our approach is that it is a different few students who have trouble in different Paradigms! Some students do not like laboratory work, but they do not encounter it in all the Paradigms. Some students are uncomfortable with group problem-solving, but not all of the courses rely heavily on this strategy. Some do not understand the Inventory of Achievement, but this is adopted in just two Paradigms.

We have just entered a new phase of teaching these courses, in which the faculty members who developed them hand them off to others. We are not surprised that this poses new challenges. Although the courses appear modular at first, they turn out to be extensively interconnected by hierarchies of developing concepts, skills, and habits. We have traced many such connections, but may be unaware of others, which we may discover as we exchange duties. We intend to keep extensive notes of the hand-off, with each experienced instructor providing support and documentation to the new crew. We will also continue to improve and develop student materials for the courses.

As we exchange assignments with each other and with additional colleagues, we will gain experience that should help us to assist other Physics Departments that may wish to adopt our curriculum for their upper-division students. We hope to conduct this dissemination in a research environment, documenting the experiences and achievements of the students and teachers. We are now in the process of applying for grant support for a collaboration to include several other schools in early ‘‘technology transfer’’ and its concomitant analysis and evaluation. We have already identified several other institutions with interested faculty, and are eager to hear from more.

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