INTEGRATING BIOLOGY AND ChE AT THE LOWER LEVELS

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Instilling a working knowledge of biological principles in students and developing their ability to apply engineering principles to biological systems (and vice versa) is recognized nationwide as a goal for chemical engineering programs.[1-5] Many schools offer specialized bio-focused curricula or courses at the senior or graduate level,[6-8] and there is a significant movement to change chemical engineering department names to reflect faculty expertise in bio-focused engineering. Integration of biology and chemical engineering at the lower levels, however, is difficult in an already overloaded curriculum.

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 that can be easily adapted to any course, students are exposed to this newest pillar of the chemical engineering curriculum.

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

Revisions to the chemical engineering curriculum include a "Biological Systems & Applications" (BS&A) course designed to introduce students to a variety of biological principles that are directly 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 BS&A 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 BS&A 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 that we describe in this paper address key areas in which chemical engineering

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and biology have a strong connection, such as bioprocess engineering (biochemical reaction engineering for production of commodities and waste treatment), bioseparations, biocatalysis, and metabolic engineering. We 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 freshman engineering students to engineering at Rowan University. In the 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.*" Multidisciplinary engineering experiments using engineering measurements are the common theme of the first semester of the clinic, while in the second semester, students reverse engineer a product or process. In the following paragraphs, 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 they 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, however, and are unaware of the analogies between physiologic systems and chemical engineering operations.

We developed a freshman-level 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.[9] 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.

During the three-hour experiment, students measure volumetric breathing rate and heart rate both 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 to 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.

Reverse Engineering of Beer Production • 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,[10-12] hair dryers, and electric toothbrushes.[13] 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. A detailed structure of the course has been previously described.[14-15] In this paper we describe the integration of principles from biology and engineering into this introductory, multidisciplinary engineering course. The principles are summarized in Table 1.

Near the beginning of the laboratory-intensive part of the project, a biology professor gives a guest lecture to provide an 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, but also illustrates the collaboration between engineering and biology faculty and the importance of multidisciplinary teamwork. Once this foundation is laid, students work in teams to investigate and reverse engineer the major steps of beer production.

TABLE 1
Biological Principles and Topics Related to Beer Production

Principles/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 students' investigation focuses on three of the major steps of the brewing process: mashing, boiling, and fermentation. The brewing process is shown in Figure 1. Mashing is the first major step in the brewing process. Using the raw materials of malted barley and water, this process produces a nutritionally complete wort for fermentation. Students mash both malted and unmalted barley and then 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 barley produces a wort containing fermentable sugars, as shown in Figure 2.

After mashing, the wort is boiled for stabilization and chilled rapidly to avoid contamination. Yeast is added and the fermentation process takes place over the next 8 to 14 days, with most vigorous fermentation occurring within the first three days. Students may also perform experiments to determine yeast viability and activity.

The fermentation process provides an impressive visual show of biological systems in action. As the fermentation proceeds, students can 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, alcohol concentrations, and pH. Students also learn about disinfection techniques and contamination issues as they clean and sterilize the glassware and other supplies used for fermentation and subsequent sampling. At the end of the experiment, engineering problems such as disposal of wastewater, organic wastes, and biochemical oxygen demand may be addressed.

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 areas in which engineering principles can be applied to biological systems: 1) using engineering principles for analysis in biomedical applications (reverse engineering of human body) and 2) using engineering principles for manipulation of microbial cultures to generate products for human use (beer-making process). The experiments illustrate basic principles and excite students about careers for which a chemical engineering degree can prepare them.

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 4-credit, lab-intensive 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 multidiciplinary engineering course that has a biological component.

Biological Systems and Applications Course • The BS&A course was designed to meet the following four objectives:

1. *To provide engineering students with a basic understanding of fundamental biological principles and a working vocabulary that would enable them to expand their knowledge base during their academic and professional careers.*
2. *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.*
3. *To provide laboratory experiences that teach "hands-on" mechanical skills such as micropipetting and culturing techniques.*
4. *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 mi-

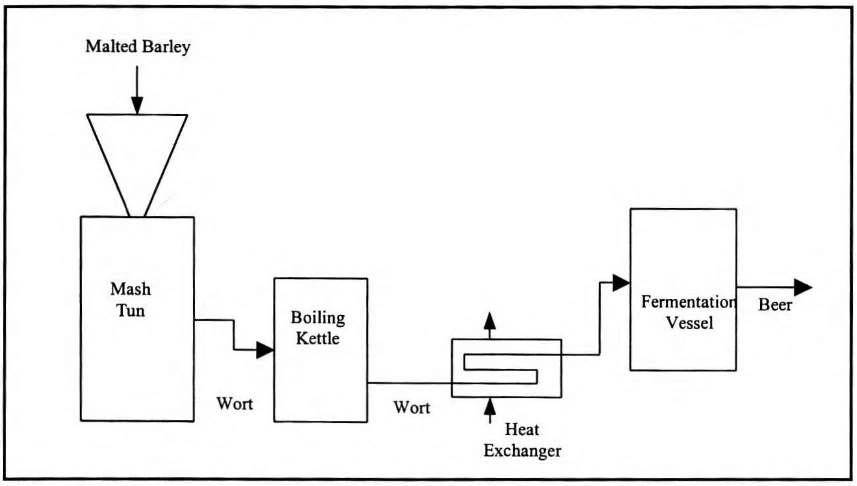

Figure 1. *Schematic representation of the brewing process showing major process steps.*

crobiology. The laboratory exercises in the course are all devoted to skill development and/or directly connected to lecture topics.[16] The BS&A course has benefited from using the "project-based" learning approach[17] and from strong interactivity between chemical engineering and biological sciences faculties. Extensive assessment data demonstrating the effectiveness of the course have been presented elsewhere.[16]

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. It combines a 1-credit multidisciplinary engineering laboratory with the 3-credit college composition and rhetoric requirement and is co-taught by engineering faculty and composition/rhetoric faculty.[18] 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 derives its energy from a MFC stack. The project reinforces concepts from earlier courses such as chemistry, biology, and physics.

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

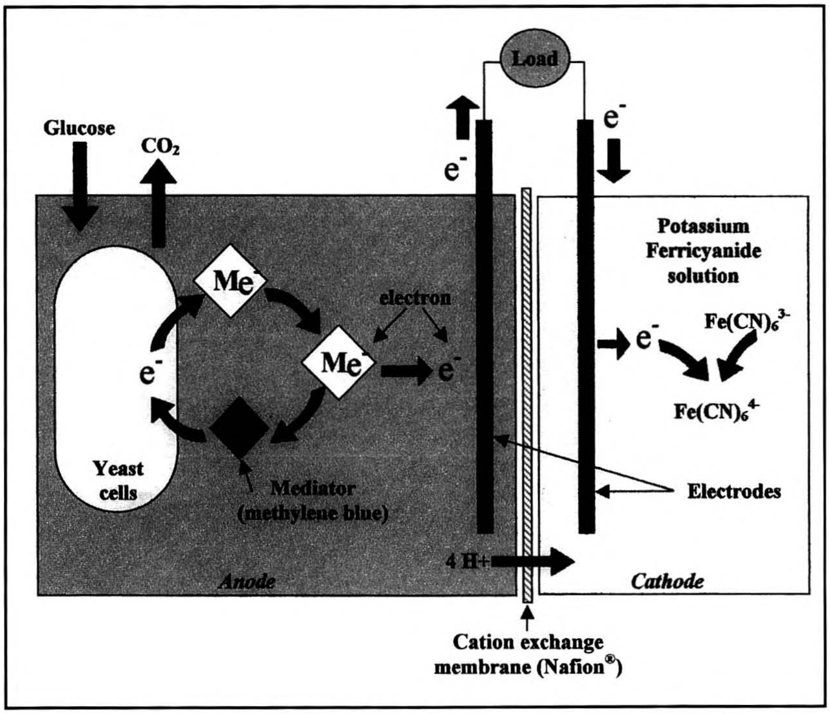

Figure 3. *Microbial fuel cell schematic, adapted from Ref. 20.*

Fuel cell technology and alternative energy sources such as biofuels and photovoltaics are developing technologies that are exciting to students. MFCs operate on the same principles as the more widely used (and more powerful) hydrogen fuel cells. Rather than a nonrenewable source such as natural gas, however, 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.

The project was inspired by the University of South Florida's research on the "Gastrobot," (a self-sustaining, semi-autonomous robot[19,20]) and educational materials available from the National Centre for Biotechnology Education at the University of Reading.[21-24] 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 makes 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:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad (1)$$

to draw energy from food or carbohydrates.[21] The above reaction can be broken down as shown in Eqs. (2) and (3)

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^- \qquad (2)$$

$$6O_2 + 24H^+ + 24e^- \rightarrow 12H_2O \qquad (3)$$

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 3. Voltage and current can be monitored using a multimeter. A single microbial fuel cell is capable of producing approximately 0.5 V.

The microbial fuel cell project introduces and reinforces 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. They 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.

IMPACT ON 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 levels. 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. Located in southern New Jersey, Rowan interacts with many companies in the pharmaceutical and food industries through its junior/senior clinic sequence. Accordingly, the chemical engineering faculty's 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 projects offered in the junior/senior clinic, from experiment development in drug delivery to the effect of packaging conditions on product spoilage.

Students often cite a potential career in biochemical engineering as the motivator for pursuing a chemical engineering degree. This interest in the interplay between biology and engineering is apparent in the student demand for bio-oriented research projects at the junior and senior levels. One measure of student interest in bio-related projects is their participation in the University's Science, Technology, Engineering, and Math (STEM) Symposium. As shown in Figure 4, the percentage of bio-related engineering projects presented at the symposium has increased from 10% in 1998 to almost 50% in 2002.

In some cases, such as the Food Microbiology laboratory exercise, the lab component of the BS&A course has directly benefited students working on research projects. In an industrially sponsored clinic project in which the effect of packaging on food spoilage was studied, a (junior) student who had taken the BS&A course became the leader of the group and taught the other members (two seniors) the techniques necessary for determining bacterial counts. This student's experience in the course helped the group hit the ground running. As the beginning cadre of 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 or bioengineering component.

Like many chemical engineering schools, Rowan offers several bio-related technical electives at the senior and graduate-student level on a rotating basis. Students may enroll in courses on drug delivery, biomedical engineering, or biochemical engineering. Other courses at this level, such as food engineering, polymer engineering, and membrane process technology, have increasing applications in the biotechnology and pharmaceutical industries. Preparing students with a course in biological systems and bio-related modules during their freshman and sophomore years aids in developing material for these courses that explore the link between biology and chemical engineering at a much deeper level. Additionally, we anticipate being able to cover more material and applications in the time that is traditionally spent in an introduction to biological principles.

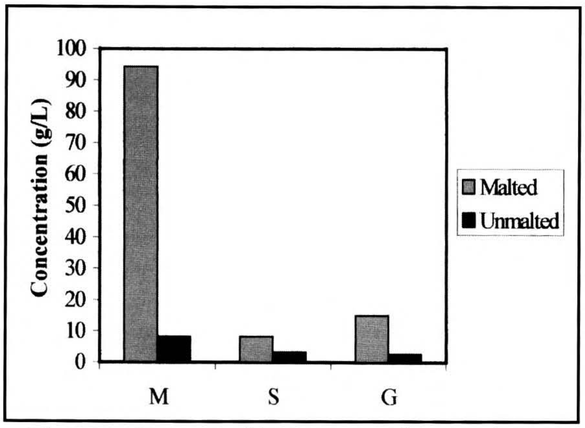

***Figure 2.** Fermentable sugars in the wort from malted and unmalted barley: M=Maltose; S=Sucrose; G=Glucose*

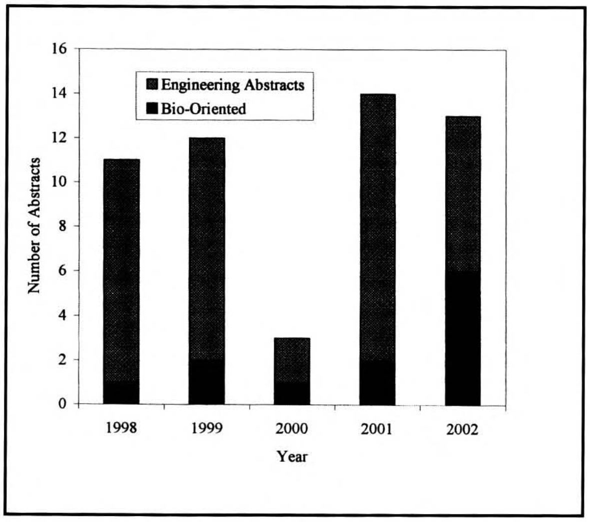

***Figure 4.** Number of bio-oriented abstracts and total abstracts submitted by engineering students at Rowan's STEM Symposium.*

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