Advances in Engineering Education

SUMMER 2011

Development of an Interdisciplinary Undergraduate Bioengineering Program at Lehigh University

LORI HERZ
Chemical Engineering and Bioengineering

M. JEAN RUSSO
Center for Social Research

H. DANIEL OU-YANG
Physics and Bioengineering

MOHAMED EL-AASSER
Chemical Engineering and International Affairs

ANAND JAGOTA
Chemical Engineering and Bioengineering

SVETLANA TATIC-LUCIC
Electrical and Computer Engineering
and

JOHN OCHS
Mechanical Engineering and Mechanics, Integrated Product Development
Lehigh University
Bethlehem, PA

ABSTRACT

The undergraduate Bioengineering Program at Lehigh University was established as part of the university's Bioscience and Biotechnology Initiative with support from the National Science Foundation through a grant from its Division of Engineering Education and Centers (EEC). The objective here is to describe the program development and implementation, as well as the challenges encountered. Bioengineering at Lehigh was designed as an interdisciplinary program, with an emphasis on experiential learning, entrepreneurship, and innovation. In this light, the goals established for the program implementation were focused on recruiting students, developing a rigorous curriculum, equipping laboratories, and fostering industrial partnerships. The curriculum initially had three key components: a core of basic requirements, three tracks allowing students to specialize within a field of bioengineering, and experiential learning. The key challenges faced are balancing breadth and depth of a curriculum in a diverse field, improving experiential learning opportunities, implementing changes while maintaining stability, and handling operations as a new program rather than as an established department. The effectiveness of these strategies has been

assessed on an ongoing basis. For example, an integrated recruitment strategy was used to encourage student enrollment, the results of which were measured through surveys and admissions data. Requiring students to select one of the three tracks, which are Biopharmaceutical Engineering, Cell and Tissue Engineering, and Bioelectronics and Biophotonics, each with an advanced laboratory course, added depth to the curriculum. Based on several sources of feedback, numerous changes have been made to the curriculum, including the addition of more bioengineering courses, especially advanced electives. The incorporation of Integrated Product Development (IPD), which was already an established hallmark program at Lehigh, into bioengineering, was a major program change that enhanced the hands-on learning and innovation opportunities. Implementing such changes, and managing them effectively, have been necessary to maintain program stability.

Key Words: bioengineering, National Science Foundation, curriculum, interdisciplinary education, experiential learning, entrepreneurship

INTRODUCTION

Lehigh University began a campus-wide Bioscience and Biotechnology Initiative in 2000, aiming to bridge fields in the life and physical sciences, engineering, business, and education, providing a wide range of research and educational opportunities for the institution. The four specific elements of this initiative are systems biology, bioengineering, biobusiness, and science education, and the establishment of the undergraduate Bioengineering Program has been a key component of this endeavor. Lehigh has recognized that bioengineering will be an important field in the twenty-first century, one that requires the removal of traditional boundaries among academic disciplines, practical experience, and collaborations among people with different backgrounds and expertise. The program was initially funded, in part, by a grant from the National Science Foundation (NSF) Division of Engineering Education and Centers (EEC) entitled "Establishing a Cross-Disciplinary Bioengineering Program with a Technical Entrepreneurship Focus at Lehigh University" [1]. This project was led by Dr. Mohamed El-Aasser, the Principal Investigator (PI), and the co-PI's were Drs. Daniel Ou-Yang, John Ochs, and Svetlana Tatic-Lucic, all of whom are authors of this paper. The funds obtained from the grant were used to develop the program, specifically to add personnel, including professional staff, clerical personnel, and students, and to purchase the laboratory equipment needed to provide undergraduates with the hands-on experiences intended for the program. Throughout the grant, the program was evaluated by Dr. M. Jean Russo, an independent evaluator from Lehigh's Center for Social Research and one of the authors of this paper [2].

Recognizing the need to provide opportunities for bioengineering education and research, many universities have added programs or departments in bioengineering or biomedical engineering over the past decade. Other universities have taken an alternate approach by incorporating bioengineering into an existing, more traditional, engineering department. In fact, chemical engineering departments at numerous universities have changed their department name to reflect the increased emphasis on bio-related activities. Many of these programs have been funded through organizations such as the NSF, the National Institute of Health (NIH), and the Whitaker Foundation.

An important element of bioengineering at Lehigh, which is aligned with the integrative philosophy, is project-based experiential learning, an approach that has been used effectively for programs at Lehigh, notably Integrated Product Development (IPD), a capstone design course which spans engineering, business, and design arts. Such hands-on instruction is also required for program accreditation, as ABET (Accreditation Board for Engineering and Technology) defines criteria for design and experimentation for programs in engineering [3]. Moreover, an understanding of the complex interactions in the life sciences and its applications, such as gene regulation, cell function, circuits, and populations, makes a systems perspective essential [1]. The importance of this approach was noted a decade ago by Dr. Floyd Bloom, retired Research Department Chair at the Scripps Research Institute and former Editor-in-Chief of Science [4] and Dr. Francis Collins, NIH Director and former director of the Human Genome Project [5].

Bioengineering will continue to be an important field as we proceed into the twenty-first century, and hands-on, practical experience will be vital for new graduates entering the workforce. While some believe that engineers without formal training in biology may be hired first and taught biology later, the field of biology has grown in complexity, requiring engineers with a background in the life sciences who can make engineering judgments about biological systems [6]. Moreover, we live in a rapidly changing, global environment, in which innovation cycles are much shorter than in years past. Researchers at the LIFE (Learning in Informal and Formal Environments) Center, a National Science Foundation (NSF) supported Science of Learning Center [7], have noted that students can become more adaptive and innovative through innovation and interactive activities, beginning early in the curriculum [8]. Charles Vest, president of the National Academy of Engineering (NAE), predicted that engineers in the workforce will face numerous global challenges in this century, and stressed the need to make engineering programs "exciting, creative, rigorous, demanding, and empowering milieus" [9]. Of the fourteen "Engineering Grand Challenges" defined by an NAE committee of renowned scientists and engineers [10], three are directly applicable to the field of bioengineering: Engineer Better Medicines, Advance Health Informatics, and Reverse Engineer the Brain.

PROGRAM HISTORY

Establishing the Bioengineering Program was in the minds of numerous faculty members and the administration. When a few faculty members proposed such a program to the university, a campus-wide workshop, followed by a faculty task force, was convened. From 2000 to 2002, a working plan was developed by the university to establish a Bioengineering program at Lehigh, in consultation with external professionals from both academia and industry.

The university established overall goals for the implementation of the Bioengineering Program in alignment with the philosophy of the Bioscience and Biotechnology Initiative, such that the program would be interdisciplinary in nature, crossing traditional departments and eliminating boundaries. The program would focus on innovation and experiential learning both inside and outside the classroom, exposing students to up-to-date techniques in the field of bioengineering. The need for a formalized plan to enroll students into the program was also recognized. In light of these needs, the goals defined for the program were as follows [1]:

1. Recruit high quality bioengineering students and open bio-related engineering degrees to students in traditional engineering departments.
2. Develop a rigorous curriculum that emphasizes hands-on experiential learning and business aspects and entrepreneurial opportunities of bioengineering.
3. Develop advanced laboratories for undergraduate training.
4. Cultivate industrial partnerships to mentor students and provide real-world problems through entrepreneurial projects.

The Bioengineering Program was started as an undergraduate program only, rather than as a graduate program or as a program for both graduates and undergraduates. It was recognized that this approach would perhaps cause the program to sacrifice its research identity in the short term. However, the rationale for this decision was that a program reaching steady-state enrollment over the first few years would provide inherent stability and set the framework for a graduate program later. This is, in fact, what has occurred, as the graduate program is being launched formally in 2010.

The program officially began in the 2002-03 academic year with the first cohort of students. The Bioengineering Program reached numerous milestones from its beginning until the graduation of the first class in May 2006, as shown by the timeline in Figure 1. The program was accredited by ABET in 2008, following a self-study evaluation and site visit. The next stage in the Bioengineering Program is the development of a Biotechnology Cluster at Lehigh, with a research focus on enabling technologies toward affordable health care, and for biomedical research and innovation. The program will build focused expertise in biosensing and bioelectronics, biomaterials, cellular and molecular engineering, and technologies such as modeling, computing, and microscopy.

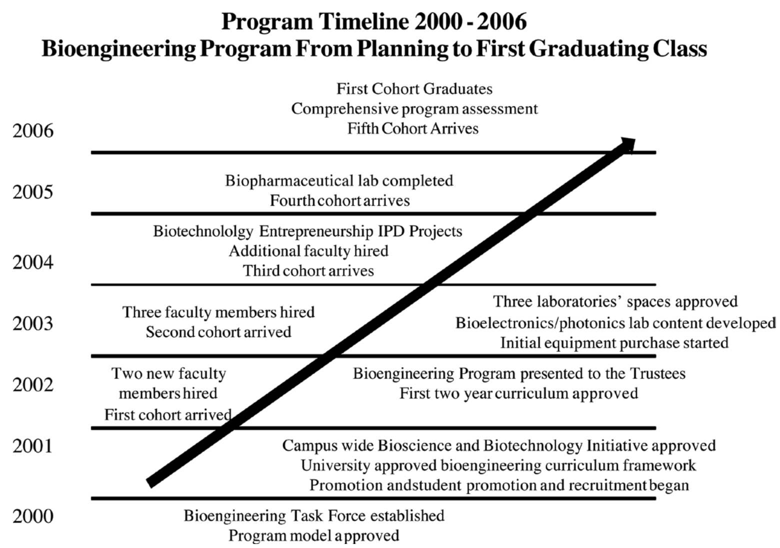


Figure 1. Program Timeline [1].

The objective of this work is to discuss the implementation and early development of the undergraduate bioengineering program at Lehigh University based upon the four goals established at the outset of the program, as well as the challenges encountered. To provide the necessary context, the program operation, curriculum design, and laboratory set-up, including its philosophy or rationale, will be presented. The broad challenges faced are as follows:

1. Balancing curriculum breadth versus depth in the curriculum.
2. Improving the experiential learning portions of the program, especially the entrepreneurship and innovation aspects of the curriculum.
3. Managing stability versus change in a young, inherently dynamic program.
4. Functioning as a program rather than a department within the university.

The discussion will include how the program has evolved as a result of these challenges to incorporate what was learned as the implementation proceeded. Where applicable, the results and analysis of the formal assessment process are presented.

RECRUITMENT OF HIGH QUALITY STUDENTS

As a first step in achieving this objective, the bioengineering program revised the advising and admissions processes to produce a more integrated system for attracting and directing students to the program. This would allow students interested in bio-related areas to clearly understand what options Lehigh could provide and enable them to make their decisions based upon sufficient information. A well-coordinated plan was needed, since a lack of cohesion could result in inconsistent information, making the process of selecting an intended program difficult for first-year students. In its early years, the program was promoted through a program brochure, catalog descriptions, and a homepage on the Lehigh University website.

The brochure gives a brief program overview, describing the learner-centered approach to the curriculum, providing faculty contact information, and also featuring the experiences of a recently graduated senior. Lehigh's course catalog for 2003–04 was changed for Bioengineering from that of the previous year, with the addition of a section defining course requirements, as well as the typical four-year schedule listing which courses students generally take each semester. Later changes to the curriculum and course offerings have been made in the subsequent course catalogs, which are updated annually. The link for the Bioengineering website contains links to Admissions, Faculty/Staff, Research, and Program Objectives [11]. Additionally, members of the bioengineering faculty have participated in Candidates' Day, which is offered each April by the University for admitted students and their families. At these sessions, potential students are given the opportunity to hear about the various programs offered by Lehigh University.

To assess the effectiveness of each recruiting method, Dr. Russo conducted a Student Baseline Survey between 2003 and 2007, and key results are summarized here [2]. In 2003, the first year of the NSF grant, data were collected from the freshmen and sophomore bioengineering classes; in subsequent years, only freshmen were surveyed. The students were asked to indicate each method they used to obtain information about the Bioengineering Program, including printed literature (i.e. catalogs, flyers, etc.), the program website, faculty, current Lehigh students, their advisor, or other methods. Most students learned about the Bioengineering Program through printed material (46.8%) or through the website (44.1%). In 2007, more than ever before, students received information about the program through their advisors (18.9%). Others learned of the program through Lehigh students (11.1%), Lehigh faculty members (10.8%), their advisors (9.0%), or faculty from other institutions (2.7%). Sixteen percent of the students heard about the program from other sources, e.g., during their campus tours, on Candidates' Day, from alumni, or from family members. The high percentage of students using printed materials or the website demonstrated the necessity of keeping these two methods updated.

To simplify the process of obtaining basic information about a program, especially for prospective and first-year students, it is preferable for students interested in a particular program to contact a minimum number of individuals. In 2003, over one-third of the students spoke to at least two individuals before being directed to the Bioengineering Program. For this reason, one of the goals was to direct such students to the program director in order to decrease the number of individuals students contacted to obtain the needed information. In 2007, 28% of the students spoke to two or more people. This was an increase from the previous year when only 6% of students contacted two or more individuals. In 2007, however, a number of students heard about the program through their advisors. Students who indicated they spoke to two individuals tended to speak to their advisor as well as the program director, or they spoke to two different program administrators. Based upon this, the program has fulfilled its goal of funneling students to the program administrators to receive the necessary information [2].

The university's Office of Admissions department tracks the number of potential students who inquire about a specific academic program, the number that indicated interest on their application, the number of offers for admission, and the number of students that send in a deposit, even if they eventually decided not to attend. Figure 2, which depicts these numbers over the program's first five years, generally shows steady upward trends in all areas each year, with the exception of 2006. In 2008–09, there were 234 inquiries, 262 students indicated interest on their applications, 140 were offered admission, and 29 students sent in deposits.

The program also tracks student enrollment. The number of students in each graduating class from 2006 to 2012 is shown in Figure 3. The first cohort, which graduated in 2006, had 21 students. Class size in subsequent years has fluctuated but with a trend that increases with time. The members of the

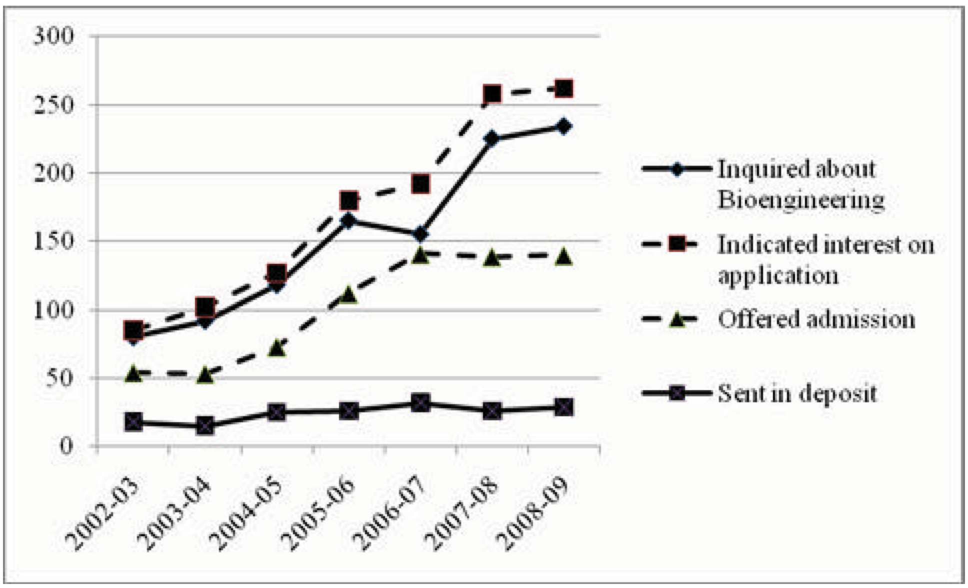


Figure 2. Correlation of Student Inquiries, Applications, and Admissions.

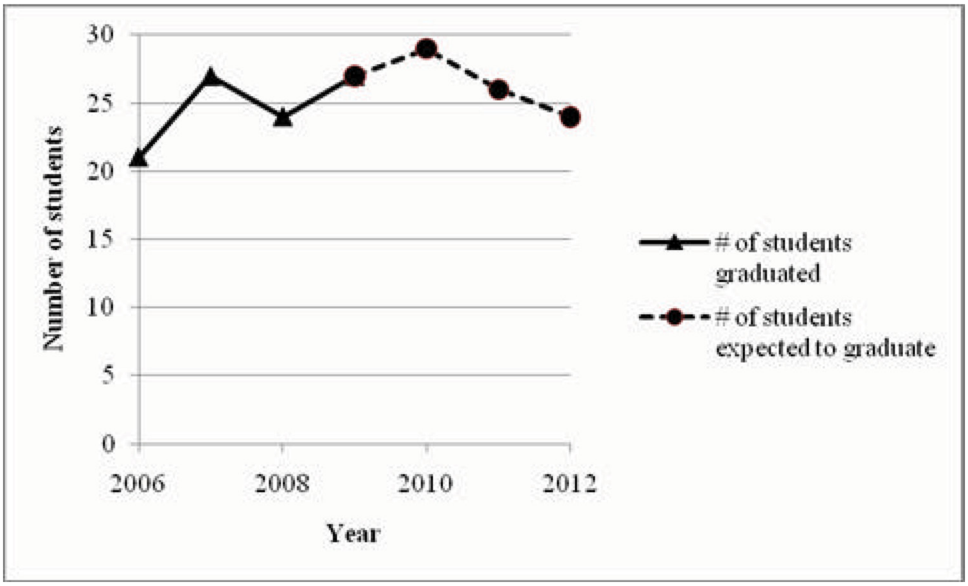


Figure 3. Bioengineering Class Size, 2006–2012.

program faculty are satisfied with this number of students, and would be comfortable increasing the class size to perhaps 35. The primary limitations to further increasing the number of bioengineering majors are the space and equipment available in the advanced laboratory courses. For this reason, Integrated Biotechnology Laboratory (BIOE 343) and Integrated Biostructural Mechanics Laboratory (BIOE 357) are each limited to ten students per semester. The course for Integrated Bioelectronics/Biophotonics Laboratory (BIOE 331) has had enrollment of just several students per year. Fortunately, space is available in the classroom and since an increase in enrollment is anticipated, the equipment has been budgeted accordingly.

While bioengineering remains a relatively young program at Lehigh, it has now been in existence long enough such that its identity and recruiting tools (i.e., the website) are well-established. Specifically, faculty members throughout engineering are knowledgeable about the program and can advise students accordingly. As such, the intensive effort initially spent recruiting students to ensure sufficient enrollment was phased out three to four years after the program was implemented.

While the initial aim of the program, as defined by the university, was to recruit high-quality students, the Bioengineering Program is not an honors program. Thus, any student meeting the academic standards of the Engineering College is permitted to major in bioengineering. To assess the quality of students in the program, SAT scores for freshman bioengineering students from 2003 to 2007 were compared with all students in the Engineering College, as well as all freshmen at Lehigh. The data, provided by Dr. Russo in the program evaluation [2], is shown in Figure 4. The average SAT scores for the Bioengineering students tended to be higher than those of all incoming freshmen and equal to or higher than all the incoming engineering students. These data point to the conclusion that the students accepted into the Bioengineering Program are of high academic caliber.

The quality of students graduating from the Bioengineering Program can also be assessed from employment and graduate education statistics. The Career Services department at Lehigh surveys alumni six months after graduation to determine undergraduate placement levels in industry and in further education. A comparison of bioengineering graduates with all Engineering College graduates from 2006 to 2009 is shown in Figure 5. Relative to alumni from other engineering programs or departments, more bioengineers pursue further education and fewer enter the workforce. This may occur because many of our students plan to pursue careers in research and development, where advanced degrees may provide more professional opportunities. The average salary for 2009 bioengineering graduates from Lehigh was $62,333, which was above the national average of $ 53,147 for bioengineers, indicating that our students are competitive among their peers.

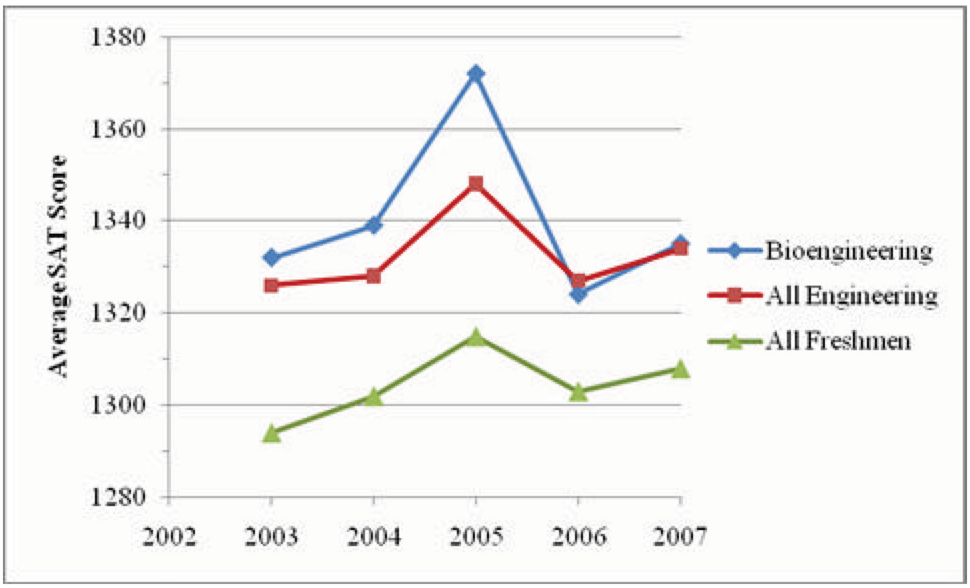


Figure 4: SAT Scores for All Matriculating Freshmen, Engineering Freshmen, and Bioengineering Freshmen, 2003 through 2007 [2]

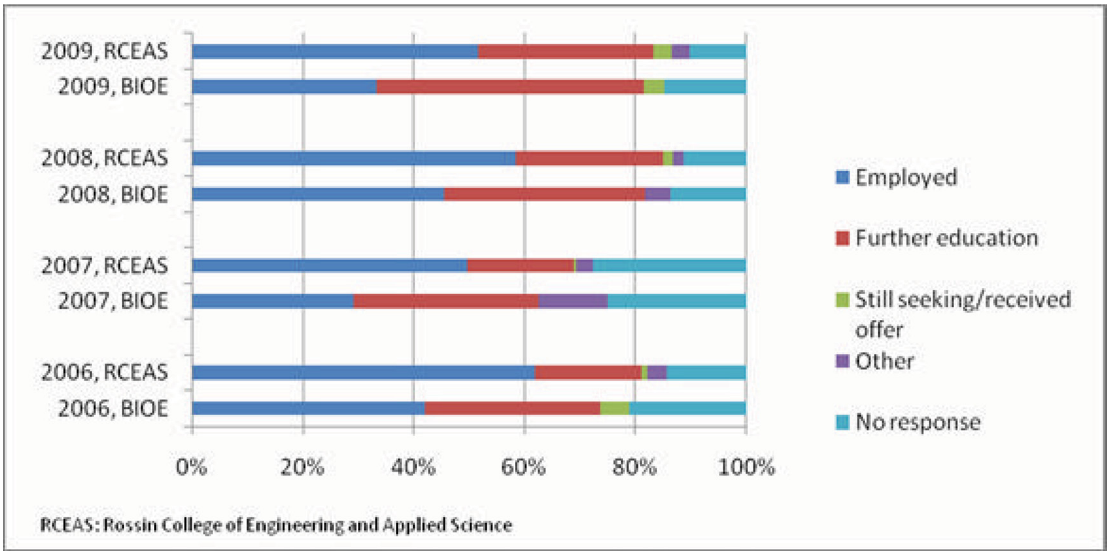


Figure 5. Undergraduate Placement Statistics.

INITIAL CURRICULUM DESIGN

The bioengineering curriculum was designed such that students can complete a B.S. in Bioengineering in four years, like the traditional engineering disciplines at Lehigh. The three overall components initially established for the curriculum were a core of basic requirements, longitudinally integrated experiential learning (LIEL), and three tracks, which allow students to focus within a field of bioengineering. Specific course requirements are described in Appendix I. The basic requirements include courses in mathematics, chemistry, biology, physics, English, economics, and bioethics. Within the basic requirements were the "integrated bioengineering" courses, consisting of two sophomore-level courses, Elements of Bioengineering (BIOE 110) and Engineering Physiology (BIOE 210), as well as a senior-level course in Bioengineering Design (BIOE 225), which was the initial capstone design course. The design class also covered topics in regulatory affairs, which is applicable to students entering the pharmaceutical, biotechnology, and medical device industries. The core bioengineering courses are listed in Appendix I, Table 5.

The second component of the curriculum, longitudinally integrated experiential learning (LIEL), which is shown pictorially in Figure 6, enables students to link theory and application starting in the first year. Freshmen take the one credit Introduction to Bioengineering seminars each semester, Theory to Practice (BIOE 1) and Current Topics (BIOE 2), exposing them to various contemporary

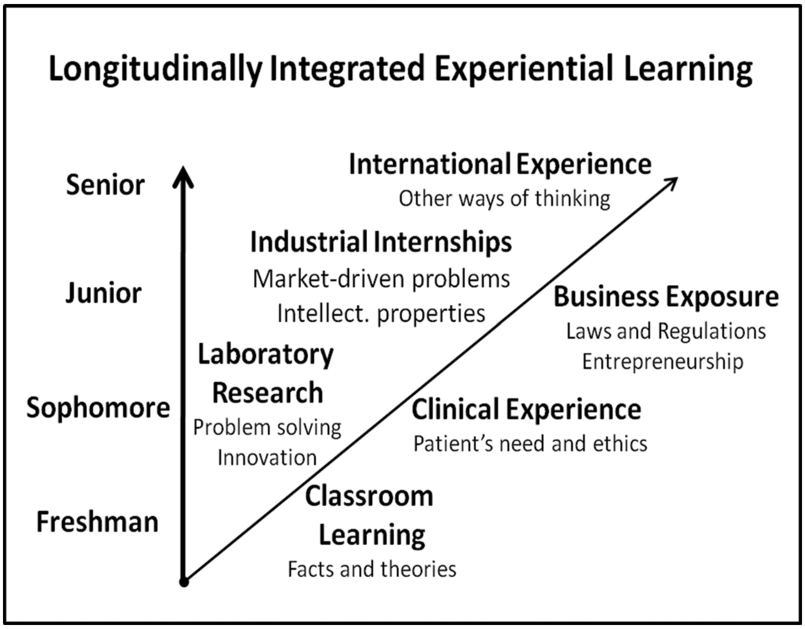


Figure 6. Bioengineering Learning Paradigm [1].

topics. When the program was first implemented, the LIEL component included undergraduate research, beginning in the second year, when sophomores prepared research proposals and started their projects (BIOE 10 and BIOE 20). During the junior and senior years, students performed three semesters of research (BIOE 132, BIOE 142, BIOE 242) under the guidance of a faculty advisor, culminating with an oral presentation and a written thesis (BIOE 290). This research sequence provided students with beneficial skills. However, after the program was rolled-out, it was recognized that the hands-on components of the program needed to focus more on entrepreneurial activities and cultivating industrial partnerships, per the initial program implementation goals. The second major challenge within the bioengineering program, therefore, has been to improve the experiential learning components of the curriculum.

Bioengineering is an incredibly broad and diverse field spanning numerous science and engineering disciplines. To enable students to concentrate in a particular area within the bioengineering realm, they specialize in one of three bioengineering "tracks", which constitute the third major section of the curriculum. The three tracks are Biopharmaceutical Engineering, Bioelectronics and Biophotonics, and Cell and Tissue Engineering. The Biopharmaceutical Engineering track is for students whose interests lie in areas such as recombinant DNA technology, bioinformatics, and drug delivery. The Bioelectronics track provides exposure to topics including signal processing, biosensors, Micro

Electro Mechanical Systems (MEMS), and optical technology for biomedical applications. The Cell and Tissue Engineering track encompasses biomaterials and biomechanics, from cells and tissues to organs and systems. Each track is aligned with a more traditional engineering discipline. Specifically, Biopharmaceutical Engineering, Cell and Tissue Engineering, and Bioelectronics are aligned with chemical engineering, mechanical engineering, and electrical engineering, respectively. Students take a set of core courses in those departments. For example, students in the Biopharmaceutical Engineering track take Material and Energy Balances, Thermodynamics, and Fluid Mechanics in chemical engineering. The specific course requirements for each track are listed in Appendix I, Table 6.

While having students take courses in other departments efficiently utilizes faculty resources, there can be drawbacks to sending our students to other departments for core courses. One issue that we are addressing pertains to the fluid mechanics and thermodynamics requirements for students in the Cell and Tissue Engineering and Biopharmaceutical Engineering tracks. Biopharmaceutical track students typically take these courses in chemical engineering (CHE 44, CHE 210), while Cell and Tissue track students take them in Mechanical Engineering (ME 231, ME 104). Students in both courses have indicated that there are few, if any, applications to biological systems. As a result, the Bioengineering Program has added a course in Biological Transport, first taught during the Spring 2011 semester, that students in both tracks will take in lieu of the fluid mechanics course in chemical or mechanical engineering. However, we have resolved the issue differently for thermodynamics. Students in the Cell and Tissue track are being encouraged to take thermodynamics in the materials science department (MAT 205), since this course already provides numerous examples of applications to biological systems. Several bioengineering students have taken MAT 205 as an alternative to ME 104, and have been pleased with the course. Alternatively, students in the Biopharmaceutical Engineering track will continue to take CHE 210, though the course will be modified slightly to include more examples of applications to biological systems. This approach has already been successful for Material and Energy Balances (CHE 31), a core course for the Biopharmaceutical track students. The instructor has been incorporating bioengineering-related examples in class for several years, resulting in positive feedback from the students.

Each Bioengineering track also has an advanced laboratory course associated with it. The three laboratory courses, Integrated Biotechnology (BIOE 343), Integrated Biostructural Mechanics (BIOE 357), and Integrated Bioelectronics/Biophotonics (BIOE 331), were created in 2003 using funds from the NSF grant [1]. These laboratories, which were designed by an interdisciplinary faculty team, are used as classrooms for the advanced undergraduate laboratories required by each track, and as research facilities. Each laboratory has experimental work stations, giving students training in theory, principle of operation, and the application of experimental techniques. The topics covered in each course are shown in Table 1. Like all Engineering College students at Lehigh, bioengineers declare

Track/Advanced Laboratory Course	Topics and Techniques	Equipment
Biopharmaceutical Engineering: Biotechnology Laboratory (BIOE 343)	sterilization, fermentation, purification operations, biochemical assays, recombinant DNA methods	fermentors, disposable bioreactor, analytical equipment, incubator shaker, ultra-low temperature freezer
Cell and Tissue Engineering: Biostructural Mechanics Laboratory (BIOE 357)	surface characterization and interactions, spectroscopy, and advanced techniques in microscopy	tissue culture microscopes, atomic force microscope, general cell culture equipment
Bioelectronics/Biophotonics: Bioelectronics/Biophotonics Laboratory (BIOE 331)	bioelectronic circuits, micropatterning of biological cells, micromanipulation of biological cells using electric fields, pacemakers, ultrasound, optic, laser tweezers and advanced imaging and optical microscopy techniques	microscopes, ultrasound, MRI imaging equipment, optical tweezers

Table 1. Advanced Laboratory Course for Each Bioengineering Track.

their majors during the spring semester of their freshman year, and at the same time, they select their track. While some students know which track they will choose when they start their freshman year, based upon course preferences and professional interests, many students need more guidance, which is provided through advising and the bioengineering freshman seminars (BIOE 1 and BIOE 2). When admitted high school seniors decide to attend Lehigh, they indicate their interest in bioengineering. Though they are not yet officially bioengineering majors, they are assigned a faculty advisor who is associated with the program, and can provide guidance about the three tracks. Students who have indicated their interest in bioengineering are also pre-registered in the freshman seminar for the fall term. Both the BIOE 1 and BIOE 2 seminars have numerous speakers from academia and industry, giving students a sense of the areas of bioengineering covered by each track.

ASSESSMENT OF LEARNING AND ACHIEVEMENT OF OUTCOMES

As required by ABET, the Bioengineering Program at Lehigh has defined Program Outcomes, which represent measurable achievements by students at the time of graduation [3]. Outcomes are achieved through satisfactory completion of the classes in the curriculum, such that each required course corresponds to at least one outcome. Achievement of outcomes was measured by assessing student performance in selected classes, and by surveying seniors prior to graduation. As part of the ABET accreditation process, we compiled grades for the core engineering courses, as well as achievement levels in the corresponding outcomes in 2006 and 2007. Since 2007, we have continued to perform annual senior surveys, which have included an evaluation of outcome achievement.

The data from 2006 to 2009 are shown in Table 2. Typically, bioengineering students earned A's and B's in their core engineering classes, and 90% to 100% of the students earned at least a C in all the classes. While having 100% of the students achieve satisfactory grades is preferable, the grades indicate that the Bioengineering students are generally learning the course material and that they are succeeding in courses in other engineering departments. These courses correspond to three different Program Outcomes, as shown in Table 2. The Bioengineering Program's goal for outcome achievement is at least 80%. Results of the surveys completed by graduating seniors indicate over 80% achievement for two out of three outcomes for all four years, and over 80% achievement for all three outcomes the past two years.

Student performance in the bioengineering laboratory courses and accomplishment of the corresponding outcomes were also assessed. For these courses, student performance was evaluated by a laboratory assessment rubric, in which course goals and levels of completion of these goals were defined. The rubric scores for 2006 and 2007, as well as the achievement levels for the corresponding outcomes per the senior surveys in 2006 through 2009, are shown in Table 3. For all the

Track	Course name	Course number	Number of students earning grades, 2006–07			
			A	B	C	D/F
All	Engineering Computations	ENGR 1	20	15	4	2
	Engineering Materials and Processes	MAT 33	7	8	3	2
Biopharmaceutical Engineering	Material and Energy Balances	CHE 31	4	5	1	1
	Fluid Mechanics	CHE 44	0	1	4	0
	Thermodynamics	CHE 210	5	4	0	0
Bioelectronics Biophotonics	Principles of Electrical Engineering	ECE 81	3	3	1	0
	Electronic Circuits	ECE 123	0	2	1	0
Cell & Tissue Engineering	Thermodynamics	ME 104	9	4	2	1
	Fluid Mechanics	ME 231	5	9	2	1
	Elementary Engineering Mechanics	MECH 2	3	0	2	0

	Students achieving outcome, per senior surveys			
	2006 (n = 17)	2007 (n = 17)	2008 (n = 17)	2009 (n = 17)
Outcome (a): an ability to apply knowledge of mathematics, science, and engineering	100%	94%	88%	100%
Outcome (e): an ability to identify, formulate, and solve engineering problems	81%	88%	82%	100%
Outcome (k): an ability to use the techniques, skills, and modern scientific tools necessary for bioengineering practice	75%	71%	82%	82%

Table 2. Assessment of Student Learning for Core Engineering Courses.

Track	Course name	Course number	No. of Students	Average Lab Assessment Rubric Score, 2006–07 (b)	(b)	(k)	(n)
All	Introduction to Engineering Physiology	BIOE 210	31	9.5	8.2	N/A	8.7
Biopharmaceutical Engineering	Integrated Biotechnology Laboratory	BIOE 343	4	8.3	9.0	> 9.0	8.7
Bioelectronics Biophotonics	Integrated Bioelectronics/ Biophotonics Laboratory	BIOE 331	3	9.0	8.5	> 8.0	9.0
Cell & Tissue Engineering	Integrated Biostructural Mechanics Laboratory	BIOE 357	9	8.5	8.8	> 8.0	8.8

Goal 1: be skillful in the conduct of experiments so as to generate useful data
Goal 2: be capable of analyzing and interpreting data to draw conclusions relevant to experimental design
Goal 3: have a working knowledge of equipment and instruments appropriate to their track
Goal 4: knowledge of bioengineering solutions that involve the interaction of living and non-living materials and systems as it relates to specific problems addressed in laboratory courses

	Students achieving outcome, per senior surveys 2006 (n = 17)	2007 (n = 17)	2008 (n = 17)	2009 (n = 17)
Outcome (b): an ability to conduct experiments, make measurements, and analyze and interpret data in living systems	94%	94%	100%	100%
Outcome (k): an ability to use the techniques, skills, and modern scientific tools necessary for bioengineering practice	75%	71%	82%	82%
Outcome (n): an ability to address the problems associated with the interaction between living and non-living materials and systems	77%	88%	82%	82%

Table 3. Assessment of Student Learning for Bioengineering Laboratory Courses.

laboratory courses, the average rubric score for all four course goals was at least eight out of ten, indicating that most students are learning the course material. Results of the surveys completed by graduating seniors indicate over 80% achievement for just one out of three outcomes for all four years, but over 80% achievement for all three outcomes the past two years.

While examples of assessing student learning in required classes and the corresponding achievement of selected outcomes have been presented, accomplishment of all Program Outcomes has also been evaluated. Over 80% of graduating seniors in 2006 and 2007 achieved nine out of fourteen outcomes, while over 80% of this constituency in 2008 and 2009 achieved twelve out of fourteen outcomes, indicating an upward trend toward reaching our goals as the program has progressed. These increases are, in part, a result of curriculum changes implemented since the start of the program in 2002. One outcome that has improved attainment is Outcome (m), an ability to apply advanced mathematics (including differential equations and statistics), science, and engineering to solve problems at the interface of engineering and biology. Over the past several years, more advanced electives have been added to the curriculum, to address the need for more applications of advanced mathematics and computing to bioengineering topics. This is discussed in Challenge 1, balancing breadth and depth of curriculum. A second outcome with sometimes unsatisfactory results is Outcome (c), an ability to design a system, component, or process to meet desired needs. Since the start of the program, the capstone design course has changed for the bioengineering students, which is addressed in Challenge 2, improving the experiential learning components of the curriculum.

Challenge 1: Balancing breadth and depth of curriculum

Within the program, the freshman seminars and the integrated bioengineering courses provide a rather extensive overview of the field of bioengineering. Essential depth is added to the curriculum through the three-track system, which enables students to narrow their focus, and includes both lecture and laboratory courses. Yet, achieving a balance between breadth and depth has been an ongoing effort for the program. Simply adding requirements for advanced courses or general bioengineering classes has not been an option, given that a total of 132 credits is required to complete the B.S., which is a challenge unto itself. However, this issue has been better addressed over the past several years, primarily by building additional course options into the curriculum with the availability of faculty resources to teach the classes.

To allow students to add depth to their studies by taking more advanced engineering electives, the number of core engineering courses was reduced from six to four, which is consistent with the other engineering programs at Lehigh. The program has also recognized the need to apply advanced mathematics to problems in the field of bioengineering, as required by ABET [3]. As such, students are now required to take an elective for which linear algebra with differential equations (MATH 205) and probability and statistics (MATH 231) are prerequisites. The courses that currently meet this requirement are: Biotechnology I (CHE 341), Molecular Bioengineering (CHE 344), and Biomolecular and Cellular Mechanics (BIOE 321). Since this requirement has been implemented, achievement of Outcome (m), an ability to apply advanced mathematics (including differential equations and statistics), science, and engineering to solve problems at the interface of engineering and biology, has increased from 71% in 2006 and 82% in 2007 to 94% in 2008 and 88% in 2009.

With the addition of faculty to teach bioengineering courses, eight advanced electives were added to the curriculum between 2007 and 2009, and one has been added in 2010, as shown in Figure 7. The need for such courses was expressed by numerous graduating seniors, alumni, and our external advisory board. They suggested the addition of more upper-level bioengineering courses, especially those requiring advanced mathematics or programming, voicing a need for more depth in the curriculum. The specific electives that were chosen were based upon a combination of

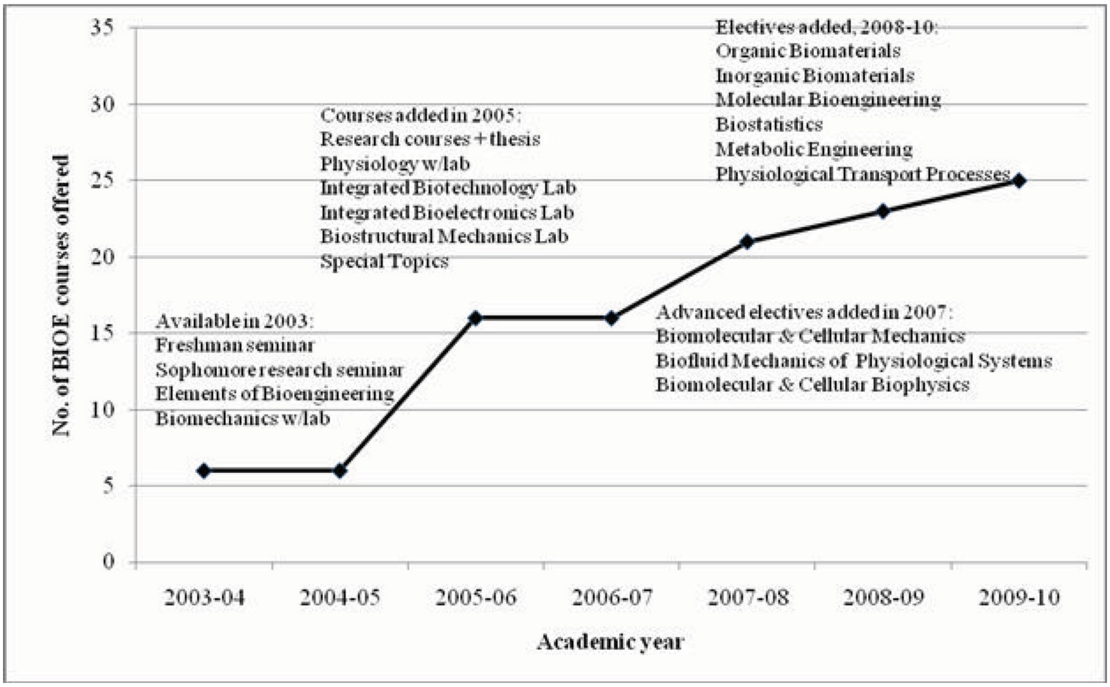


Figure 7. Increase in Bioengineering Course Offerings.

faculty expertise and the need to offer diverse subjects across the field of bioengineering. Some of the classes, such as biostatistics and the biomaterials' courses, appeal to students across all three tracks, while others are more geared to students in specific tracks. For example, Molecular Bioengineering (CHE 344), Biomolecular and Cellular Mechanics (BIOE 321), and Biomolecular and Cellular Biophysics (BIOS 380), while not track exclusive, are targeted to students in the Biopharmaceutical, Cell and Tissue, and Biolectronics tracks, respectively. Due to the interdisciplinary nature of these subjects, numerous electives are cross-listed in other departments. For example, Metabolic Engineering (BIOE/CHE 397) is cross-listed in chemical engineering, and Organic Biomaterials (BIOE/MAT 324) and Inorganic Biomaterials (BIOE/MAT 325) are cross-listed in materials science. Many of these courses added recently are mathematically intensive and have, perhaps, further helped improve the achievement of Outcome (m).

Challenge 2: Improving the experiential learning components of the curriculum

The goals established when the Bioengineering Program was in the planning stages included a curriculum emphasizing hands-on experiential learning, entrepreneurial opportunities, and industrial partnerships. As the program was initially designed, these aims were achieved through undergraduate research, summer internships, and, to a lesser extent, the Bioengineering Design course (BIOE 225). Laboratory research and internships provided valuable hands-on instruction, but it was recognized early on that there was a need to improve both the innovation component of experiential learning, as well as the capstone design portion of the program. The Bioengineering Program was able to strengthen this aspect of the curriculum by leveraging an already established, respected program within the university. Specifically, Integrated Product Development (IPD), an interdisciplinary program at Lehigh in which students from engineering, business, and design arts work on a team with other students on a real-world industry sponsored project [12], was incorporated into the bioengineering curriculum. Student participation in IPD has been instrumental in helping bioengineering achieve its fourth goal, to cultivate industrial partnerships and provide entrepreneurial projects.

IPD was started in 1990 as a result of a meeting of industrial leaders gathered at Lehigh to help and advise the mechanical engineering faculty on how to improve the quality of graduates who plan to work in industry. The program is directed by Dr. John Ochs, one of the authors of this paper. In 1996, the program received the American Society of Mechanical Engineers curriculum innovation award. The program has also received several large grants from alumni, foundations, state and local government for the development of infrastructure to support real-world, industry-sponsored projects [13]. The IPD courses stress innovation and entrepreneurship, making it an important component of the bioengineering curriculum and enabling the program to better achieve its initial objectives. Elements of its philosophy are that innovation is a process learned by doing it, experiential learning comes from engaging students in real world projects provided by industry partners, and diverse interdisciplinary teams applying creative processes and methods have the best chance for success [13]. The IPD program obtains industry sponsors through an active recruiting process, which includes a network built from Lehigh's Corporate Relations Department, alumni, and former IPD students. Additionally, interested companies outside this group have contacted the IPD program themselves and have subsequently become project sponsors. Several medical device companies have historically participated in IPD. However, when bioengineering students began taking IPD, the program more actively recruited sponsors for bioengineering-related projects from the existing network.

Bioengineering students in IPD take two courses, for a total of five credits. In the first course (ENGR 211), the student team focuses on understanding the technical issues in a business and social context, developing customer needs, creating innovative concepts, identifying the best concept, and developing it. The following semester, in ENGR 212, each student team continues the development, fabricates a prototype and tests it, and develops the plans for future product launch or process implementation [14]. At the start of the first IPD course, students attend a "Project Fair", in which the sponsors discuss their projects with students, who then select their top several project choices. The Bioengineering students are strongly encouraged to select Bioengineering-related projects. IPD staff then assign students to a project, based upon a combination of student preference, interdisciplinary balance, and, when possible, academic caliber. To provide a sense of the range of projects in which students participate, a list of the bioengineering-related design projects for 2009 is shown in Table 4.

With the addition of IPD to the curriculum, the course in Bioengineering Design (BIOE 225) was split into two separate courses: (1) cGMP Good Manufacturing Practices and Regulatory Affairs (BIOE 225) and (2) Special Topics, Bioengineering Design (BIOE 350). To fulfill the design requirement, students in the Classes of 2007 through 2010 have had the option to take Bioengineering Design or IPD. However, students were strongly advised to participate in IPD, and the majority opted to enroll. Between 2006 and 2008, bioengineering participation in the program ranged from 78% to 92%, and increased to 97% in 2009. Due to the positive response from the students and to better meet the ABET capstone design requirement [3], it was decided to make IPD a requirement rather than an option for the Class of 2011 and beyond. In fact, ABET recognized IPD as a bioengineering strength, stating that the design sequence is superior and commending its incorporation into the program [15]. As a result of this change, the course in Bioengineering Design has been phased out of the curriculum. However, the course in GMP's and Regulatory Affairs remains a requirement due to the importance of understanding government regulations in the healthcare industry.

Capstone design is a critical course for achieving Program Outcome (c), an ability to design a system, component, or process to meet desired needs. Achievement of this outcome, based upon responses from seniors in surveys, has ranged from 71% to 88%. The survey results do not distinguish

Company	Project
Aesculap	Distraction Instrument for Spinal Surgery
B Braun Medical	Innovative IV Set Packaging
Ecotech Marine	Protein Skimmer
Ethicon	Tissue Approximation Device
Lifeserve Innovations, LLC	Facemask for Oxygen Delivery
Stryker Orthopaedics	Post Removal in Revision Knee Surgery
Ultraflex	Prosthetic Socket for Below Knee Amputees in the 3rd World
Playtex	Alternative Materials for Infant Mealtime Products

Table 4. Bioengineering Students IPD Projects, 2009.

between those who took Bioengineering Design as Special Topics (BIOE 350) and those who took IPD. Information obtained from the senior exit interviews in 2008 and 2009 provides more clarity about the survey results. Approximately 40% of students, when asked about their opinion of the experiential portion of the program, provided only positive feedback about IPD, indicating, for example, that they were glad it became a requirement and that it is a very good or beneficial course. Nearly one-fourth of the students had a mixed opinion about IPD. While they believed that there were strengths to the program, there were also some negative aspects, such as working on a team with only bioengineers (i.e. not interdisciplinary), or that there were few projects that were process-oriented. This outcome will be further evaluated by faculty, especially now that all students take IPD.

While the addition of IPD has been the most significant change in the experiential learning portion of the curriculum, the undergraduate research course sequence has also been modified. It was determined that requiring laboratory research, while beneficial to students aspiring to pursue graduate studies in engineering fields or careers in research, was not necessarily relevant or of interest to students with other career aspirations. As a result of this change in philosophy, the sophomore seminars in literature reviews and research proposals, as well as the undergraduate research sequence, were dropped as requirements, but remain as electives. As such, students are provided numerous opportunities to perform research, adding to the hands-on aspect of their education.

To gain experience outside the classroom environment, bioengineering students are encouraged to participate in summer internships in academia or industry, especially in the summers prior to their junior and senior years. Students have had different types of internship experiences applicable to the field of bioengineering in industry, academic and other research institutions, and in medical settings such as hospitals. These opportunities have also helped achieve the goal of fostering industrial partnerships. The number of each type of internship from 2004 to 2009, compiled from student responses, is shown in Figure 8. Based upon the available data, there have been a total of 122 summer internships in bioengineering-related areas and other technical fields since 2004. Of all the positions, 44% have been in industry and of those, 77% have been at pharmaceutical, biotechnology, or medical device companies, or at firms that makes products for those industries. Approximately half the internships involved research at universities or other research institutions, 35% of which have been at Lehigh. Internships in hospitals and doctor's offices account for about 9% of all summer positions.

Employers of interns have been surveyed annually to assess student performance and to solicit input on the Bioengineering Program at Lehigh. Overall, their supervisors were quite satisfied with the students' performance.

Strengths noted by the respondents were strong technical, problem solving, and computer skills, having a solid work ethic, as well as good interpersonal and team skills. Student weaknesses

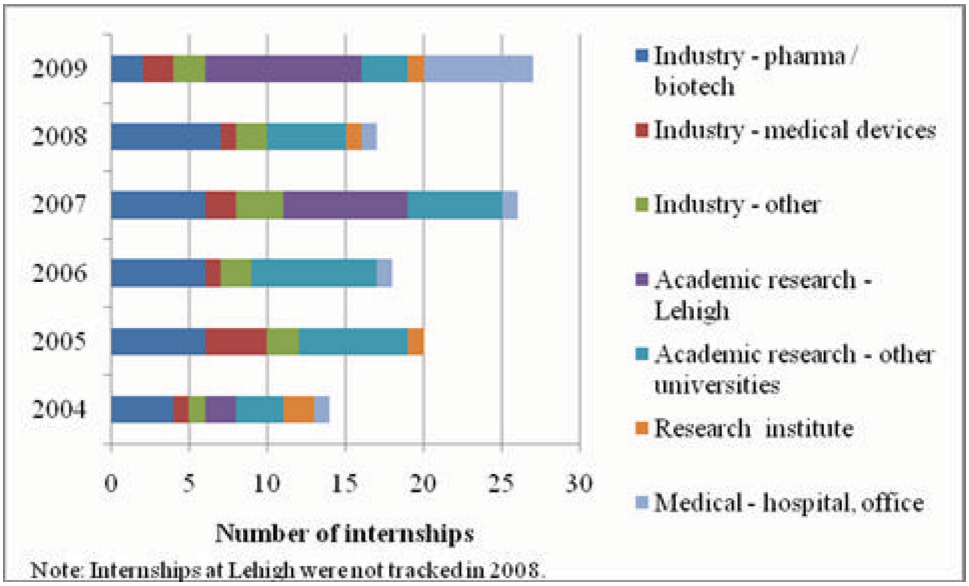


Figure 8. Student Participation in Summer Internships.

mentioned in the responses were minimal and pertained more to inexperience and confidence rather than technical ability. Although they may have reported the students' inexperience with specific laboratory techniques, some pointed out that the students improved significantly in these skills during the course of the summer. Some respondents suggested different types of training that would make the students more valuable to their institutions. These included hands-on experience with relevant techniques, modeling and simulation tools, basic biology and genetics, and fundamental bioprocessing [2].

Challenge 3: Managing program stability versus change

As presented in the previous sections, there have been many changes since the program launched in 2003. These include an increase in the number of available courses, the renovation of advanced laboratories used for courses and research, and changes in the design requirements. Program modifications have been made through a continuous assessment and evaluation process, with input from internal and external constituents. Each class of graduating seniors has made valuable suggestions on how to improve the program, but they have also commented that there were too many changes, causing distress and confusion, especially in the initial years of the program. The rate of change has been managed in several ways, but the overall philosophy has been to change, but not too quickly.

Therefore, while improvements are necessary in a young program, controlling the rate of change is also important to maintain a sense of stability. The program is bound by the university to define requirements for graduation in the catalog for the year in which students enter the university. Any changes made subsequently are optional, rather than mandatory, for the students in that particular class, which is one means of managing program modifications. Updates in the requirements can then be made in the subsequent version of the annual course catalog, which then impacts the next entering class. Changes have also been introduced slowly, by controlling the number of new courses per year. Moreover, it is important to keep the channels of communication open. Specifically, when the bioengineering faculty program committee agrees upon changes in the curriculum, this information must be communicated to all the advisors of students so that they can communicate new options to their advisees in a timely manner. This may be necessary when new electives are added to the program or when a class becomes acceptable as a substitute for a required course.

Challenge 4: Bioengineering is a program rather than a department

Since bioengineering at Lehigh is a program, rather than a department, faculty members are drawn from other departments in the Colleges of Engineering and Arts and Sciences, such as chemical engineering, mechanical engineering, materials science, electrical engineering, or physics. This factor remains largely invisible to students, as they must meet requirements of the university, engineering college, and their major in order to graduate, like all other students at Lehigh. This does, however, potentially place an additional burden on the faculty, as they have teaching, advising, and other administrative duties in both their home department and in bioengineering. This leads to an inherent "double duty" of responsibilities in both bioengineering and their home departments, which needs to be managed appropriately. This issue was noted during the program evaluation process, in which a questionnaire was sent to faculty members each year from 2004 to 2006 [2]. At the start of the program, respondents to the survey asked for more associated faculty to reduce the teaching load for those teaching bioengineering courses.

Lehigh has hired more faculty members to support the program, such that the number of core faculty members has increased from seven in 2002 to thirteen in 2010. The increase in program-associated faculty is shown in Figure 9. Based upon the university's plans for a Biotechnology Cluster focused on diagnostic and therapeutic technologies, increasing faculty headcount by approximately 40% in the next five years is anticipated, which will further support the ability to balance multiple responsibilities. The teaching load in bioengineering has also been eased, in part, by the use of non-tenure track faculty, called Professors of Practice, who have fewer research activities than the tenure-track faculty, and, therefore, have more time to devote to teaching classes and advising students. For new hires, the relative amount of time spent between bioengineering and the home

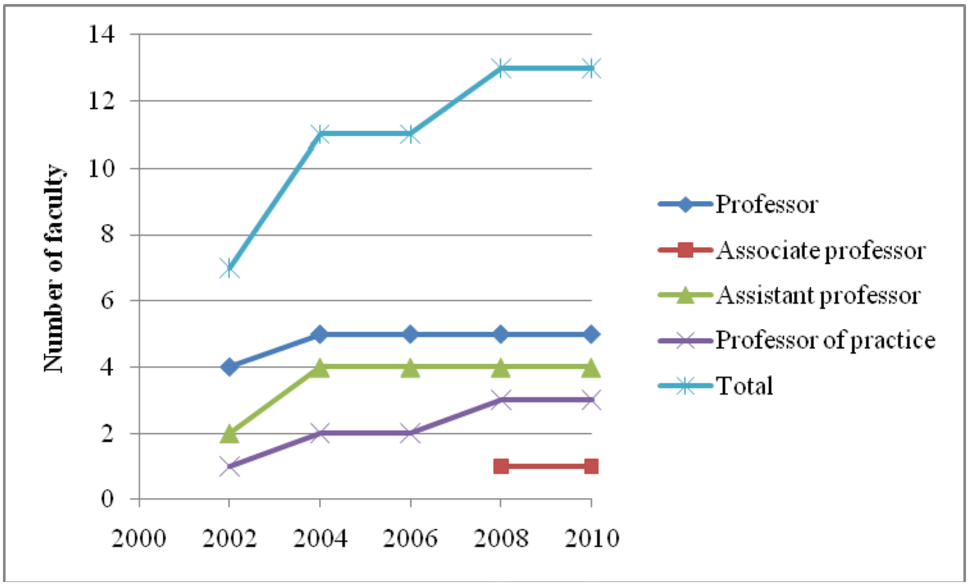


Figure 9. Number of Bioengineering Core Faculty Members.

department is mutually agreed upon by both parties. Depending on the position, the time devoted to bioengineering can range from 10% to 100%. Those with responsibilities only in Bioengineering are Professors of Practice, while tenured or tenure-track professors are typically 25% to 75% dedicated to the program. Faculty members designated as up to 25% dedicated often teach just one Bioengineering class *or* have administrative responsibilities, while those with at least 50% responsibility to the program typically teach multiple bioengineering courses *and* have administrative duties. Having "double duty" in two programs has not seemed to adversely affect attainment of tenure, though it may be premature to draw conclusions. The two tenure-track professors hired between 2002 and 2004 who are still at Lehigh have received tenure in the established timeframe. (Other hires during this period chose to leave Lehigh to accept academic positions at other institutions.) The assistant professors who have been hired since 2005 will not be due for tenure until 2011 or later.

CONCLUSIONS AND NEXT STEPS

The Bioengineering Program at Lehigh University, established as a component of the Bioscience and Biotechnology Initiative, is a part of the university's vision for the twenty-first century. The implementation was partially supported by a grant from the National Science Foundation. The four overall goals set in the program's planning phase were to: (1) recruit high quality students and open bio-related engineering degrees to students in other engineering departments, (2) develop a curriculum that stresses experiential learning and provides entrepreneurial opportunities, (3) equip advanced laboratories to be used for coursework and research, and (4) use industrial collaborations as opportunities for students to participate in real-world problems. The focus of this paper has been to describe the development and roll-out of the program, and to discuss the major challenges and lessons learned from this effort.

Based upon its status as a program, especially a *new* program, special effort was made to ensure sufficient enrollment and to formally assess the recruitment effort. While the strategy has been phased out, now that bioengineering is well-established, the effectiveness of each recruitment tool has been well-documented.

The program and Career Services track where students go after graduation. The data to date show that approximately half the graduates have entered industry, primarily the pharmaceutical, biotechnology, and medical device industries, while the rest pursue further education immediately after graduation.

The core philosophy of the curriculum set at the start of the program, which included basic requirements essential for engineering majors, three tracks of classes aligned with a traditional engineering discipline, and integrated experiential learning beginning in the freshman year, still remains intact. The three laboratories established, in part, with support from the funds from the NSF grant, Integrated Biotechnology, Integrated Biostructural Mechanics, and Integrated Bioelectronics / Biophotonics, which are used for both coursework and research, have played a key role in the curriculum. They have allowed students in all three bioengineering tracks to perform hands-on experiments in their fields of interest, in newly renovated facilities. However, there have been numerous changes to the program in the past six years, many of which have been quite significant. Many of these changes have arisen from challenges encountered within the program, notably the need to balance breadth with depth in an already rigorous curriculum and the need to strengthen the experiential aspects of the curriculum, especially the capstone design requirement. Over the past several years, the addition of numerous advanced electives, several of which require the application of advanced mathematics and computer programming, has added depth to the curriculum. Some of the decisions to modify the curriculum originated from the assessment and evaluation process, which included feedback from both internal and external constituents. Providing higher level courses, and requiring students to take at least one of these courses, have the added benefit of strengthening our position with ABET, as the application of advanced mathematics is necessary [3].

The undergraduate literature review and research courses culminating in a senior thesis were dropped as requirements, and changed to electives, still providing students with numerous opportunities to do research in areas of interest. However, the experiential learning component has been improved by incorporating Integrated Product Development (IPD) into the curriculum, first as an option, and after several years, making it mandatory. The IPD program emphasizes innovation and entrepreneurship more than the previous Bioengineering Design course, as well as strengthening the capstone design requirement, while leveraging a well-recognized program already at Lehigh. All the changes that have been made to Lehigh's bioengineering curriculum are reflected in the current course catalog. Requirements for all bioengineering students and the requirements for each track are shown in Appendix I. The reader may also refer to the university course catalog for more detailed information [16].

While the goals initially established for the program have been achieved, not all the plans have been implemented. During the planning phase and launch of the program, the possibility of bio-related degrees in traditional engineering departments, as well as a minor in computational biology, was explored. Specific plans were developed to form a bioengineering minor for any student majoring in another engineering discipline. On examination, it was determined that a minor would lack the depth needed to make such an option worthwhile, due to the inherent breadth of bioengineering, as previously discussed. It was decided that it was much better pedagogically to develop minors within existing departments. For example, the bioengineering courses needed for a chemical engineering student would differ from those of a student majoring in mechanical engineering. At Lehigh, engineering students have the option to minor in Biotechnology, which is based in the Chemical Engineering Department and requires an additional fifteen credit hours. Additionally, the initial intent to establish a minor in computational biology has been put on hold.

The decision to operate bioengineering as a program rather than a department or as a part of a department offers some benefits. Notably, faculty members are drawn from numerous departments, bringing a diverse and vast knowledge base into the program, making it truly interdisciplinary in nature. Operating as a program also works for the three-track system, as each track is aligned with a different type of traditional engineering discipline. With these advantages come the challenges of balancing the duties of bioengineering with those of their home departments. This has been addressed through the addition of faculty resources and through clear communication between the program and the participating department.

Development of the Bioengineering Program at Lehigh will continue, as part of the university's Biotechnology Cluster project, which is focused on affordable health care and biomedical research and innovation. Given the emphasis on diagnostic and therapeutic technologies, partnerships will be multifaceted, ranging from corporate partnerships to hospitals and medical schools, with a focus on technology transfer, entrepreneurship, and economic development. This will build upon the program's and university's philosophy of innovation and entrepreneurship. A new graduate program in Bioengineering was launched in 2010 and admits students seeking M.S. and Ph.D. degrees. The graduate program will train students to solve problems that require the application of interdisciplinary knowledge, combining life sciences, physical sciences, and engineering. The program will emphasize cellular and biomolecular science and engineering, and is aiming to attract students with diverse academic backgrounds. Program leaders are working with the Mayo Clinic to develop a joint graduate program with a focus on "Engineering Tomorrow's Technologies and Processes for Affordable Medicine". The Biotechnology Cluster project will provide even more opportunities for students in the Bioengineering Program to enhance their educations, as the program proceeds into the next decade and beyond.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the National Science Foundation for its support in establishing the Bioengineering Program at Lehigh (NSF EEC-0343283). We would also like to thank Donna Goldfeder, Director of Career Services at Lehigh, for providing information on undergraduate placement, as well as Lisa Getzler-Linn, Associate Director of Integrated Product Development (IPD), for providing input about the program. Lastly, we would like to acknowledge the efforts of the bioengineering program committee, program secretary, oversight committee, and advisory board.

REFERENCES

[1] El-Aasser, Mohamed, H. Daniel Ou-Yang, John Ochs, and Svetlana Tatic-Lucic. "Establishing a Cross-Discoplinary Bioengineering Program with a Technical Entrepreneurship Focus ." *NSF EEC-0343283.* 2003.

[2] Russo, M. Jean. "NSF EEC-0343283, Establishing a Cross-Disciplinary Bioengineering rogram with a Technical Entrepreneurship Focus at Lehigh University, Final Evaluation Report." 2007.

[3] ABET. "2009-2010 Criteria for Accrediting Engineering Programs." 2008. http://www.abet.org/Linked%20Documents-UPDATE/Criteria%20and%20PP/E001%2009-10%20EAC%20Criteria%2012-01-08.pdf (accessed August 8, 2009).

[4] Bloom, Floyd. "Think Ahead." *Science* 284 (April 1999): 47.

[5] Collins, Francis S., and Karin G. Jegalian. "Deciphering the Code of Life." *Scientific American* 281 (December 1999): 86-91.

[6] Johnson, Arthur T., Hubert Montas, Adel Shirmohammadi, and Fredrick W. Wheaton. "Change is Necessary in a Biological Engineering Curriculum." *Biotechnology Progress* 22 (2006): 167–172.

[7] *LIFE Center -- About LIFE.* http://www.life-slc.org/life-center/about (accessed August 10, 2009).

[8] Bransford, John. "Preparing People for Rapidly Changing Environments." *Journal of Engineering Education*, January 2007: 1–3.

[9] Vest, Charles M. "Context and Challenge for Twenty-First Century Engineering Education." *Journal of Engineering Education*, July 2008: 235–236.

[10] "Grand Challenges for Engineering Final Book." *Grand Challenges for Engineering.* 2008. http://engineeringchallenges.org/Object.File/Master/11/574/Grand%20Challenges%20final%20book.pdf (accessed August 8, 2009).

[11] *Lehigh Bioengineering Program.* http://www.lehigh.edu/~inbioe/ (accessed August 10, 2009).

[12] *IPD Welcome.* http://www.lehigh.edu/ipd/index.html (accessed August 8, 2009).

[13] *IPD, About IPD - History.* http://www.lehigh.edu/ipd/about_history.html (accessed August 10, 2009).

[14] *IPD, About IPD - Philosophy.* 2008. http://www.lehigh.edu/ipd/about_philosophy.html (accessed August, 11, 2009).

[15] ABET. "Final Statement, Lehigh University." 2008.

[16] "Lehigh University, Academics, Course Catalog." 2009-10. http://www3.lehigh.edu/academics/catalog/default2.asp (accessed August 24, 2009).

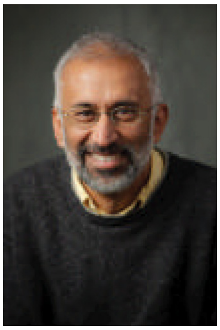
AUTHORS

Lori Herz, Ph.D. joined the Bioengineering Program and Chemical Engineering Department at Lehigh University in 2008 as a Professor of Practice. She currently teaches course in physiology, metabolic engineering, and design, and has responsibility for managing ABET accreditation activities in the Bioengineering Program. She has also served as a faculty adviser for the Integrated Product Development (IPD) program. Prior to joining Lehigh, she worked for over eight years in the pharmaceutical industry, during which she held several positions in Pharmaceutical Development and Technical Operations at Bristol-Myers Squibb. Her areas of expertise include sterile drug product manufacture, technology transfer, and regulatory compliance, as well as the development of cell culture, tangential flow filtration, and lyophilization processes. Her Ph.D. research in Chemical and Biochemical Engineering from Rutgers University involved the study of metabolic flux control in plant biochemical pathways.

M. Jean Russo, Ph.D., is a Senior Research Scientist/Scholar at Lehigh University's Center for Social Research. She is currently conducting evaluations of two academic programs supported by the National Science Foundation and one by the Howard Hughes Medical Institute. She is also the Project Director of The Family Study, a longitudinal study collecting a fourth wave of data. Dr. Russo has been an investigator on numerous funded projects in human services, technology, and the sciences.

Daniel Ou-Yang, Ph.D. is a professor of physics and bioengineering, and director of Emulsion Polymers Institute. Dr. Ou-Yang received his Ph.D. from UCLA in 1985 and did his postdoctoral training at the University of Pennsylvania, Department of Physics and the Corporate Research Laboratory of the Exxon Research and Engineering Company. He joined Lehigh University in 1988 as an assistant professor in the physics department. He was a co-PI and the project manager of the NSF funded project for establishing a bioengineering program with a focus on technical entrepreneurship at Lehigh University. His soft matter research group is focused on the use of optical methods to investigate materials ranging from colloidal nanoparticle suspensions to viral particles and the mechanical properties of biological materials and cells.

Mohamed El-Aasser, Ph.D. is Vice President for International Affairs and Professor of Chemical Engineering at Lehigh University. Prior to this appointment Dr. El-Aasser served Lehigh University as Provost and Vice President for Academic Affairs from 2004 to 2009; the Dean of the P.C. Rossin College of Engineering and Applied Science from 2001 to 2004; and as Chairman of the Department of Chemical Engineering from 1996 to 2001; appointed the Lee Iacocca Professor of Engineering from 1992 to 2000; Co-Director/Director of the Emulsion Polymers Institute from 1978 to 2009, and professor of chemical engineering from 1974 to the present. He received his Ph.D. ('72) in physical chemistry at McGill University, Montreal, Canada. He is internationally known for his research in Emulsion Polymerization and Latex Technology. His principal research interests in the field of polymer colloids and polymerization processes are associated with kinetics and mechanisms of hetero-polymerization processes including miniemulsions, the colloidal and surface interactions in latex systems and their film formation.



Anand Jagota, Ph.D. is the Director of the Bioengineering Program and Professor of Chemical Engineering at Lehigh University. He received his Ph.D. in Mechanical Engineering from Cornell University in 1988. His research group works on the application of mechanics and computational methods to problems in the processing and properties of materials, especially those related to bioengineering. Their current interests include the manipulation of carbon nanotubes using biological molecules, biomimetics of fibrillar adhesion in lizards and insects, and the mechanics of soft materials. Prior to joining Lehigh in 2004, he worked for nearly fourteen years as a researcher at the DuPont Company.

Svetlana Tatic-Lucic, Ph.D. received her Ph.D. in 1994 from Caltech for her work on *Micromachined Devices for In Vivo and In Vitro Studies of Neural Networks*. She then joined Ford Microelectronics Inc., in Colorado Springs, where she worked on automotive sensors, primarily next-generation accelerometers for air-bags. Following this, she was a Consulting Engineer for Coventor, Inc. where she was working on micro-mirrors for fiber-optic communications and RF switches. Finally, she joined the Lehigh University faculty in the Fall of 2002, where she has been appointed P.C. Rossin Assistant Professor. She was promoted to associate professor in 2008. Dr. Tatic-Lucic received a National Science Foundation CAREER award in 2005 for her research proposal that focused on the development of a system for extracellular recording from patterned neural networks with sensing applications. Dr. Tatic-Lucic is the recipient of the Alfred Noble Robinson Award from Lehigh University, for outstanding performance in service to the University and unusual promise of professional achievement. Her research interests include BioMEMS, microfabrication technology, and design, as well as packaging and reliability of microsensors.

John Ochs, Ph.D., joined the Lehigh faculty in 1979 as an assistant professor of Mechanical Engineering, was promoted to associate professor in 1983, and to full professor in 1990. He founded and directed of the Computer-Aided Design Labs in the Mechanical Engineering and Mechanics Department from 1980 to 2000. From 1996 to the present, he has directed the University's Integrated Product Development (IPD) program. This multi-level undergraduate and graduate program brings together students from all three undergraduate colleges to work in multidisciplinary teams on industry sponsored product development projects. In 1996 the pilot program for this course won the American Society of Mechanical Engineers' curriculum innovation award and in 1997 the Newcomen Society award for the promotion of America's free-enterprise system. In 2006 Professor Ochs received the Olympus Innovation Award for his work in technical entrepreneurship through the IPD program. Professor Ochs is a member of the American Society for Engineering Education and past chairman of its Entrepreneurship Division and the American Society of Mechanical Engineers.

Address correspondence to:
Dr. Lori Herz
Lehigh University
111 Research Drive
Iacocca Hall
Bethlehem, PA 18015
email: loh208@lehigh.edu

APPENDIX I: BIOENGINEERING COURSES AND COURSE SCHEDULES

Courses currently required for all bioengineering students are defined in Table 5. Students have additional course requirements, based upon their chosen track. Specific requirements for the Biopharmaceutical, Bioelectronics/Biophotonics, and Cell and Tissue Engineering tracks are described in Table 6.

Area	Course No.	Course Description (credits)
General Requirements (27 credits)	ENGL 1	Composition and Literature (3)
	ENGL 2	Composition and Literature: Fiction, Drama, Poetry (3)
	PHIL 116	Bioethics (4)
	ENGR 1	Engineering Computations (3)
	ECO 1	Principles of Economics (4)
		Electives to satisfy HSS requirements; Free electives (10)
Mathematics (18 credits)	MATH 21	Calculus I (4)
	MATH 22	Calculus II (4)
	MATH 23	Calculus III (4)
	MATH 205	Linear Methods (3)
	MATH 231	Probability and statistics (3)
Chemistry (12 credits)	CHM 30	Intro. Chemical Principles and Lab (4)
	CHM 31	Chemical Equilibria in Aqueous Systems (4)
	CHM 110, 111	Organic Chemistry I and Lab (4)
Physics (10 credits)	PHYS 11, 12	Intro Physics I and Lab (5)
	PHYS 21, 22	Intro Physics II and Lab (5)
Biological Sciences (8 credits)	BIOS 41, 42	Biology Core I: Cellular and Molecular and Lab (4)
	BIOS 115, 116	Biology Core II: Genetics and Lab (4)
Integrated Bioengineering (16 credits)	BIOE 1	Freshman Seminar I, Intro. to Bioengineering I: Philosophy to Practice (1)
	BIOE 2	Freshman Seminar 2, Intro. to Bioengineering II: Current Topics (1)
	BIOE 110	Elements of Bioengineering (4)
	BIOE 210	Intro. to Engineering Physiology (4)
	ENGR 211	Integrated Product Development (IPD) I (3)
	ENGR 212	Integrated Product Development (IPD) II (2)
	BIOE 225	cGMP Good Manufacturing Practice and Regulatory Affairs for Engineers (1)
Advanced Bioengineering Elective (3 credits)		Students select from a list of courses having MATH 205 and MATH 231 as prerequisites. Current courses on the list include: Biotechnology I (CHE 341), Molecular Bioengineering (CHE 344), and Biomolecular and Cellular Mechanics (BIOE 321).
Approved Electives (9 credits)		Students select from a list of courses in bioengineering, life sciences, physical sciences, and other engineering disciplines.

Table 5. Bioengineering Core Requirements.

Track	Course No.	Course Description (credits)
Biopharmaceutical (23 credits)	CHM 112	Organic Chemistry II (3)
	BIOE 343	Integrated Biotechnology Lab (3)
	MAT 33	Engineering Materials and Processes (3)
	CHE 31	Material and Energy Balances (3)
	CHE 210	Chemical Engineering Thermodynamics (4)
	CHE 211	Chemical Engineering Reactor Design (3)
	CHE 44	Fluid Mechanics (4)
Bioelectronics / Biophotonics (22 credits)	ECE 108	Signals and Systems (4)
	BIOE 331	Integrated Bioelectronics / Photonics Lab (2)
	ECE 81	Principles of Electrical Engineering (4)
	ECE 123	Electronic Circuits (3) or
	PHYS 190	Electronics (3)
	PHYS 212	Electricity and Magnetism I (3)
	MECH 3	Elementary Engineering Mechanics (3)
	MAT 33	Engineering Materials and Processes (3)
Cell & Tissue Engineering (21 credits)	BIOE 120, 121	Biomechanics and Lab (4)
	BIOE 357	Biostructural Mechanics Lab (2)
	MECH 3	Elementary Engineering Mechanics (3)
	MECH 12	Strength of Materials (3)
	MAT 33	Engineering Materials and Processes (3)
	ME 104	Thermodynamics (3)
	ME 231	Fluid Mechanics (3)

Table 6. Track-Specific Engineering Requirements.