Implementing Curricular Change

Analytical skills provide the theoretical framework for much of physics. In the real world, however, solutions to problems typically require creative combinations of analytic, experimental, and computational techniques. Recognizing this need, the physics department at the University of St. Thomas developed an integrated physics curriculum emphasizing analytical, computational, experimental, and communication skills.

Six years ago, the University of St. Thomas's physics curriculum looked fairly typical. Our program's primary focus was giving students a solid analytical framework complemented by a set of experimental skills. We had made improvements to the program over the years—such as introducing active learning techniques to the introductory courses and starting an undergraduate research program—but the reforms didn't significantly impact the content of the upper-division courses or the program's overall design.

During an internal program review in early 2002, it became clear that we needed to comprehensively evaluate our curriculum. Merely applying analytical skills to idealized situations wouldn't make students successful: they had to be able to tackle real problems with messy and ill-defined boundary conditions. The better students could already take on those tough problems, but where did they acquire their extended skill sets? Their electronics aptitude and well-rounded computation knowledge came from somewhere. We needed to identify what helped them and find ways to bring that experience to all of our students. Although it was easy to take pride in exceptional students doing well in graduate school, we wondered to what extent our curriculum led to their success.

As we looked for characteristics that differentiated our students, one trend became clear: the best students came from integrated experiences. Outside the normal mode of instruction, such as in a summer research experience, they could apply computational, analytic, or experimental skills when the need arose. The intermediate computer course wasn't the first time they had programmed a computer, so by the time they took upper-level advanced laboratory in their senior year, the better students already knew much of the material. They had been gaining new skills since their first day in the program. We needed all of our students to achieve this level of performance, not just a few.

To develop an integrated experience for our students, we started by reworking our departmental goals. We hammered out a mission that emphasized the importance of analytical, computational, experimental, and communication skills, and made working these elements into all of our classes a department goal. Analytical skills were entrenched throughout the curriculum, but we needed other elements as well. Whereas communication elements were fairly easy to add to our courses, devel-

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oping experimental and computational skills in a more continuous manner required significantly revising the curriculum. As the task's enormity became clear, a phased plan evolved.

Steps to Building an Integrated Curriculum

It was clear from the start of our project that curricular revision required sustained effort by the entire faculty over a substantial period of time. As we worked through the process of curricular revision, several principles evolved.

Develop a Clear Mission and Vision

Before diving into the details, think about your program's role. For our department, this was fairly straightforward. We're an undergraduate program centered on teaching, and we strive to provide a high-quality education for all of our students. Our program's teaching emphasis provided the anchor for all planning. We wanted to provide an education that built a physicist holistically, integrating a variety of skills and knowledge. We solidified our commitment to the integrated approach by embedding it into our mission. The mission statement emphasizes the importance of analytical, experimental, and computational skills:

> "Both inside and outside the classroom, the University of St. Thomas Physics Department provides undergraduate students with a broad understanding and appreciation of physics, cultivates problem-solving skills involving analytical, experimental and computational techniques, and teaches how to effectively communicate technical ideas. We strive to instill values that enable individuals to responsibly engage the world they live in."

Our mission isn't complicated, but it and an accompanying vision statement help guide our curricular decisions. The process of developing the mission and vision statement helped unite the department and is an essential first step in the curricular revision process.

Be Inclusive

The US National Task Force on Undergraduate Physics' recent *Strategic Programs for Innovations in Undergraduate Physics* (Spin-Up) report notes that a key characteristic of a thriving department is the active involvement of a substantial majority of the faculty.[1] One person might initiate curriculum revision, but it's very difficult for an individual to sustain it. In our case, much of the effort focused on computation. By working collaboratively, we were able to reinvigorate the curriculum. Faculty with expertise in laboratory and computation skills addressed those areas, but all faculty discussed them. This helped not only to integrate efforts, but also to educate faculty in areas they were less familiar with. This was especially important with the computational portion of the curriculum.

A major hindrance to the integration of computational elements into the curriculum is the lack of faculty familiarity with computational tools. Many faculty members might need help and time to develop the skills needed to integrate computational elements into their courses. We have a professional obligation to remain current in our field, but this is often difficult in small departments with high course loads.[2] A supportive environment in which faculty help each other develop new skills is crucial. Our emphasis on an integrated curriculum helped us develop a collaborative environment. The transfer of skills goes in multiple directions, and we affirm faculty for their contributions as well as newly learned skills. It's amazing how fast learning takes place in this environment.

The discussion surrounding our mission and vision statements helped us refine our program goals and also brought us together as a team. Without a team approach involving the entire faculty, it's extremely difficult to produce lasting change.

Learn from Others

You don't have to reinvent the wheel when revising your curriculum, although it does help to adapt the design to your own road. Several ideas from other institutions influenced us. Elements from three programs in particular fit our objectives: Oregon State's "Paradigms in Physics" and the computational programs at Clark University and Lawrence University.

The ambitious "Paradigms in Physics" curriculum entails an intensive restructuring of upper-level physics courses.[3] In their junior year, students work on a series of well-planned, three-week modules focused on a single topic. The modules weave analytical, experimental, and computational elements into the discussion, with computational elements embedded in the courses instead of tacked onto the curriculum. Senior-year courses tie together traditional physics subdisciplines and current research topics. We didn't attempt such a compressive revision of our curriculum. However, inspired by their efforts, we're working to build themes into our course structure more systematically than we have in the past.

Clark University's physics department developed five general principles for implementing computational methods into their curriculum. Two key ideas evolved from these principles:

- computation plays an active role in the development of new physics, and
- the infusion of computational methods throughout the physics curriculum is essential.

Computational methods should be taught both inside and outside the traditional classroom. With the goal of integrating computational elements across their courses, Clark University developed new courses and refined existing ones. The resulting curriculum models the problem-solving techniques used in academia and industry. Central to the curriculum is an intermediate computer-simulation laboratory that introduces students to computation. Students can take the simulation laboratory or an electronics course to fulfill a laboratory requirement. Although they don't have to take both courses, most students recognize their usefulness and complete both.

Integrating computation across the curriculum isn't easy. Open-ended laboratory courses are effective, but are too time-intensive for many programs. Thus, we're left with the difficult task of integrating computation into the classroom. As Harvey Gould points out, "It is more efficient to incorporate the computation into the entire curriculum than to do a separate course. The difficulty is that such a reform assumes that the faculty can act coherently, an assumption that applies to only a few departments."[4] This statement reaffirms our earlier point that a strong and cohesive faculty base is essential to a meaningful curricular revision. Without a cohesive faculty, revision efforts seldom last.

Lawrence University has refined the idea of focused expertise. Its physics department is small, but it has made a significant impact on the teaching of undergraduate physics. It started the effort to add computational elements throughout the curriculum by developing a set of underlying convictions that included two key ideas:

- introduce computing techniques early in the curriculum, and
- computational resources should permeate the curriculum.[5]

Both ideas are common themes in successful programs. At Lawrence, the sophomore laboratory course in computation is spread over three terms, which facilitates the integration of computational techniques into parallel courses in theoretical mechanics and electricity and magnetism. Students see the interplay of computational techniques applied to a variety of problems in their core physics courses, and they develop an impressive array of skills.[6]

Build Allies

Although the effort to revise the physics curriculum starts in your home department, your institution will often have other programs that can get involved. In our case, discussions with engineering, mathematics, and computer science faculty identified several courses ripe for improvement. We've formed working groups with the other departments to address course issues that affect all of our programs, which has led to the revision of three allied courses in engineering, math, and computer science to include more computational content.

Although broadening the discussion of computational content to departments outside of physics might seem to merely affect the choice of computer language and some of the course content, the coordinated efforts have a much greater impact on our students because they see how all their courses are integrated. The physics faculty also benefit from cross-program interchanges. For example, we've learned how to use the professional simulation package ANSYS to solve difficult electromagnetic field problems, and our computer skills have thus taken a leap forward.

Value Curricular Reform

Assuming your departmental planning has gone well and a creative department-wide reform effort is under way, you'll still need significant resources to keep the project moving forward. Obtaining funding for necessary hardware and software might not be easy, but the most difficult resource to find is time. More good ideas fail from lack of faculty time than from lack of faculty acceptance.

Just as the department's mission and vision are important in setting program direction, the standards for faculty evaluation must align with the overall departmental mission. Expecting large-scale curricular changes on top of the standard faculty load won't produce a healthy long-term program. Aligning faculty work expectations with the program's vision and design lets faculty commit the necessary time and signals a strong departmental commitment to continuous improvement. If the development of material isn't valued at a department level, the faculty won't take time developing it. Programs as diverse as engineering and medical education have recognized the benefits of tying departmental aspirations to faculty expectations as well as the damaging affects of misalignment.[7,8]

Our institution has adopted the Boyer model of scholarship, which we've applied to our program. Using Boyer's fourfold scholarship model, our department recognizes the scholarship of discovery, the scholarship of integration, the scholarship of application, and the scholarship of teaching as valid areas for professional engagement when properly documented.[9] The range of appropriate professional activities in this model includes course and program development and consultation with industry or government as well as traditional scientific research.

As Charles Glassick, Mary Taylor Huber, and Gene Maeroff emphasize in their companion book to Boyer's initial work,[10] any professional engagement must have the following characteristics, which form the basis of scholarship review:

- clear goals,
- adequate preparation,
- appropriate methods,
- significant results,
- effective presentation, and
- reflective critique.

Having evaluation standards that affirm the importance of course and program development has encouraged our faculty to initiate the overhaul and rework of our physics curriculum.

Be Patient

Once the plan and resources are in place, you need patience—change is a slow process. The successful programs at Clark University, Oregon State, and Lawrence University share two characteristics:

- each enjoys large-scale faculty support, and
- each department has a long-term commitment to the project.

These programs have evolved over a decade. After examining your options, plan a realistic path to realizing the local vision. Work hard to involve the entire department in the project and don't expect your plan to remain fixed—good ideas evolve.

Revision at the University of St. Thomas

Our traditional curriculum started with courses in mathematics and classical physics, followed by a two-semester sequence in modern physics. Students typically didn't squeeze in a computer course until their junior year. Clearly, this needed to change. To achieve a balanced curriculum that integrates analytical, experimental, and computational skills into as many courses as possible, students needed to start developing computational skills much earlier than their junior year.

The logical place to start was the classical physics sequence. However, after reviewing our freshman introductory sequence, we chose to leave it alone for the time being. At first glance, this might not seem to make sense, but our introductory course wasn't the weakest link in the system. Although it's not perfect, the integrated lecture and laboratory format used in our introductory physics course sequence works well. Therefore, we focused our efforts on developing new transition courses and reworking the modern physics sequence and the upper-level courses. Skipping over the introductory courses in classical physics kept us from focusing all of our energy on a single sequence. We'll revise the introductory physics sequence after we stabilize the upper-level courses and develop a new freshman computing course.

> ***To achieve a balanced curriculum, students needed to start developing computational skills much earlier than their junior year.***

The first phase in the curricular revision consisted of adding two courses with an experimental and computational emphasis as well as adding computational materials to existing courses. The second phase expanded the integration efforts to include courses in computer science, mathematics, and engineering. Table 1 illustrates the courses impacted by the first two phases of curricular revision.

Central to initiating the first phase of our curricular revision were three US National Science Foundation Course, Curriculum, and Laboratory Improvement (CCLI) grants addressing specific plan aspects. The grants helped provide needed resources. More important, the act of writing them helped us refine our vision for the integrated curriculum.

The first grant focused on the development of a sophomore course in experimental methods to replace our senior-level advanced laboratory course. The new course introduces students to some of an experimentalist's standard tools while addressing a single experiment over the entire semester. Currently, we're investigating the behavior of a chaotic pendulum. The students appreciate the complexity

Table I. Phased integration of computational elements into the physics major.*

2000–01		Phase I: 2005–06		Phase II: 2008–09	
1st semester	2nd semester	1st semester	2nd semester	1st semester	2nd semester
Freshman					
Calculus I	Calculus II	Calculus I	Calculus II	Calculus I	Calculus II
	Classical Physics I		Classical Physics I	*Computing in Science and Engineering*	Classical Physics I
			Intro. to Computing		
Sophomore					
Calculus III	Differential Equations and Linear Algebra	Calculus III	Differential Equations and Linear Algebra	Calculus III	*Differential Equations and Linear Algebra*
Classical Physics II	Modern Physics I	Classical Physics II	*Modern Physics I*	Classical Physics II	*Modern Physics I*
		Electronics	*Methods of Experimental Physics*	*Electronics*	*Methods of Experimental Physics*
Junior					
Modern Physics II	Stat. Mechanics and Thermodynamics	*Modern Physics II*	*Stat. Mechanics and Thermodynamics*	*Modern Physics II*	*Stat. Mechanics and Thermodynamics*
E & M	Electronics	*E & M I*	*E & M II*	*E & M I*	*E & M II*
Introduction to Computing		*Optics*		*Optics*	
Senior					
Theoretical Mechanics	Quantum Mechanics	*Theoretical Mechanics*	*Quantum Mechanics*	*Theoretical Mechanics*	*Quantum Mechanics*
Advanced Lab I	*Advanced Lab II*				

**Italicized courses have a significant computation element*

that comes out of the fairly simple system and are intrigued with the topic of chaos. Woven into the discussion are topics in nonlinear dynamics, numerical differentiation and integration, modeling, data acquisition and instrument control, signal conditioning, and overall experimental design. The specific experiment is not as important as the breadth of topics it introduces and its ability to engage students for the entire semester. For example, students could investigate sonoluminescence, the production of light from sound. The topic is fascinating, not typically covered in the curriculum, and involves enough areas in both theory and experiment to keep students' interest. By the end of the course, students have been introduced to computer hardware and software, and have developed a proficiency in LabVIEW and the use of basic laboratory instrumentation. Having these skills before their junior year has significantly affected our students' summer research experience. Whether they work with us, participate in Research Experience for Undergraduate Programs off site, or serve as interns in industry, they can make solid contributions to their respective projects.

The second grant expanded the computational modules we were using in the theoretical mechanics course to all of our upper-level physics courses. Projects such as simulations of the three-body problem introduced in theoretical mechanics had improved students' computational skills, and we wanted our other courses to continue the effort. Simulations of atomic orbitals in the quantum mechanics course and modeling the equilibrium distribution of charge on a 1D finite wire in the electricity and magnetism course are typical examples of recent computational modules introduced into our upper-level courses.

Problems posed in scientific literature are the major source of the modules. Students read the papers and then conduct their own investigations. By carefully integrating computational modules to existing courses instead of offering them as standalone laboratory exercises, you introduce the theory behind an algorithm as well as its application. Key to the project's success was the use of a common computing environment (in our case, Matlab), which helped students and faculty develop computation skills. The grant's principal investigator worked with the other department faculty to integrate the modules into their respective courses. As faculty expertise grows, additional modules continue to come online.

The third grant integrates both computational and experimental skills in the context of a junior-level optics course. Building on skills introduced in earlier courses, the students apply and expand their knowledge of instrumentation, LabVIEW, and Matlab as they work on a series of optical experiments with a biomedical emphasis. In particular, students learn about noninvasive skin cancer detection, fingerprint identification, environmental sensing, and how certain animals navigate and communicate using polarized light. These experiments give students a solid introduction to image acquisition and processing techniques with the National Instruments Vision Development Module. They complete their own coding in LabVIEW IMAQ, and learn how to apply affine transformations, averaging, filtering, thresholding, shape matching, and other standard routines to the images they acquire. In the long run, we envision approximately two to three major computational models and several smaller "homework"-sized problems in all of our courses.

The second phase of our curricular revision involves allied courses outside of our department. Because we're a small program, we rely on other departments to deliver our introductory computing and electronics courses. After refining our approach at the department level, we were ready to work with other programs. With the computer science, mathematics, and engineering departments, we're designing a new introductory computational course covering basic skills in Matlab and C++. Although the computer science department offers the course, it involves faculty from all four areas and will act as a gateway to all of the programs. Additionally, courses in differential equations and electronics are being reworked to fit our new approach. Faculty in all four departments are excited about topics they can introduce to students with computational skills.

In the third phase, revisions to the introductory sequence will exploit the Matlab skills developed in the new freshman computer science course and introduce more modern themes. Other ideas will no doubt develop.

Curricular revision is an ongoing process, and we're nowhere close to being done. However, computation now plays a central role in our integrated program, and we can say with some confidence that the students' skills are due to the curriculum, not in spite of it.

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