

**AC 2007-2230: DEVELOPING STUDENT DESIGN AND PROFESSIONAL SKILLS
IN AN UNDERGRADUATE BIOMEDICAL ENGINEERING CURRICULUM**

Donna Ebenstein, Bucknell University

Joseph Tranquillo, Bucknell University

Daniel Cavanagh, Bucknell University

Developing Student Design and Professional Skills in an Undergraduate Biomedical Engineering Curriculum

Abstract

Frequently, students' exposure to biomedical engineering design and professional skills is concentrated in their senior design capstone courses at the end of the curriculum. While common, this approach may lead to instances where students apply these skills for the first time in their projects with little opportunity for continued reinforcement. In addition, some projects may not appropriately address all necessary skill areas. One curricular model that may address these limitations has recently been implemented by our Biomedical Engineering Program. This new model, consisting of a sequence of four courses spanning the junior and senior years, was created to ensure that all students receive repeated exposure to a wide range of skills relevant to the biomedical engineering profession as well as those required for accreditation.

In this sequence, the first and second courses are each half-credit and focus on specific 'soft' and 'hard' biomedical engineering skills, respectively, that students may find valuable in senior design. The first course, taken in the spring of junior year, is aimed at introducing students to a wide range of 'soft' skills including regulatory issues, teamwork, environmental impacts, and formal decision making. Students then take a course in the fall of the senior year that focuses on developing relevant 'hard' skills including CAD, machining tools, rapid-prototyping, mammalian cell culture, and statistics-based experimental design. The other two courses of this sequence make up the two-semester senior design capstone experience that follows a traditional project based model. However, in addition to in-depth exposure to the formal engineering design process, students are also required to interact professionally with an external project mentor, complete extensive professional communication assignments, and bring all relevant design and professional skills together to complete their specific project.

Overall, this four course model exposes students to a wide range of soft and hard skills relevant to biomedical engineering. The sequential structure of the courses requires students to transfer knowledge and skills between courses in the sequence and from courses previously taken. The culmination of the sequence in the senior capstone provides students with repeated exposure to, and refinement of, many skill sets. Further, as students are required to decide which skills should be applied to their specific design projects, this course sequence not only introduces students to an array of skills, but also provides opportunities for students to learn to identify the appropriate application of each skill.

Introduction

Frequently, students' exposure to biomedical engineering design and professional skills is concentrated in their senior design capstone courses at the end of the curriculum.¹⁻⁴ While common, this approach may lead to instances where students apply these skills for the first time in their projects with little opportunity for continued reinforcement. In addition, some projects may not appropriately address all necessary skill areas. One curricular model that may address these limitations has recently been implemented by our Biomedical Engineering Program. This

new model consists of a sequence of four courses spanning the junior and senior years. It was developed to ensure that all students receive repeated exposure to a wide range of skills relevant to the biomedical engineering profession as well as those required for accreditation. The topics covered include a wide range of ‘soft’ skills,⁵ such as regulatory issues, environmental impacts, and project management, in addition to laboratory-based ‘hard’ skills, such as rapid prototyping and computer-aided design (CAD). While this sequence does not address the issue of the senior capstone being the students’ only exposure to open-ended design, it does provide them with appropriate skills and tools to draw from to tackle that open-ended design problem.

Course Sequence

In this sequence, the first and second courses are each half-credit and focus on specific ‘soft’ and ‘hard’ biomedical engineering skills, respectively, that students may find valuable in senior design. As half credit courses, these introductory courses consist of 2 hours per week in class, with the expectation of up to 5 hours per week of work time outside of class. The final two courses of this sequence make up the two-semester senior design capstone experience that follows a traditional project-based model. The senior capstone courses are full-credit courses consisting of 3 to 4 class and laboratory hours per week.

The first course in the sequence, taken in the spring of the junior year, is aimed at introducing students to a wide range of ‘soft skills’ including regulatory issues, teamwork, environmental impacts, and formal decision making. Students then take a second course in the fall of the senior year that focuses on developing relevant ‘hard skills’ including computer-aided design (CAD), machining tools, rapid-prototyping, mammalian cell culture, and statistical analysis of cell culture experimental results. The final two courses of this sequence (the first of which is taken concurrently with the half-credit course on hard skills) make up the two-semester senior design capstone experience that follows a traditional project-based model. However, in addition to in-depth exposure to the formal engineering design process, students are also required to interact professionally with an external project mentor, complete extensive professional communication assignments, and bring all relevant design and professional skills together to complete their specific project. Each course will be described in detail below. The ABET requirements addressed in each course are summarized in Table 1.

Course 1: Research Methods I (soft skills), spring of junior year

Before introducing students to more rigorous technical and hands-on professional skills, they are first exposed to a wide variety of ‘soft’ professional skills relevant to the biomedical engineering field in their Research Methods I course. In addition to providing the opportunity for students to learn and directly apply these skills, this course also provides the faculty with an opportunity to assess student performance and learning in these areas as required for accreditation. Overall, the course is centered around the application of a wide range of these soft skills in a semester-long medical device benchmarking project.

Table 1: ABET Requirements Addressed by the Four Course Professional and Engineering Skills Sequence. RM = Research Methods. SC = Senior Capstone.

ABET Criterion	RM I	RM II	SC I	SC II
<i>General</i>				
3a. an ability to apply knowledge of mathematics, science, and engineering			X	X
3b. an ability to design and conduct experiments, as well as to analyze and interpret data		X	X	X
3c. an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability			X	X
3d. an ability to function on multi-disciplinary teams			X	X
3e. an ability to identify, formulate, and solve engineering problems		X	X	X
3f. an understanding of professional and ethical responsibility	X		X	X
3g. an ability to communicate effectively	X		X	X
3h. the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	X		X	X
3i. a recognition of the need for, and an ability to engage in life-long learning	X	X	X	X
3j. a knowledge of contemporary issues	X			X
3k. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice		X	X	X
<i>Biomedical Engineering Specific</i>				
An understanding of biology and physiology, and the capability to apply advanced mathematics (including differential equations and statistics), science, and engineering to solve the problems at the interface of engineering and biology		X	X	X
The ability to make measurements on and interpret data from living systems, addressing the problems associated with the interaction between living and non-living materials and systems		X	X	X

To initiate the projects on the first day of class, students are required to complete a survey indicating their personal interest levels in a number of over-the-counter medical devices. From these surveys, student teams are formed for the projects after which the devices are distributed. From that point on, nearly every assignment and activity in the class focuses on the devices. Examples of assignments include:

- Completion of a thorough background search on the device including: FDA recalls, intellectual property histories, consumer ratings and opinions, and corporate profiles
- Evaluation of relevant regulatory issues including: FDA device classification, human subjects testing, and clinical trials
- Evaluation of environmental concerns and impacts
- Proposal of device improvements evidenced by an analysis of competitors and user needs

In addition to assisting the students in learning about the many sides of medical device development, these assignments simultaneously challenge them in developing a wide range of non-device oriented skills such as:

- Project management skills including: meeting agendas, meeting minutes, professional written communication, and project timelines
- Formalized engineering design decision methodologies
- Oral communication skill building through individualized review of video recordings
- Learning styles analysis

To provide current and relevant insight into the design of medical devices in a wide range of environments, experienced individuals from international medical device companies, national and regional medical care institutions, and small business development organizations are invited to give presentations to the students. At the end of the semester, students give final presentations on their evaluations of the devices in addition to the proposed improvements. While the students do not learn all of the fine details of areas such as FDA regulations and human subjects research, they do acquire a fundamental understanding of these important biomedical engineering areas.

In this half-credit course, the two hours per week spent in class are devoted to class discussion, group activities, and guest lectures. Students are expected to spend substantial time (~ 5 hours per week) outside of class analyzing their devices and applying the professional skills.

Course 2: Research Methods II (hard skills), fall of senior year

The goal of Research Methods II is to expose students to a variety of laboratory skills and techniques that are both useful for professional engineers and potentially valuable for their senior design projects. While not all the topics introduced in this course will be applicable to all senior design projects, this course was designed to provide students with exposure to both engineering and biological tools that are not covered elsewhere in the curriculum.

The engineering portion of the course is focused on device fabrication through developing skills in computer-aided design (CAD), machine shop tools, and rapid prototyping. The students use

CAD software (SolidWorks) to design a simple biomedical device with at least two parts. These designs are then implemented using a combination of tools in the machine shop and the rapid prototyping machine, and assembled to produce prototype models. Thus, students gain experience using CAD software, instruments in the machine shop, and the rapid prototyping machine. For the first year of the course, the device to be fabricated was a flow chamber for flow visualization. The designs were based on finite element models of flow through physiologically relevant geometries that the students had created for an earlier Biotransport course. In this course, the students transformed their 2-D finite element geometry into a 3-D channel. They designed the channel in SolidWorks, built the base in the rapid prototyper and machined the lid from a sheet of acrylic. They then assembled the flow chamber, and pumped fluid and dye through the chamber to visualize streamlines. This general approach could easily be adapted to other device fabrication projects as well, tailored to the program's curriculum.

The biological portion of the course is focused on basic mammalian cell culture techniques and statistical analysis of biological data. The students spend 4-5 weeks in the lab learning sterile technique, culturing cells, determining growth rates for their cell lines, and investigating how growth rates change with variations in cell culture conditions. The students then analyze the results of their cell culture experiments using appropriate statistical analysis techniques. Through this unit, students gain skills in cell culturing, microscopy and image analysis, and apply statistics to biomedical problems. This year, experiments were performed on human osteosarcoma cells, and the effect of calf serum concentration on cell growth rates was statistically analyzed.

In this half-credit course, the two hours per week spent in class are devoted to hands-on computer and cell culture laboratory work, in-class presentations of results, and occasional supplemental lectures. Students are expected to spend substantial time (~ 5 hours per week) outside of class completing laboratory and homework assignments and being trained on instruments in the machine shop.

Course 3: Biomedical Engineering Capstone I, fall of senior year

The goal of the fall semester senior capstone is a formal introduction to the design process with a focus on professional communication. Students are led through the design process via a step-by-step sequence of writing exercises. Topics include problem definition, specifications, formulation of alternative solutions, evaluation criteria, technical drawings and feasibility tests. The final product is a written proposal that is used as a guide for Senior Capstone II. An emphasis is placed on integrating the hard and soft skills learned in other portions of the four course sequences. For example, the technical drawing is assigned with little explicit direction. The intention is for students to transfer their knowledge of computer-aided drawing from Research Methods II.

Our Biomedical Engineering Program utilizes a combined internal and external mentoring program to enhance the biomedical relevance of the projects. Student groups of two or three students are assigned external mentors at a nearby medical center. The role of the external mentor is to explain to the students common clinical problems they have encountered. The students are responsible for conducting meetings with their external mentor to not only identify a

problem, but also arrive at a solution that could realistically solve the problem. The Senior Capstone I course is coordinated by a single faculty member who is responsible for leading the class through the design process and grading the regular written assignments. Each design group is also assigned an internal faculty advisor in the Biomedical Engineering Program. The task of the internal advisor is to help student groups navigate the specific technical aspects of their project as well as their relationship with the external mentor. Regular communication between all parties involved in a particular project is achieved through weekly student-written memos.

The initial assignment of both the students and the internal advisor to each project is similar to the process used in Research Methods I. The external mentors are asked to provide brief descriptions of their research areas. Then the students and faculty members fill out surveys ranking their interest in the available topic areas. These surveys are then reviewed blindly, and as many participants as possible are matched with one of their top two choices. The result is a team of two or three students and one internal advisor matched with each external mentor.

Course 4: Biomedical Engineering Capstone II, spring of senior year

The goal of the spring semester senior capstone is for students to focus on fabrication and testing of their design project, while still maintaining a focus on professional communication. Students are exposed to different aspects of design evaluation via writing exercises and case studies. Topics include safety and liability, materials selection, and lifetime analysis. The final written report includes a summary of their design process and a thorough evaluation of their final design. In addition, each group is expected to produce a prototype or model of their design for their external mentor. An emphasis is placed on integrating the hard and soft skills learned in other portions of the four-course sequence. For example, students are asked to identify what regulatory constraints have to be met for their proposed device with little explicit direction. The intention is for students to transfer their knowledge from Research Methods I. The mentoring and advising structure is the same as for the fall semester, with a single faculty member coordinating the course and a faculty mentor and external mentor assigned to each group project.

Interrelationships Between Courses

This four-course sequence has been designed to provide students with preliminary exposure to professional and design topics in Research Methods I and II just before the knowledge is needed in their Senior Capstone courses. For example, the ‘soft skills’ covered in Research Methods I are the tools needed in the first semester of senior design, which focuses on professional communication, problem identification and project planning. Hence, Research Methods I is taught the semester before Senior Capstone I. In contrast, the ‘hard skills’ in Research Methods II are most applicable to the second semester of senior design, where the focus is on fabrication and testing of devices. Hence, Research Methods II is taught the semester before Senior Capstone II. While this means that Research Methods II is taught concurrently with Senior Capstone I, this “just-in-time” approach is expected to facilitate the transfer of knowledge between courses. Because some senior design groups may reach the initial prototyping stage before the end of Senior Capstone I, the computer-aided design and rapid-prototyping unit of Research Methods II is taught before the cell culture unit. Thus, the students are familiar with

fabrication methods in time to use them in Senior Capstone I even though the two courses are taught concurrently.

This course sequence provides many opportunities to reinforce and apply material learned in previous courses. For example, students are expected to perform patent searches on their proposed devices in the Senior Capstone without any formal presentation on the subject, since they already learned to do patent searches in Research Methods I. Other design-related soft skills taught in Research Methods I, such as regulatory issues, are also applied, where relevant, in the senior design project proposals and reports. The professional communication and project management skills taught in Research Methods I are also utilized in establishing relationships with the external mentors for the senior design projects and in managing the projects as the students progress from design to fabrication and testing of their devices.

Skills learned in Research Methods II are also applied to senior design, even in the fall semester. For example, the goal of most of the senior design projects is to design an improved medical or experimental device. Because they have already learned how to use a CAD drawing program and the rapid prototyping machine early in the semester in Research Methods II, senior design groups are able to create first iteration prototypes in the first semester of senior design. This facilitates getting feedback from the external mentors. The machine shop exposure gained in Research Methods II is also used in the first semester of the senior capstone to motivate designs that students may not have considered without that knowledge.

In addition to the application of skills learned in Research Methods I and II to their senior design projects, students are also asked to draw upon their previous coursework while completing all four courses. For example, for the design project in Research Methods II, the students build flow chambers to visualize fluid flow through physiologically relevant geometries. These designs are an extension of a previous finite element modeling (FEM) project the students had completed in a course in the spring of their junior year. They approach the same medical problem, but this time with the skills to design and test a prototype flow chamber and compare the outcome to what they observed in their FEM models. As is typical of capstone courses, students also draw upon previous coursework throughout the BME curriculum when working on their senior design projects, with the coursework utilized depending upon the project topic. For example, some students have projects that require analysis of fluid flow in a device, for which they can draw upon their previous Biotransport courses. Other student projects require them to design basic circuits, which they learned about in Bioinstrumentation courses. The unique aspect of this four-course sequence is that the students also have an array of professional and design skills to draw from as they approach their senior design projects, rather than just technical skills.

Course Outcomes

Through this four-course sequence of professional skills, we hope to provide students with the opportunity to:

1. Apply all aspects of design (though not necessarily to their senior design projects),
2. Understand and apply professional project management skills,
3. Communicate effectively with experts in their field, and
4. Transfer skills between courses in the sequence.

The first outcome is addressed through repeated exposure to many design-related soft skills starting in the spring of their junior year. Rather than learning the concepts only in the context of their Senior Capstone, where a particular topic such as regulatory affairs may not be relevant to their particular project, students are exposed to soft skills as a separate and important entity in professional engineering education. During the initial exposure to each topic in Research Methods I, each student has the opportunity to apply these soft skills in their medical device benchmarking project. Hence, it is not necessary to require them to evaluate irrelevant topics for their senior design project in order to ensure exposure to an area of design. Through this approach, students are expected to gain a stronger understanding of the role of soft skills in both design and professional life. We also hope that they will be better able to determine whether a particular skill should actually be applied in their design project.

A second outcome of this sequence, an understanding and application of professional project management skills, is also addressed primarily through repeated exposure in Research Methods I and the Senior Capstone. Research Method I introduces students to project management skills such as writing meeting agendas, recording meeting minutes, and developing Gantt charts to monitor project timelines, all in the context of their medical device benchmarking project. These skills are then applied in the Senior Capstone to help them manage their senior design projects and interactions with the larger group that includes the student team members, their faculty mentor, and their external mentor.

Professional communication skills are a third focus of the design and professional skills sequence. This objective is achieved by utilizing external mentors in the senior design projects. Through the use of external mentors, the students are required to develop a relationship with a medical professional outside of the university. This requires direct application of the professional writing and communication skills taught in Research Methods I and the Senior Capstone courses, such as memo writing and meeting scheduling. The students may have found it rather contrived to apply such skills when communicating with professors whom they see regularly and informally. Instead, they use them to initiate and maintain a relationship with a medical professional who serves as both a mentor and a client. This provides a real-world setting in which to apply and develop their skills.

Opportunities for the students to achieve the fourth goal, the transfer of skills between courses in the sequence, are provided by two means. First, students are frequently expected to apply knowledge learned in Research Methods I and II to their Senior Capstone projects without further instruction, forcing them to draw upon the skills gained in their introductory courses to complete required assignments. Such topics include engineering drawing skills (from Research Methods II) and patent searching (from Research Method I), which are applied but not taught in the Senior Capstone courses. Second, the introduction of manufacturing related hard skills early in the senior year through Research Methods II allows students to gain relevant design-related skills at a time when they are just starting to identify their senior design problems and potential solutions. This encourages the students to make use of the machine shop and prototyping facilities when developing their initial design plans, and allows rapid transition from design to construction or prototype. This application of skills from the earlier courses in the sequence is self-motivated.

Assessment

This four-course sequence will be completed for the first time in the Spring of 2007. Hence, there has not yet been opportunity for rigorous assessment of the impact of this approach on the Biomedical Engineering Curriculum. Observationally, it is clear that students are applying the skills that they learned in Research Methods I and II to their senior design projects in the Senior Capstone courses, as described in Interrelationships Between Courses. Student feedback will be collected from the first class of students to complete the full sequence of design and professional skills courses, and will be included in the presentation of this paper. Additional methods for direct and indirect assessment of the sequence are also under development.

Conclusions

Overall, this four course model exposes students to a wide range of design and professional skills relevant to biomedical engineering. The sequential structure of the courses provides students with repeated exposure to, and refinement of, many skill sets. Further, as students are required to decide which skills should be applied to their specific design projects, this course sequence not only introduces students to an array of skills, but also provides opportunities for students to learn to identify the appropriate application of each skill. Hence, by providing the students with exposure to design and professional skills prior to their senior design project, the senior capstone serves as a capstone not only of technical skills but also of design and professional skills.

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