

Integrating Biology and Chemical Engineering at the Freshman and Sophomore Levels

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Abstract

Preparing chemical engineering students for careers in emerging technologies, such as bioengineering and pharmaceutical engineering, is essential in today's competitive market. To meet the industry (and student) demand for training in bio-focused engineering, many schools offer specialized curricula that concentrate on the interface between biology and engineering, or offer elective courses at the senior or graduate level. However, integration of biology and chemical engineering at the lower levels and in core courses is often difficult in curricula that are already filled to capacity.

The chemical engineering curriculum at Rowan University has been revised to include a Biological Systems & Applications course designed to introduce students to a variety of biological principles that are relevant to chemical engineering. Additionally,

several laboratory modules and projects that can be easily incorporated at the freshman and sophomore levels have been developed. These modules include reverse engineering of the human body, reverse engineering of the beer making process, and designing a microbial fuel cell. Modules developed for the freshman year expose students to chemical engineering principles as they apply to living systems. The Biological Systems & Applications course, specifically designed for sophomore chemical engineering students and taught by faculty in biology, introduces students to a wide variety of topics, from prokaryotic and eukaryotic regulatory systems to food microbiology. A sophomore-level engineering project on microbial fuel cell design reinforces concepts in microbial growth and nutrition that are covered in the Biological Systems & Applications course. This collaborative approach to integrating biology and chemical engineering helps prepare students for industrially-sponsored projects at the junior and senior level, and for jobs in the food, biotech and pharmaceutical industries. This paper will discuss the implementation and impact of these modifications to the curriculum.

Introduction

Instilling a working knowledge of biological principles and the ability to apply engineering principles to biological systems (and vice versa) in students is recognized nationwide as a goal for chemical engineering programs (2,6,15,17,18). Many schools offer specialized bio-focused curricula or courses at the senior or graduate level, but integration of biology and chemical engineering at the lower levels is difficult in an already overloaded curriculum.

At Rowan, we have developed an integrated, collaborative approach between

engineering and biology faculty to introduce chemical engineering students to the application of engineering principles in biological systems at the lower levels through specially designed courses and active learning modules. The systematic implementation of this philosophy exposes students to key areas of collaboration between biologists and chemical engineers at early stages in their undergraduate education. This strategy also enables faculty to build in increasing detail and technical content into problems and projects that address the interface between biology and engineering because students develop a cumulative knowledge of biological principles as they progress through the curriculum.

Revisions to the Chemical Engineering curriculum at Rowan University include a Biological Systems & Applications course designed to introduce students to a variety of biological principles that are relevant to chemical engineering. Additionally, several laboratory modules and projects that can be easily incorporated at the freshman and sophomore levels have been developed. These modules include reverse engineering of the human body, reverse engineering of the beer making process, and design of a microbial fuel cell. These modules in the freshman year expose students to chemical engineering principles as they apply to living systems. The Biological Systems & Applications course, specifically designed for sophomore chemical engineering students and taught by faculty in biology, introduces students to a wide variety of topics, from prokaryotic and eukaryotic regulatory systems to food microbiology. A sophomore-level engineering project on microbial fuel cell design reinforces concepts in microbial growth and nutrition that are covered in the Biological Systems & Applications course.

This collaborative approach to integrating biology and chemical engineering helps prepare students for industrially sponsored projects at the junior and senior level, and for careers in the food, biotechnology and pharmaceutical industries. The projects, courses, and activities described in this paper address key areas in which chemical engineering and biology have a strong connections, such as bioprocess engineering (biochemical reaction engineering for production of commodities and waste treatment), bioseparations, biocatalysis, and metabolic engineering. This paper will discuss the implementation and impact of these modifications in the engineering curriculum.

Experiments at the Freshman Level

A two-semester Freshman Clinic sequence introduces all freshmen engineering students to engineering at Rowan University. In the Freshman Clinic we immediately establish a hands-on, active learning environment for the reason explained by scientist and statesman Benjamin Franklin: “Tell me and I forget. Show me and I may remember. Involve me and I understand.” The first semester of the course focuses on multidisciplinary engineering experiments using engineering measurements as a common thread . In this section we describe two experiments that have been incorporated in the first and second semesters of this unique course sequence. The experiments, of varying lengths (from one three-hour lab to a semester project) illustrate various methods for integrating biological concepts at the lower levels.

Biomedical Experiment

The human body is an exquisite combination of interacting systems that can be

analyzed through the application of chemical engineering principles. Familiar examples include fluid flow of blood through arteries and veins, mass transfer in the lungs, pumping of the heart, and chemical reactions in cells. Biomedical topics in Chemical Engineering are explored in many curricula through advanced level elective courses, and are sometimes worked into homework problems in core courses. Freshman and sophomore chemical engineering students are rarely exposed to real biomedical applications of their discipline, and are unaware of the analogies between physiologic systems and chemical engineering operations.

We have developed a freshman level engineering experiment that is used to introduce students to a wide range of chemical engineering principles through their application to physiological processes. The details of the experimental procedure and analysis are provided elsewhere (7). Students take measurements of physiologic variables both at rest and during exercise, and then perform engineering calculations that involve basic principles of mass and energy balances, fluid flow, chemical reactions, energy expenditure, mechanical work and efficiency. These measurements and principles are summarized in Figure 1.

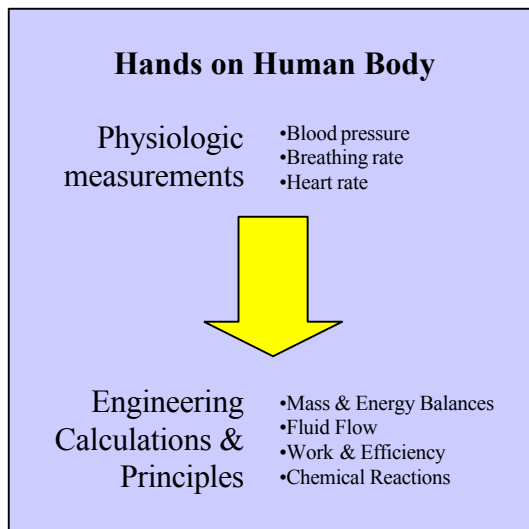


Figure 1: Measurements and principles illustrated in the hands on the human body freshman module.

During the three-hour experiment, students measure volumetric breathing rate and

heart rate at rest and during exercise on a bicycle ergometer. They also measure blood pressure at different elevations in the body using a blood pressure cuff (sphygmomanometer). Students use their physiologic data for breathing rate and heart rate to estimate their rate of oxygen consumption, blood flow rate, and rate of energy expenditure. The blood pressure measurements are used to calculate hydrostatic pressure differences and compare with expected values. This experiment provides an initial exposure to a variety of principles from engineering, physiology and cellular metabolism, and provides motivation and framework for future courses on related topics.

The theme of the second semester is the reverse engineering of a commercial product or process. Previous reverse engineering projects have involved products such as automatic coffee makers (11-13), hair dryers and electric toothbrushes (16). One of these semester-long modules, an investigation of the beer production process, incorporates the biology and reverse engineering of a

biochemical process into our Freshman Clinic. The detailed structure of the course has been described previously (8,9). In this paper, we describe the integration of principles from biology and engineering into this introductory, multidisciplinary engineering course. This interrelation of these principles is

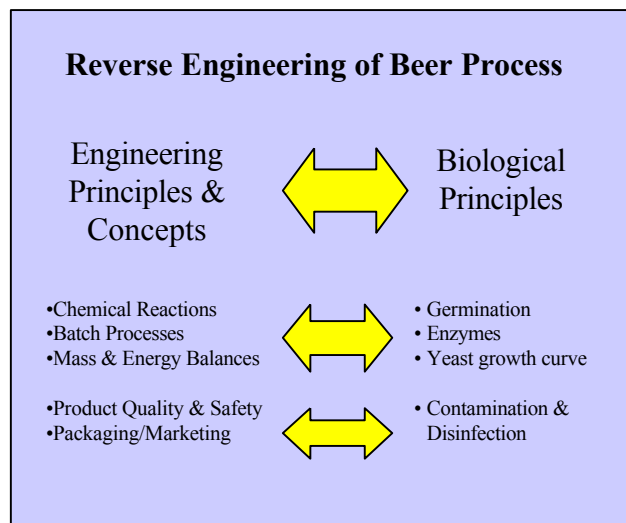


Figure 2: Interrelationship of Biological and Engineering Principles in the Beer Brewing Process.

shown in Figure 2.

The students' investigation focuses on three of the major steps of the brewing process: mashing, boiling, and fermentation. The brewing process is shown in Figure 3.

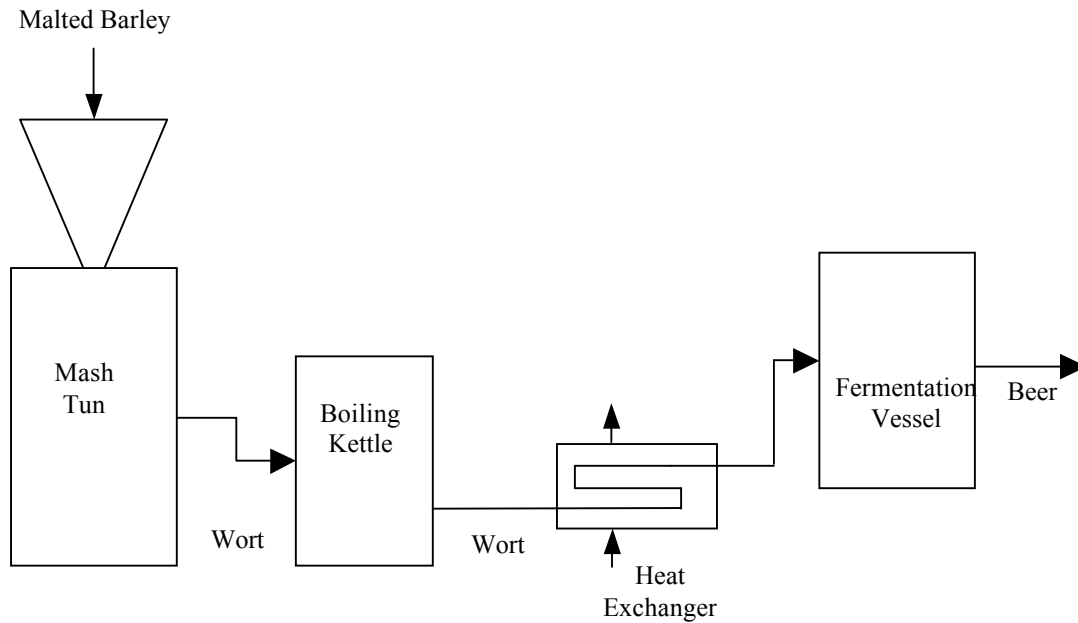


Figure 3: Schematic Representation of the Brewing Process Showing Major Process Steps

Near the beginning of the laboratory-intensive part of the project, a biology professor gives a guest lecture that provides the above overview of the biological processes involved in the production of beer. The addition of this guest lecture emphasizes not only the interdisciplinary aspects of biochemical processes, it also illustrates the collaboration between engineering and biology faculty and the importance of multidisciplinary teamwork. Once this foundation is laid, students then work in teams to investigate and reverse engineer the major steps of beer production.

The mashing step is the first major step in the brewing process. With raw materials of malted barley and water, this process produces a nutritionally complete wort for fermentation. Students mash both malted barley and unmalted barley, and they compare the worts obtained from each type. Analyses of the total extract and concentrations of fermentable sugars using an enzyme test kit reveal that only the malted

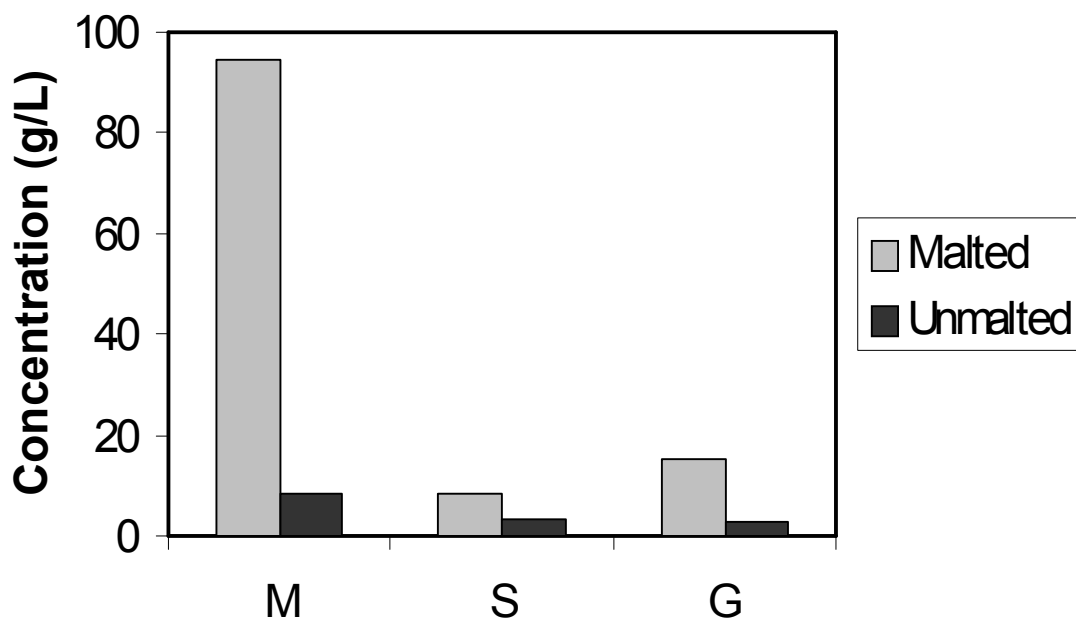


Figure 4: Fermentable sugars in the wort from malted and unmalted barley. M=Maltose, S=Sucrose, and G=Glucose.

barley produces a wort containing fermentable sugars, as shown in Figure 4.

After mashing, the wort is boiled for stabilization, and chilled rapidly to avoid contamination. When the temperature of the wort has been reduced to about 21°C, the yeast can be added for fermentation. The fermentation process takes place over the next 8-14 days, with the most vigorous fermentation occurring within the first 3 days.

The fermentation process provides an impressive visual show of biological systems in action. As the fermentation proceeds, students visually observe changes in color and turbidity, the formation of bubbles, and eventually the settling of yeast. The fermentation pathway and yeast growth curves are followed analytically as sugars are consumed to produce more yeast, alcohol and carbon dioxide; analytical measurements include yeast, sugar, and alcohol concentrations as well as pH. Students also learn about disinfection techniques and contamination issues as they clean and sterilize their glassware and other supplies used for fermentation and subsequent sampling. Biological principles for each step of the brewing process are shown in Table 1.

Table 1. Biological principles and topics related to beer production

Principle / Topic	Where Applicable
Germination and enzyme production	Malting
Enzymatic reactions	Starch hydrolysis to sugars during mashing; protein breakdown to amino acids during mashing
Yeast growth curve	Fermentation process
Fermentation	Fermentation
Fermentation monitoring	Fermentation
Disinfection and contamination	Fermentation and sampling

The brewing process is a fun and exciting biochemical engineering process. Through a series of experiments investigating the major aspects of the brewing process, freshman students are introduced to the important role biological systems can play in engineering processes. This hands-on project provides motivation for future study of the

underlying biological and engineering principles that are applied in the brewing process.

Experiences at the Sophomore Level

The two freshman-level modules discussed above introduce the interplay between biology and engineering using familiar systems. These modules also expose students to two different the application of engineering principles to biological systems for analysis and biomedical applications (reverse engineering of human body) and manipulation of microbial cultures to generate products for human use (beer-making process). The experiments excite students about careers that a chemical engineering degree can prepare them for as well as illustrate basic principles.

Before tackling in-depth analysis and manipulation of biological systems using engineering principles, however, students must have a firm grounding in biological principles that only a course can provide. A chemical engineer who is well-versed in biological, biochemical, and microbiological applications is an attractive candidate for employment in the pharmaceutical, biotechnology, and food manufacturing industries. To meet the anticipated growing demand for biology-literate engineers in these industries, biological sciences and chemical engineering faculty worked closely together to develop a course that prepares chemical engineering students for these careers. The course is open only to fall semester sophomore Chemical Engineering majors who have completed Advanced Chemistry I. Concurrently with this specially-designed biology course, students also are enrolled in a multidisciplinary engineering course that has a biological component.

Biological Systems & Applications course

The Biological Systems & Applications (BS&A) course was designed to meet the following four objectives: to provide engineering students with a basic understanding of fundamental biological principles and a working vocabulary that will enable students to expand their knowledge base during their academic and professional careers; to convey to the students an appreciation of the wide variety of engineering applications that are related to the fields of biochemistry, cell biology, genetics, general microbiology, and environmental microbiology; to provide laboratory experiences that teach "hands-on" mechanical skills such as micropipetting and culturing techniques; and to provide additional laboratory experiences that collectively instill in the students a general "biology common sense" that can be applied to work in any microbiology laboratory or project. Beyond the basics of cell and membrane biology, highlights in the lecture portion of the course include units about prokaryotic and eukaryotic regulatory systems, biotechnology, genomics, microbial growth and nutrition, the physiological diversity of microbes, environmental microbiology, industrial microbiology applications and concerns, and food microbiology. The laboratory exercises in the course are all devoted to skill development and/or directly connected to lecture topics (10). The BS&A course has benefited tremendously from the use of the "project based" learning approach (14) and strong interactivity between the Chemical Engineering and the Biological Sciences faculty. Extensive assessment data demonstrating the effectiveness of the course have been presented elsewhere (10).

Microbial Fuel Cell Semester Project

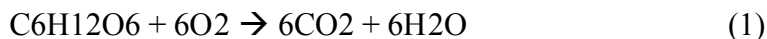
Chemical Engineering students who are taking the BS&A course also take Sophomore Clinic I, a multidisciplinary engineering design and practice course that is integrated with technical communications. Sophomore Clinic I combines a 1-credit multidisciplinary engineering laboratory with the 3-credit college composition and rhetoric requirement and is co-taught by engineering and composition and rhetoric faculty. The course structure is described in-depth elsewhere. The 1-credit lab for the course includes a semester-long project in which student teams design and create a microbial fuel cell (MFC) that powers a Lego® Mindstorms robot. The project combines mechanical, chemical, civil & environmental, and electrical & computer engineering skills. Students determine how changing certain fuel cell parameters and conditions affect voltage and current, then construct a Lego® Mindstorms robot that will derive its energy from a MFC stack. The project reinforces many concepts from courses early in the curriculum, such as chemistry, biology, and physics.

Fuel cell technology and alternative energy sources such as biofuels and photovoltaics are developing technologies that are exciting to students. Microbial fuel cells operate on the same principles as the more widely used (and more powerful) hydrogen fuel cells. Rather than a non-renewable source such as natural gas, however, microbial fuel cells (MFCs) use biomass as the substrate and microorganisms as the catalyst. While MFCs in which various types of substrates and waste products are converted to energy by a range of microorganisms, this project focused on yeast as the catalyst and glucose as the primary substrate.

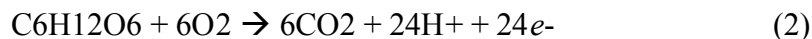
This project was inspired by the University of South Florida's research on the

“Gastrobot,” a semi-autonomous robot that is self-sustaining (19,20) and educational materials available from the National Centre for Biotechnology Education at the University of Reading(1,3-5). This combination of readily available educational kits and supplies (see <http://www.ncbe.reading.ac.uk> for supplies) and accessible literature (see <http://www.eng.usf.edu/~wilkinso/gastrobotics/>) that describes cutting edge research make the project feasible yet stimulating for the students.

A microbial fuel cell takes advantage of the metabolic reactions of microbes to generate electricity. Organisms carry out the following respiration reaction



to draw energy from food, or carbohydrates(5). The above reaction can be broken down as shown in (2) and (3), which follows the activity of electrons:



A redox mediator (methylene blue) can traverse the cell membrane and scavenge electrons from intermediates in which the electrons are stored. The mediator can then present these electrons to an electrode, and if an electron sink is provided (potassium ferricyanide), the circuit is completed. This process is shown in Figure 5. Voltage and current can be monitored using a multimeter. A single microbial fuel cell is capable of producing approximately 0.5 V.

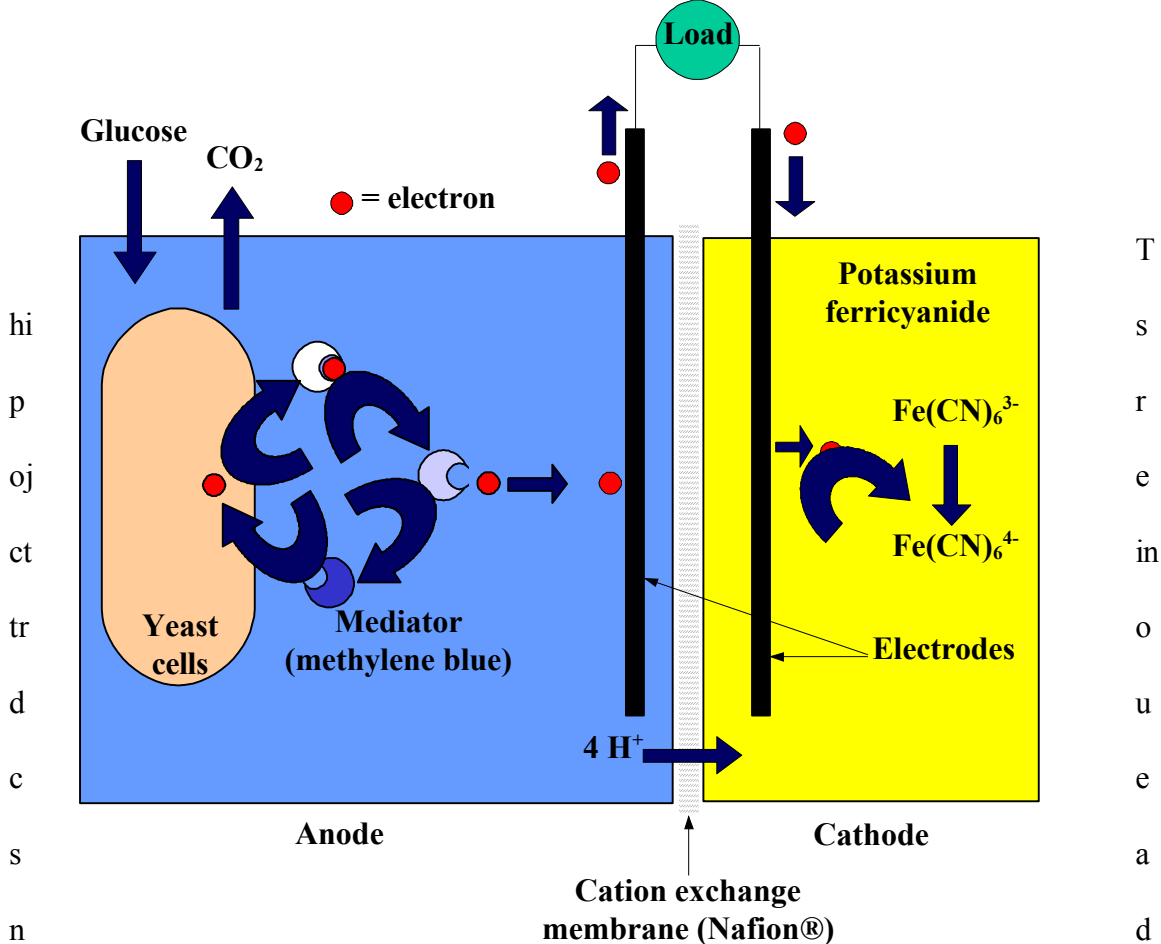


Figure 5: Microbial Fuel Cell Schematic (adapted from National Centre for Biotechnology Education, University of Reading, U.K, see <http://www.ncbe.reading.ac.uk>)

s several key concepts (summarized in Table 2): stoichiometry, cells as biocatalysts, cell metabolism, and modeling of the system to enhance design and performance. Student teams are asked to design a microbial fuel cell based on optimization experiments performed with a prototype. Students investigate the effect of glucose and yeast concentration on voltage and current produced by the cell. As the yeast consumes the glucose, the current produced drops until no glucose remains and the cell is unable to produce current. By varying the initial amount of glucose and yeast and plotting the concentrations of these two variables, students are introduced to the kinetics of batch fermentation.

Table 2. Biological principles and topics related to microbial fuel cell design

Principle / Topic	Where Applicable
Reaction stoichiometry/yield	Calculating theoretical yield of electrons based on initial glucose concentrations
Metabolic pathways	Investigating pathways for metabolism of glucose
Yeast growth curve, doubling time, fermentation	Determining “feeding time” for cell to continuously produce current
Fermentation monitoring	Current and glucose monitoring

Impact in the Curriculum

The combination of experiments and modules at the freshman and sophomore level and a Biological Systems & Applications course specifically designed for chemical engineers helps prepare students for research and industrial projects at the junior and senior level. As part of the Clinic sequence at Rowan, students participate in sponsored research projects during their junior and senior years. Each semester, students work in multidisciplinary teams as part of a 2-credit course. Project funding is provided through government or industrial grants or sponsorships. Situated in southern New Jersey, Rowan interacts with many companies in the pharmaceutical and food industries. Accordingly, the chemical engineering faculty's areas of expertise reflects this bio-intensive regional interest: over half of our faculty have training in biomedical, bioprocess, and biotechnology fields. This research interest is reflected in the types of clinic projects offered in the Junior/Senior Clinic course, from experiment development in drug delivery to the effect of packaging conditions on product spoilage.

Students often cite biochemical engineering as a motivator for pursuing a chemical engineering degree. This interest in the interplay between biology and engineering is apparent in the demand by students for bio-oriented research projects at the junior and senior levels. One measure of student interest in bio-related projects is their participation in Rowan University's student symposium in Science, Technology, Engineering and Math (STEM Symposium). As shown in Figure 6, the percentage of bio-related engineering projects that have been presented at the symposium has increased, from 10% in 1998 to almost 50% in 2002.

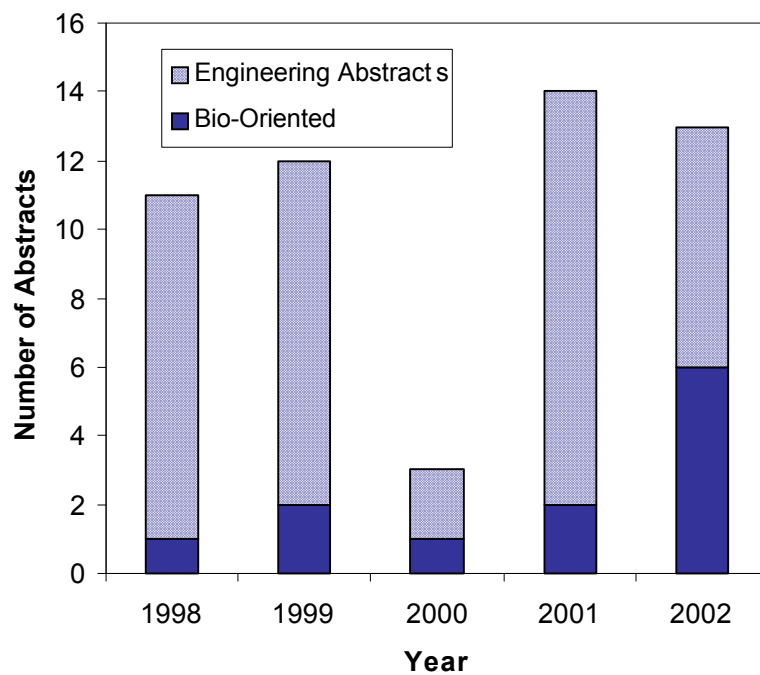


Figure 6: Number of bio-oriented abstracts and total abstracts submitted by engineering students at Rowan University's STEM Symposium

In some cases, such as the Food Microbiology laboratory exercise in the Biological Systems and Applications course, the lab component of the course has directly benefited students working on research projects at Rowan University. In an industrially-sponsored clinic project in which the effect of packaging on food spoilage was studied, the student (a junior) who had taken the Biological Systems & Applications course became the leader of the group, and taught the other members of the group (two seniors) the techniques necessary for determining bacteria counts. This student's experience in the course helped the group get started on the project much faster than if the students had received no prior training in microbiology.

As these students who have been exposed to these innovations in the curriculum progress, we expect to see similar results in future junior/senior clinic projects, as well as in engineering courses that have a biotechnology component.

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Biographical Information

STEPHANIE FARRELL received her B.S. in 1986 from the University of Pennsylvania, her MS in 1992 from Stevens Institute of Technology, and her Ph.D. in 1996 from NJIT. Prior to joining Rowan in 1998, she was a faculty member at Louisiana Tech University. Her research expertise is in the field of drug delivery and controlled release, and is currently focusing efforts on developing laboratory experiments related to membrane separations, biochemical engineering, and biomedical systems for all level students.

GREGORY HECHT has extensive research experience in prokaryotic genetics and molecular biology. With Dr. Mosto, he has developed a new course for Chemical Engineering students, Biological Systems and Applications. Dr. Hecht is the creator and coordinator of the Rowan University Student Research Symposium, an annual forum at which Rowan students from all of the SMET disciplines present the results of their independent research.

KATHRYN HOLLAR received her B.S. in Chemical Engineering and English from North Carolina State University and her Ph.D. in Chemical Engineering from Cornell University. Her research expertise is in the field of recombinant protein production. Her current focus is on developing laboratory experiments and course activities in food processing, biochemical engineering, and green engineering, particularly at the freshman and sophomore levels.

PATRICIA MOSTO has extensive environmental science experience. She has been actively involved with field and laboratory projects related to water quality and water pollution issues for the last 30 years. She worked with the Department of Water and Power and the Department of Sanitation in Los Angeles, CA for 10 years. In her 9 years at Rowan, she has supervised 33 independent undergraduate projects.