Engaging Undergraduates Through Interdisciplinary Research in Nanotechnology

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To recruit and retain more students in all science disciplines at our small (5,000 student) public university, we implemented an interdisciplinary strategy focusing on nanotechnology and enhanced undergraduate research. Inherently interdisciplinary, the novelty of nanotechnology and its growing career potential appeal to students. To engage students in learning and to keep them engaged, we offer progressively more independent research opportunities with faculty mentors and encourage participation in a robust science learning community that supports students outside the classroom. Activities beginning in the freshman year build connections with faculty members and student peers and foster a growing individual identity as scientists. Since implementing this approach in 2005, a total of 73 students have enrolled and 32 have graduated. Half of the currently enrolled students are biology–chemistry majors and the rest are physics majors. We have significantly increased the number of student publications in peer-reviewed journals. These gains were achieved without sacrificing standards: 32 graduates have earned on average 148 credits and maintained a mean GPA of 3.17, and half have gone on to graduate school.

The low proportion of U.S students earning science degrees is a source of concern. The consequences for America's prominence in science and technology have been described in near-crisis terms (Committee on Prospering, 2007). Over several decades, the United States' ranking for the proportion of college-age population earning science and engineering degrees has dropped from 3rd to 17th. Approximately one-third of all bachelor's degrees awarded in the United States are in science and engineering fields. By contrast, more than half of all first university degrees awarded in Japan (63%), China (53%), and Singapore (51%) are in science, technology, engineering, or mathematics (STEM) disciplines. Just over four million STEM bachelor's degrees were awarded worldwide in 2006: 21% in China, 19% in the European Union, but only 11% in the United States (National Science Board, 2010).

Limited role models and mentors, poorly equipped secondary schools, and financial obstacles contribute to the paucity of science, math, and engineering majors. Fundamental changes in philosophy about and methods for teaching science are essential to increase recruitment and graduation of traditional and underrepresented students in STEM disciplines.

Several identified patterns explain the ineffectiveness of traditional approaches to increasing science enrollment. One entrenched, but often unacknowledged, systematic problem is the "weeding out" of seemingly unmotivated or poorly prepared students. To stop the weeding out, faculty members need to invest extra effort in these students. Physics and preengineering students who lack strong mathematics preparation are especially at risk. Studies show, however, that students who remain in science and those who change majors do not differ in high school preparation, performance scores, or effort expended. Also, exceptionally gifted and talented students leave the sciences when they find introductory science courses to be narrow in focus, formulaic, and unchallenging. These students foster the belief that other fields are more stimulating and promise a fuller educational experience (Margolis & Fisher, 2001; Meyer, 2002; Seymour & Hewitt, 1996).

Since 2005 we have worked to recruit, support, and graduate more students in all science disciplines. Our approach is grounded in the Building Engineering and Science Talent Committee's (2004) principles to increase representation of minorities in science and engineering: institutional leadership, targeted recruitment, engaged faculty, personal attention, peer support, enriched research experience, bridges to the next level, and continuous evaluation.

To translate these principles into practice, a cohesive, interdisciplinary strategy focusing on nanotechnology and enhanced undergraduate research was created. Inherently interdisciplinary, the novelty of nanotechnology and its growing career potential appeal to students. We engage students by offering progressively meaningful research opportunities with faculty mentors to foster a growing identity as scientists. Additionally, many activities beginning during the freshman year connect students with the program and peers.

The preliminary results are encouraging. Since implementing the Nanotechnology program in 2005, the number of graduates in the physics program has doubled, and it is now the third largest physics program in Pennsylvania's State System of Higher Education, despite the fact that our 5,000-student university is 11th of 14 in undergraduate enrollment (Goonewardene, Tzolov, Senevirathne, & Woodhouse, 2011). Of the 32 graduates from the Nanotechnology program, half were engineering/physics majors; the rest majored in biology and chemistry. Half of all graduates are now in masters or doctoral programs. Our students have produced nearly 40 peer-reviewed articles and presentations. Our interdisciplinary program continues to grow: of 35 students currently enrolled, 31 were recruited in the past two years, 9 in engineering/physics and 22 in biology and chemistry. Student demographics are also shifting. Approximately half the new recruits are women and many are first-generation college students.

Described here is our approach to recruit additional, and more diverse, science students and engage them through increasingly sophisticated and independent undergraduate research. Strong evidence has indicated that a comprehensive approach addressing all aspects of student–faculty engagement is a hallmark of effective programs (Atkin, Green, & McLaughlin, 2002; Bowman & Stage, 2002; Hilborn & Howes, 2003; Tobias, 1992; Whitten, Foster, & Duncombe, 2003).

Purpose and methods

Nanotechnology is not a separate department at Lock Haven University. Rather, the interdisciplinary nanotechnology program utilizes faculty from all science departments and has its own funding for operations and equipment. Three physics professors were recruited to lead nanotechnology research initiatives and manage five interdisciplinary laboratories while teaching a full load in the physics and nanotechnology programs. Labs were developed using seed funding from the university in 2004 that was leveraged for multiple grants from Pennsylvania's Department of Community and Economic Development (PA-DCED). Grants for research-grade instruments totaled approximately $350,000, including matching contributions from the university, which also provided 3,000 sq. ft. of laboratory space. In 2008 and 2009 the program received nearly $700,000 of National Science Foundation (NSF) funding to expand the program, acquire more research-grade instrumentation, and provide student scholarships (NSF Stem Award #0806660; NSF MRI Award #0923047).

Biology, chemistry, and health sciences faculty help the physics faculty implement the program. This Nano Group, consisting of eight faculty members, recruits students, supports the student Nano Club, mentors students involved in undergraduate research, and shares nanotech developments within their disciplines (Whitling et al., 2010).

The research in the nanotechnology program is interdisciplinary (Drayer, 2008a, 2008b; Drayer, Girardi, & Tzolov, 2007; Ganther, Yarunova, Overton, & Senevirathne, 2010a, 2010b; Yarunova, Senevirathne, Overton, & Tzolov, 2009). For example, faculty in physics and chemistry are investigating liposomes as drug-delivery platforms, and faculty in physics and biology are analyzing fungi using nanotechnology tools and techniques.

The goal of this uniquely organized "department" is to infuse nanotechnology into the curricula of all science disciplines and provide students with the fundamentals of nanoscience and skills of nanotechnology, which they can apply within their respective disciplines. This department, therefore, has no majors of its own; rather, it expands student options by offering a minor in nanotechnology and an associate of applied science in nanotechnology. Either path complements the BS-degree major in all science disciplines.

The nanotechnology program is coordinated by a director who receives a half-time release from teaching to maintain student records and manage budget lines totaling $34,000 per year for equipment, student lab workers, and operations. He identifies external funding opportunities and supports and encourages faculty to develop competitive proposals for external funding, a key part of the program.

Recruitment

Our recruitment approach is comprehensive and vigorous. To attract local students we present an annual nano open house that showcases our laboratories and describes educational and career opportunities. This event brings 50–70 high school students and teachers onto campus for research presentations and demonstrations by undergraduate nano students. To reach beyond our region, we sponsor a booth at the Pennsylvania Science Teachers Association annual meeting. Undergraduates (rather than faculty) staff the booth and describe their experiences and the opportunities at Lock Haven University to teachers from throughout the state. Our students are our best ambassadors; they connect and have more credibility with their peers than professors or admissions counselors. Finally, we visit distant school districts to showcase our programs to high school students and their teachers and guidance counselors. We also identify and publicize scholarship opportunities, supported by a National Science Foundation grant, that are open to science students in the Nanotechnology program.

Once students enroll, our efforts focus on exciting and engaging them in science learning through progressively sophisticated and independent research opportunities and through a student-learning community that supports them throughout their academic career.

Introduction to Nanoscience seminar

Introduction to Nanoscience is a one-hour seminar for first-year students curious about nanotechnology, similar to other freshmen seminars that attract and engage students (Adams, 2009; Sullivan et al., 2008; Tahan et al., 2006). The informal and interactive format encourages students to actively participate rather than passively listen to lectures. Experiential learning also comes from touring the nanotechnology labs at Lock Haven University and the nearby cleanroom facility at Penn State University. Students are introduced to hot topics in nanotechnology across all disciplines and to the popular scientific literature. They learn to conduct literature reviews using online and offline library resources. Throughout the semester, students present what they researched to the class, and the professor guides them to additional resources to strengthen their presentations. Because the students choose the topics, class discussions range across all science disciplines. Finally, they present a topic of their choice from their literature survey to a science class of peers (e.g., an introductory physics class for biology, chemistry, or physics majors) using verbal (PowerPoint) and visual (Publisher) modes.

Science learning community—Nano Club

Interaction with other students is an essential element of our approach. The science learning community built around the Nano Club and run by upper-division students is the "glue" that keeps students and faculty connected and engaged throughout the students' university career. Especially during the critical first two years when they complete required introductory courses in their respective disciplines, all science students are encouraged to attend Nano Club activities (pizza helps), where they meet other students and faculty members.

Among the activities is an informal multidisciplinary Nanotechnology Seminar Series that brings together faculty members, students, and guest speakers who exchange ideas and research experiences to inform and engage students. Presentations by upper-division students serve two purposes: first- and second-year students learn firsthand from upperclass peers about their work, and upper-division students can present on campus before making formal presentations at scientific conferences. Students feel more comfortable asking questions and engaging in discussions with their peers than with faculty or outside speakers.

The students plan activities such as visits to science museums and research labs, industrial tours, and travel to student conferences. Alumni working in industry or attending graduate school present at the annual university-wide Nanoscience Awareness Day. This provides students with firsthand accounts of the opportunities offered by broadening their science education with the nanotechnology experience. The Nano Club forum nurtures communication and professional relationships across science disciplines for both faculty and students. It also offers recreational and social opportunities (e.g., bowling, flag football, picnics) that bring students from different majors together. The Nano Club learning community is supported through university student activity fees and provides out-of-classroom opportunities for student interaction outside their own discipline. We promote and foster this supportive science learning community to engage students beyond the classroom and help them stay motivated and focused. Data show that students do not make precipitous decisions about staying or leaving the sciences (Seymour & Hewitt, 1996).

Undergraduate research

Our curriculum is designed to motivate students and provide them with content knowledge and skills to carry out meaningful research. We offer a sequential approach that progressively advances students toward independent research.

Nanotechnology research requires specific laboratory skills and techniques using sophisticated instrumentation. In their second-year summer, students who remain interested in nanoscale science attend the 18-credit Nano Manufacturing Technology (NMT) semester at Penn State's NSF-supported Nanotechnology Applications and Career Knowledge (NACK) Center (NACK Center, 2009), where they work in a cleanroom environment and master basic techniques. Our partnership with Penn State has enabled us to send students to this experience at the cost of Lock Haven University tuition. Partial board and lodging grants are also available to Pennsylvania residents through grants from PA-DCED.

Students who complete the NMT semester can do a one-year faculty supervised research project (Advanced Lab Experience PHAP431). This course is a hybrid between independent research and a laboratory experience course that goes beyond the "cookbook" approach of traditional structured lab courses.

Students are guided by a faculty mentor who initially provides detailed instructions and repetitive exercises to make students comfortable with techniques. As the student masters various techniques, the faculty member gradually encourages experimentation designed to develop scientific reasoning. By journaling and reflecting on these experiences, students learn to define scientific problems and to identify solutions using the scientific method. As a result, students become increasingly independent and develop an identity as a scientist and researcher.

At this stage (usually in their senior year), students are encouraged to carry out an independent research project, typically a continuation of work initiated in PHAP431, which often leads to a publication or presentation. We pair senior students with junior students who "shadow" and assist their senior mentors. Juniors who earned this opportunity have demonstrated high academic achievement during their first year. This aligns with our philosophy of student-to-student engagement. To the extent possible, pairings are same sex because there is evidence that men and women have different learning and communication styles (Whitten et al., 2003). Same-sex pairings are also practical because much of the independent research occurs at night and on weekends when students are alone in the labs.

To date, 25 students have presented their research at regional, state, or national conferences, and 8 have coauthored peer-reviewed journal articles. One student is a coinventor on patent-pending device technology (Tzolov & Swiontek, 2010). This publication record helps our students compete with graduates of more selective schools when applying to graduate schools. Moreover, completing independent research and contributing to the scientific community as a coauthor strengthens a student's identity as a scientist and builds confidence and self-worth (King, 2008). This kind of maturity cannot be instilled by mere classroom or guided laboratory experience.

Assessment

In spring 2010, we surveyed graduates of the nanotechnology program, students taking nanotechnology courses, and students who expressed interest by taking the Introduction to Nanoscience course or by participating in the Nano Club.

A total of 58 current and graduated students were surveyed, and 26 (45%) responded: 15 men and 11 women; 17 undergraduates and 9 alumni; 10 biology/chemistry majors, 7 physics majors, 5 biology majors, 3 engineering majors, and 1 chemistry major; and 7 NSF-nanoscience scholars and 13 nonnanoscience scholars. Respondents were asked why they chose Lock Haven University and the

TABLE 1

Results of survey of student opinions.

	N	Mean	SD
Introduction to Nanoscience course			
Increased interest in nanotechnology	23	4.35	0.935
Increased knowledge in nanotechnology	22	4.27	0.935
Increased understanding of applications of nanotech to specific science majors	22	4.27	0.935
Identify application of nanotech to career goals	22	4.09	0.971
Improved presentation skills	22	4.32	0.894
Improved literature search skills	13	3.46	1.127
Touring Lock Haven's nano lab increased excitement about field	20	3.95	1.050
Touring Penn State nano lab increased excitement about field	20	4.40	1.095
Exposure to cutting-edge research increased interest in conducting research	22	4.14	1.082
Science learning community			
Attending conferences increased involvement	17	4.65	0.996
Attending nanotechnology annual picnic increased involvement	17	4.35	1.057
Attending field trips increased involvement	22	4.18	1.368
Informal contact with faculty increased involvement	23	4.17	1.029
Nano Club participation increased interest in the field	24	4.04	0.999
Nano Club participation increased knowledge of the field	25	4.12	1.054
Undergraduate research opportunities			
Conducting research increased student confidence	12	4.67	0.651
Conducting research increased student identity as scientists	6	4.83	0.408
Conducting research helped students believe that they could contribute to the field	15	3.67	1.047
Faculty effectiveness			
Quality of faculty	25	4.88	0.332
Commitment of faculty	24	4.75	0.532

Note: A 5-point Likert scale was used, with 1 = *strongly disagree*, 2 = *disagree*, 3 = *neutral*, 4 = *agree*, 5 = *strongly agree.*

nanotechnology program and about their experiences in and satisfaction with the nanotechnology program, specific nanotechnology courses, and the elements of our program described previously (i.e., Introduction to Nanoscience, Nano Club, research opportunities). Open-ended questions elicited opinions about program strengths, weaknesses, and recommendations for change. Students provided a positive evaluation of all areas of the program. Satisfaction with the science learning community/Nano Club, undergraduate research opportunities, and program faculty was especially high. Mean responses (using a 5-point Likert scale with 1 = *strongly disagree*; 5 = *strongly agree*) to specific program elements are summarized in Table 1.

Conclusions

There are many reasons why STEM majors comprise a low proportion of college students. Altering this pattern requires effort at every educational level, including primary and secondary schools in which students are first introduced to science. At the university level, eliminating financial barriers through scholarship programs is a necessary but insufficient measure. To encourage more science majors and to help them succeed, we must examine how students learn and how we teach science and engineering.

We use nanotechnology, an interdisciplinary field, to generate interest and attract students across all disciplines and to offer progressively challenging research opportunities with faculty mentors while sequentially building skills. We encourage student-to-student support to foster rapport, comradeship, and program ownership through Nano Club activities.

The nanotechnology program is not a substitute for proficiency in science or mathematics; students must successfully complete coursework in their discipline. Nano students successfully completed an average of 73 credits by the end of their sophomore year (completing 60 credits is "on track" to graduate in four years). The fact that half of our nanotechnology graduates have gone on to graduate school (the 32 program graduates earned an average of 148 credits with a mean GPA of 3.17) demonstrates that it is possible to increase science enrollment without lowering standards. We continue to promote group research projects that are truly interdisciplinary. For example, we have recently started collaborating with medical researchers and engineers at Penn State University to involve undergraduates in designing and testing biosensors for neurological applications. Our goal is to develop an interdisciplinary platform where students from different disciplines work together and faculty members model interdisciplinary collaboration. Beyond learning scientific content, students gain real-life experience with group process; such group activities promote student retention, especially among underrepresented minorities (McIlwee & Robinson, 1992; Rosser, 1997).

Our interdisciplinary education model produces undergraduates who have a deep disciplinary background while also receiving a robust cross-disciplinary education. These students can be ideal candidates for further training and research in "convergence science," the subject of the recent Massachusetts Institute of Technology (2011) white paper, "The Third Revolution: The Convergence of the Life Sciences, Physical Sciences, and Engineering." Our model can also serve as a workforce development model for this area at the undergraduate level.

Although we think that the ideal approach is interdisciplinary, this model can be replicated within a single department or discipline that emphasizes or is expanding undergraduate research. Student clubs can form the core of a student learning community that provides support, encouragement, and motivation outside the classroom. ■

Acknowledgments

We thank Dr. Mike Cullin for his help drafting and revising the manuscript. We also acknowledge contributions by Dr. Marian Tzolov, Dr. Indrajith Senevirathne, Dr. Carina Howell, and Dr. Amy Way, members of the faculty Nano Group. Their contributions were essential to the successful implementation of our nanotechnology program.

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