
AC 2012-3771: DEVELOPING A SMALL-FOOTPRINT BIOENGINEERING PROGRAM

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Developing a Small-Footprint Bioengineering Program

Abstract

The field of bioengineering is rapidly changing and expanding to include not only more traditional bioengineering applications (e.g. device-focused areas such as prosthetics, imaging) but also more recent sub-fields and technologies (e.g. more biologically-focused areas such as those enabled by tissue engineering and microfluidics). This rapid change, coupled with the intrinsically interdisciplinary nature of bioengineering, presents a unique challenge to the developers of academic programs, as they need to both select relevant content and strike a balance between depth and breadth. We, the architects of the bioengineering program at the undergraduate-only Franklin W. Olin College of Engineering, which enrolled its first class in 2003, faced a significant additional challenge of our small size (~300 students, ~35 full time faculty, and ~1.5 dedicated bioengineering faculty). Our approach was to create a flexible program that aims to provide students with a strong grounding in both biology and engineering and which leverages Olin's broad-based foundation in engineering fundamentals and emphasis on hands-on learning experiences. Feedback from alumni/ae, employers and graduate schools regarding our first six graduating classes indicates that an undergraduate education focusing on biology and engineering problem-solving has prepared them well for their current endeavors. The positive response to the program and its graduates confirms that our approach results in graduates who are well-prepared to create the future of bioengineering.

Introduction

The field of bioengineering (for the purposes of this paper, used interchangeably with 'biomedical engineering') grew out of the application of traditional engineering disciplines to biological problems. In many cases the relevant problems (e.g. prostheses, imaging technologies) involved the application of chemical, electrical, or mechanical engineering concepts but did not require a sophisticated understanding of biology. However, as our understanding of biology and ability to manipulate biological systems has advanced, bioengineering has begun to move in the direction of an integrated application of engineering and biology.

Increasingly, bioengineering is expanding beyond a focus on devices to include emergent biologically-focused subfields and technologies, such as tissue engineering, cellular imaging, and neuronal interfaces. These new areas in bioengineering are leading to new companies that can develop and market these technologies, and therefore a rapidly expanding sense of what constitutes bioengineering practice. Coupled with an aging US population, this means that the field of bioengineering is growing rapidly. As of 2010, the United States Department of Labor records 15,380 jobs in Biomedical Engineering, and they project a 72% increase in the number of biomedical engineers between 2008 and 2018,¹ making it not just the fastest-growing engineering discipline, but one of the fastest-growing professions.

There is therefore a clear incentive to grow bioengineering programs or develop new ones, in order to meet this increased demand for graduates. At present, the dominant bioengineering fields in industry are medical implants, prosthetics, and imaging. These applications have historically not required a strong knowledge of biology, but have required a deep grounding in electrical or mechanical engineering; in fact, biomedical engineering positions frequently require graduate degrees.¹ However, the emergent technologies in bioengineering are deeply rooted in biology, and therefore require engineering graduates with a deep understanding and appreciation of biology in addition to engineering. While it is frequently a challenge for bioengineers to educate employers about what they bring to the table, bioengineers bring a unique knowledge of and approach to biology that is increasingly relevant. With the expansion of bioengineering into new areas, there is an increasing demand for bioengineers in both established companies and in newer, start-up companies. Particularly in these companies, but more generally in the now rapidly-evolving field, bioengineers need to be both well-grounded in biological and engineering fundamentals and also equipped with the self-directed and lifelong learning skills to adapt to new technological developments. This suggests that there is an opportunity to reconsider the undergraduate bioengineering curriculum to prepare graduates for this new world of bioengineering practice.

If the field of bioengineering is in flux, what are the knowledge and skills that graduating bioengineers need? Bioengineering, rooted as it is in many different areas of biological sciences and engineering, presents a unique challenge to those developing academic programs, as they need to both select relevant content and strike a balance between depth and breadth. The now-defunct Whitaker Foundation established a bioengineering curriculum philosophy² that captures some key ideas:

- 1. A thorough understanding of the life sciences, with the life sciences a critical component of the curriculum;*
- 2. Mastery of advanced engineering tools and approaches;*
- 3. Familiarity with the unique problems of making and interpreting quantitative measurements in living systems;*
- 4. The ability to use modeling techniques as a tool for integrating knowledge;*
- 5. The ability to formulate and solve problems with medical relevance, including the design of devices, systems, and processes to improve human health.*

This curriculum philosophy captures an important component of bioengineering that is demanded by industry: the ability to apply an ‘engineering mindset,’ including quantitative and analytic tools, to biological problems. But there is also an increasing appreciation of the role of the so-called ‘soft skills’ in engineering, including teamwork and communication, as well as the value of design and problem-solving skills. For example, the National Academy of Engineering’s Grand Challenges for Engineering³ are interdisciplinary and have a significant social component.

If we treat these as exemplifying the types of problems our graduates should be prepared to tackle, these social and professional skills cannot be treated as an afterthought in the curriculum design process.

In this paper, we present an example of a forward-facing, small-footprint bioengineering program, developed at Franklin W. Olin College of Engineering (Olin), with a focus on the specific facets of the program that may be useful models for other programs, as well as some information on student outcomes from the first six years of the program.

A description of the Bioengineering Program at Olin College

As architects of the bioengineering program at the undergraduate-only Olin, which enrolled its first class in 2003, we faced a significant challenge of reconciling our small size (~300 students, ~35 full time faculty) with a relatively broad array of academic offerings. Olin offers degrees in Engineering (E), Electrical and Computing Engineering (ECE), and Mechanical Engineering (ME). Within Engineering, students can choose a concentration, and Engineering with Biology, or BioE, is one of the established concentrations. Note that while the E, ECE, and ME degrees are ABET-accredited, individual concentrations are not. The Olin curriculum has a strong emphasis on hands-on project-based learning and on engaging in open-ended engineering work, beginning early in students' academic careers. More information about the curriculum can be found online.⁴

In order to develop our program, we consulted with academic and industrial leaders in the field, focusing on its future directions and the skills and training bioengineers would need to solve these new professional challenges. Based on their input, which reflected the trends described above, our approach was to create a flexible BioE program that aims to provide students with a strong grounding in both biology and engineering. In particular, this program was designed to leverage Olin's broad-based foundation in engineering fundamentals and complement, not duplicate, our existing offerings in mechanical and electrical/computer engineering. The program was designed with the expectation that BioE graduates would go on to either graduate study or to work at companies which focused on these emerging areas of biology-focused bioengineering (rather than 'traditional' bioengineering companies). The program was also designed to maximize the effectiveness of our 1.5 full-time BioE faculty.

All students at Olin take foundational engineering courses to give them a grounding in engineering problem solving, computer programming, modelling and simulation, as well as an introduction to mechanical and electrical engineering concepts. The Olin engineering curriculum also includes a four-course design stream that reaches from a first-year engineering design course through the senior capstone engineering design project. All students also take courses in math and science (including physics, chemistry and biology). Together, these courses provide students with their technical fundamentals. Required coursework in arts, humanities, the social

sciences and entrepreneurship, including a capstone experience, provides context to their science and engineering background.

The BioE program, then, complements this engineering foundation by both providing a deep understanding of biological systems and through the application of engineering approaches in a bioengineering context. Given the limited number of courses we could offer, we chose a focus area for the program; specifically, cell-biomaterial interactions and the role of the cellular microenvironment, as these represent a rapidly growing area of bioengineering exploration and are in line with Olin faculty expertise. Emphasizing these areas allows us to provide students with both theoretical knowledge and hands-on experiences, through coursework (involving lab-based projects) and involvement in experimental research. As well, it allows us to leverage the expertise of the biology faculty at Olin and at our partner institutions.

While the number of courses we can offer may be limited, the program requirements were deliberately designed to be very flexible, in recognition that students may be interested in many areas under the broad umbrella of bioengineering. Students are required to take 3 BioE-relevant courses, a relevant advanced math course, a relevant advanced biology course, and an additional chemical sciences course, in addition to the general requirements discussed above (which include core mathematics, introductory biology, and a course in chemical sciences). A key aspect of our program is that students work with BioE-affiliated faculty to define their area of interest and to lay out a set of courses that fit those interests, are in line with their post-graduate plans, and comprising an academic plan with depth, breadth, coherence, and rigor.

We offer six courses regularly, including Topics in Bioengineering, an introductory survey course; Structural Biomaterials, which emphasizes the structure-function relationships of biological materials; Transport in Biological Systems, which covers mass and fluid transport in biological systems; Biomedical Materials, which focuses on biological responses to materials; Cellular Bioengineering, which uses quantitative methods to study and influence cell behavior; and Tissue Engineering, a lab-based course in which students grow engineered tissues *in vitro*. Other BioE-relevant courses that have been offered in the past include Biological Thermodynamics, Materials Visualization, and Microfluidics. These courses complement advanced biology electives such as Immunology, Microbial Diversity, Emerging Technologies in Cancer Research and Therapy, and Engineered Microbial Systems. Finally, students can also cross register at neighboring Wellesley College and Brandeis University to take courses relevant to their BioE course plans. Though some students pursue other areas of BioE, the majority take these core courses and many of those students continue on in the area of cell-biomaterial interactions as they go on to graduate school or industrial employment.

Perhaps more important than the disciplinary content of the courses we teach is skill-building in context. The general approach of the Olin curriculum is to focus on teamwork, open-ended

problems, self-directed learning, and hands-on experiences. Within the BioE program, these skills are developed through a variety of self-directed, team-based projects which include literature reviews, modelling and simulation, research proposals, and lab work. Lab experiences are not ‘canned’; rather, students typically have a great deal of autonomy in proposing projects and designing experiments. This self-directed approach to lab work helps students move towards being independent researchers while providing them with scaffolded educational environment in which to learn the fundamentals of experimental design, how to choose analysis techniques, and how to analyze data.

Another theme throughout our courses is the development of life-long learning skills, which largely manifests through the reading of primary literature. In many courses, students are expected to critically read and discuss journal articles provided by the instructor, as well as to find their own articles for presentation or use in projects. The ability to fully utilize the primary literature is a skill that is not typically taught until graduate school, if at all. By providing our students with these tools, they are equipped with the tools to learn new technical material on their own.

Finally, communication skills are extensively developed through seminar-style discussion, formal and informal presentations and writing assignments, and poster presentations. Technical papers, such as literature reviews or a project reports, are common deliverables in BioE courses. A key component of teaching effective technical communication is providing detailed, formative feedback to students about both their writing and their ability to convey technical ideas though appropriate detail and use of evidence. Collectively, the development of these professional skills enable our graduates to effectively utilize their technical knowledge.

In order to provide some specific context for these approaches, we provide case studies on two courses, Biomedical Materials and Transport Phenomena in Biological Systems.

Case Study 1: Biomedical Materials

The Biomedical Materials course at Olin College is designed to provide students with a broad-based exposure to key concepts in the interaction of materials with cells and tissues. The entire course uses a ‘reverse homework’ studio model, in which students do readings (of both relevant textbook chapters and primary literature) prior to class, and then classroom time is devoted to a discussion of the material. The first module in the course is an introduction to the biological responses of the body. Other modules include introductions to implant classes (orthopaedic, cardiovascular, etc.) as well as medical device regulation and bioethics. In addition to the studio discussions, the students participate in two major projects. One is an individual literature review, in which students engage deeply with a biomedical materials topic while developing their lifelong learning and communication skills. This project is scaffolded with a workshop on using online and library resources, submission of an outline and annotated bibliography for review and

feedback, peer review of first drafts, formative feedback on the revised draft, and finally the final draft of the report and an oral presentation to the rest of the class. The second major component is a team-based self-directed laboratory project. Student teams ideate around laboratory projects, then draft a research proposal including a description, timeline, and budget. The project is scheduled for approximately one month, and teams use both in- and out-of-class time to work on the project (12 hrs/week). Benchside mentorship is provided by both the instructor and by laboratory assistants, normally students with advanced laboratory skills developed through research. At the conclusion of the project, teams submit write a draft and final report, as well as present their work orally to the rest of the class.

Case Study 2: Transport in Biological Systems

The Transport in Biological Systems course takes a modeling and simulation approach to mass and fluid transport in biological systems and is structured around 3 major projects and 4-5 smaller exercises. In-class time is split between lecture, discussion of relevant primary literature, work on exercises, and work on projects. Exercises are designed to build student skills in modeling and/or practice using transport concepts they learn through readings and lecture. An initial exercise involves implementing a simple 3-compartment model of glucose-insulin oscillation from a paper in MATLAB in order to refamiliarize them with using MATLAB and coding (which they all have done in the first year). The second exercise involves looking at a system to measure permeability of endothelial cells on a membrane in order to develop an analytical solution for the steady state concentration profile of a molecule in a double-layer membrane system. Students then implement a time-dependent solution for the concentration profile in MATLAB. The remaining exercises are essentially BioE-relevant problem sets that build student confidence in applying concepts. The link between theory and practice is further emphasized by reading and discussing relevant papers from the field at various times in the course. In the most recent iteration of the course, projects included implementation and exploration of a model of morphogen gradient generation in fruit fly embryos (which builds upon the time-dependent membrane code), exploration of models of binding site barriers in tumors (something discussed extensively through literature discussions), and a topic of the students' choice. Projects were typically done in groups of two to three students. The first two project deliverables were short technical papers and the third was a technical presentation. While exercises are quite constrained, the projects are designed to increasingly provide opportunities for student autonomy with respect to choice of topic and approach to exploring it. For in-class project work, student groups work while the faculty member circulates through the room to discuss progress and relevant concepts with each group.

Outcomes of the Olin Bioengineering Program

BioE is one of the most popular and well-established Engineering concentrations at Olin, with 5-10 students graduating in BioE or a related concentration each year. Though this is a small number in absolute terms, it represents ~28% of all Engineering majors and 11% of our six

graduating classes (49 students out of 432 total graduates). Women, who make up approximately half of all Olin students, are more highly represented in BioE as seen at other schools; 73% of our BioE graduates are women.

To complement their academic programs, our students frequently engage in bioengineering work during the summers. They have been quite successful in obtaining academic research positions (e.g. REUs) and industrial internships. Some of these opportunities are provided by Olin: 46% of students spend at least one summer on campus, performing research. In total, an estimated 83% of our students performed research in an academic institution for at least one summer. Additionally, 40% of students spent at least one summer working at a bioengineering company. (All percentages are based on an 80% response rate to postgraduate surveys.) Supervisors frequently cite our students' experience with research-oriented and hands-on courses as a reason for hiring them. Further, feedback from employers and research mentors indicates that Olin students are valued because of their ability to work independently and their familiarity and experience with laboratory environments. The course content, course experiences (including lab experiences and project-based learning), and summer experiences in research institutions and bioengineering companies synergistically provide students with an integrated education in bioengineering.

Twenty seven percent of our BioE graduates have gone to graduate school and many have been accepted into competitive labs at some of the top bioengineering programs in the country (e.g. UC Berkeley/UCSF, UPenn, MIT, and UCSD). Additionally, five BioE graduates have received NSF Graduate Research Fellowships and another received a Fulbright Scholarship to do bioengineering research. Another 35% of our graduates are employed in bioengineering fields and have been hired by a range of employers, including large medical device companies, small start-ups, and research labs. Of the remaining students, 12% have gone to medical school and the remaining 27% have pursued non-bioengineering careers.

Student feedback indicates that an undergraduate education focusing on biology and engineering problem-solving has prepared them well for their current endeavors. Learning to critically read unfamiliar technical literature is one of the skills most cited by graduates in surveys. The BioE program's emphasis on written and oral technical communication, with extensive feedback and opportunities for revision, was also frequently described as being a key contributor to a level of communication ability that sets them apart from their peers and serves them well regardless of current occupation. Graduates also highlight the use of course projects, particularly hands-on projects as useful in several ways: helping them explore and find what they are interested in (or not interested in); experiment planning; authentic laboratory experiences (complete with failure and regrouping); and data analysis. Having had the freedom to do their own lab experiments gave students an appreciation for how challenging experimental work is, even within the well-scaffolded learning environment in which they learned how to do independent work. Further,

students also cited these hands-on lab experiences as critical to helping them obtain summer employment, particularly in their early years. Even students who are not working in bioengineering cited these skills as useful in their current careers.

Conclusions

Bioengineering is a rapidly changing, highly interdisciplinary field. Given that the terrain will likely look completely different in 20 years, we believe that we should be preparing young bioengineers to be self-directed, life-long learners with a grounding in engineering and biology. Engineering is not a set of facts or a static toolbox, so much as a mindset, a way of thinking, and a way of approaching problems. To be successful, a bioengineer needs to draw on more than just a quantitative skill set. The practice of engineering involves working and communicating with an interdisciplinary team of individuals to solve open-ended technical problems. Though these are in many ways generalizable skills, it is necessary to learn them in a disciplinary context. Conversely, the retention of disciplinary content is increased by engagement in authentic, project- or laboratory-based experiences.⁵

We recognize that the Olin BioE program is unusual in two major ways. First, we had the opportunity to intentionally design our program from the ground up. Second, we are a very selective school that attracts a particularly bright, motivated group of students. Though we acknowledge the exceptionalism of Olin students, the graduate feedback suggests that the experiences that they draw upon most in their professional or academic careers include their hands-on, self-directed, communication-intensive experiences. Based on six years of graduate data, we are confident that our approach results in graduates who are well-prepared to create the future of bioengineering.

As currently described, the Olin BioE program could meet the requirements of an ABET-accredited Biological Engineering program and could serve as a basis for an ABET-accredited Bioengineering/Biomedical Engineering program. In addition to the application of quantitative and qualitative engineering skills, it should be noted that the curriculum we discuss explicitly addresses a number of ABET student outcomes criteria including experimental practice, teamwork, communication, and life-long learning.

The Olin program was designed to be a small footprint BioE program at a small school. We believe that the approaches described above are relevant to other schools and are accessible with minimal resources or changes to existing curricula. In particular, we've shown that it is possible to create effective programs with relatively few faculty, making this particularly relevant for other small schools interested in starting bioengineering programs. In addition, many established bioengineering programs have strong programs in the traditional bioengineering subfields (such as imaging and prosthetics); focusing on emerging biology-based technologies provides a unique niche for new programs. Student-driven, project-based courses can be instructor-intensive, which

is why they work well for small schools, and we understand there may be challenges in scaling these approaches up to larger schools. However, larger schools typically also have access to different resources, such as graduate student lab assistants, who already have well-developed experimental skills. Development of skills such as teamwork, communication, and experimental design are key to the professional development of students, making it worthwhile to incorporate them into the curriculum in an institution-specific manner.

Our experience demonstrates that a small footprint bioengineering program can effectively prepare graduates for careers in the field if it leverages local expertise, integration within a larger academic program, and focuses on holistic student development.

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