

# MICROBIOLOGY EDUCATION

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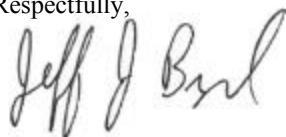
In reviewing submissions for the fourth volume of *Microbiology Education* we were pleased at the wide range of manuscripts received. This diversity in manuscripts encompassed both type of institution and type of microbiology course being taught. In this volume you will find papers from large universities, a liberal arts college, and a community college. In addition, the courses discussed include general microbiology, microbial physiology, allied health, and microbiology for chemical engineers. It is encouraging to see that at all types of institutions and in the various corners of microbiology education, microbiologists are focusing on the improvement of teaching and learning of our students.

It is critical that we, as microbiology educators, seize the moment and disseminate good and accurate information about microorganisms. As the mass media focuses on the potential harm caused by the release of bioterrorism agents, we must also make the public aware of the benefits provided by and the diversity of the microorganisms in our surroundings. There is no more critical place for this dissemination of information to occur than our institutions of higher learning. While it is commonplace for ecology labs to go out into the field to sample, this is not necessarily the case for microbiology labs. This volume includes a paper by Taras that discusses a laboratory course that takes community college students out on a boat to collect their own environmental samples. Without this course, many of these students would not have had the opportunity to relate the specific environments with the presence of the microbes. The connection between microbe and environment is especially important for those citizens that may contemplate utilizing microbes in their work. Hecht et al. present a paper on a course in applied microbiology designed specifically for chemical engineering majors. This course is unique in that it was structured in such a way as to help engineering students make connections with microbiology, so that they are better prepared for the workforce. It is the hope of the authors that as chemical engineers embark on their careers, they will have a greater appreciation for the microbes.

It is also critical to get students to analyze the information in current microbiology texts and the mass media and begin to think beyond that information. McInerney and Fink present a paper in which they utilize team-based learning and current literature to stimulate the students to synthesize what they learned and apply it to a current metabolic question. Their findings show that this approach increased retention of information and stimulated interest in metabolism, an area that many microbiology students find to be tedious or uninteresting. In a complementary paper that addresses dissemination of accurate information, Breakwell presents an allied health microbiology course that utilizes primary literature. While microbiological information may not always be accurately portrayed in the mass media, it is critical for those in the allied health fields to know where to find accurate information and how to digest the information as presented in journal articles. In this manner they are better prepared to serve their discipline.

As you enjoy this fourth volume, we encourage you to contemplate how you can assess the techniques you are using to educate your students. Through adequate assessment and analysis you will be better able to determine the level of student learning in your classroom. When you find interesting results about teaching and learning, we encourage you to share them with the wider community. *Microbiology Education* stands ready to serve as the conduit for your research results.

Respectfully,



Jeffrey J. Byrd

Chair, Editorial Board for *Microbiology Education*

## Effectiveness of an Applied Microbiology Course Specifically Designed for Chemical Engineering Majors

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**In recent years, the disciplines of microbiology and chemical engineering have developed an increasing convergence. To meet the needs of their future employers, today's chemical engineering students must receive some background in microbiology. This report describes the development and content of "Biological Systems and Applications," a novel course specifically designed to provide basic biology and applied microbiology knowledge, skills, and experience to sophomore chemical engineering majors. Data collected from entrance and exit surveys of the students demonstrated that the course is successful. The importance of the "project-base" learning technique and of interdisciplinary faculty-student and faculty-faculty collaborations are proposed as elements essential to the success of this particular course.**

The changing face of the chemical industry and increasing emphasis on life sciences has spurred many chemical engineering departments to review their curricula. At Rowan University, the Biological Sciences faculty have developed a unique biology course for the chemical engineering students as a result of student and faculty assessment. The new four credit sophomore-level Biological Systems and Applications course (BS&A) addresses a need in the educational experience for Chemical Engineering students not only at Rowan, but also serves as a model for other schools. Its hands-on laboratory component enhances student learning and provides the necessary background in the biological sciences for students to succeed in upper-level courses, projects, and their careers.

A nationwide effort is underway to examine engineering curricula and encourage the incorporation of more topics from the life sciences. Industries in the pharmaceutical, biotechnology, biomedical, food, and related fields indicate a strong demand for engineers with training in the life sciences. A conventional approach would be to add some standard biology courses, but a separate new course optimally developed for engineering students provides a more focused learning experience.

For these reasons, the course we designed was an interdisciplinary effort between the faculty of the Department of Biological Sciences in the College of Liberal Arts and Sciences and the Department of Chemical Engineering in the College of Engineering. We designed this course especially for chemical engineers due to their particular needs. This type of basic science course is consistent with current Accreditation Board for Engineering and Technology requirements of Engineering Criteria 2000 (1). Previously two semesters of physics and 16 credits of chemistry were required; however, the new Engineering Criteria 2000 requirements encourage innovative curricula in which basic math and sci-

ence courses are used to satisfy the direction and mission of the Chemical Engineering program. This course is part of an effort to include innovative methods of teaching and learning and cutting-edge curricula to prepare students better for a rapidly changing and highly competitive marketplace, as recommended by the American Society for Engineering Education (3).

This course best serves engineering students by providing them with a working knowledge of a broad range of biology principles and techniques that will be used by chemical engineers throughout their curriculum and after graduation. This follows the recommendations of Westmoreland (13). The biological background ideally needed for chemical engineering students includes basic biochemistry, cell biology, genetics, general microbiology, and environmental microbiology, as well as applications of each. The current course offerings from the Biological Sciences department would require chemical engineering students to enroll in Biology I, Biology II, Introduction to Biochemistry, Microbiology, and Environmental Microbiology in order to cover all of these areas. Unfortunately, there is insufficient space in the chemical engineering curriculum to insert a sequence of five biology courses. Moreover, the five-course sequence would include a great deal of information that would be considered superfluous in the context of an Accreditation Board for Engineering and Technology chemical engineering program review. This single course on the other hand presents the salient topics in a concise and unified fashion coordinated with extensive and rigorous hands-on experiences during the laboratory sessions.

### METHODS

**Overall course structure.** The syllabus for BS&A is presented in Table 1. The objective underpinning the arc of the entire course was to furnish Chemical Engineering majors with a basic background in fundamental biology, biochemistry, and applied microbiology. The laboratory component of the course was designed to provide not just hands-on mechanical skills such as micropipetting and culturing techniques, but also first-hand experience that would pro-

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TABLE 1. Syllabus outline for the Biological Systems and Applications course<sup>a</sup>

Month	Lecture components	Laboratory components	
September	Biologically important molecules	Students receive their microbial pets <sup>b</sup>	
	Membranes	Aseptic technique and micropipetting <sup>c</sup>	
	Eukaryotic cell biology	Titration of overnight culture <sup>c</sup>	
	Prokaryotic cell biology → linked to → DNA structure and function	Assemble Winogradsky column Microscopy and staining <sup>c</sup> Antibiotics <sup>c</sup>	
October	Prokaryotic regulatory systems → linked to → Eukaryotic regulatory systems	Finish microscopy and staining Quorum sensing	
	Prokaryotes as dynamic genetic systems	Experimentation on individuals vs. experimentation on populations	
	The cell cycle → linked to → Biotechnology and genomics	Microscopic observation of onion root tip cells Microbial growth curve <sup>c</sup>	
	November	Finish biotechnology and genomics → linked to → Basic microbial metabolism and physiology → linked to → Microbial nutrition and growth	Polymerase chain reaction Physiological tests <sup>c</sup>
		Metabolic diversity → linked to →	Winogradsky column used as a visual aid
December	Environmental microbiology → linked to → Applied microbiology → linked to → Food microbiology	Winogradsky column (final evaluation) Evaluation of activated sludge Food microbiology	

<sup>a</sup>Shaded bars designate direct linkages between particular lecture topics and specific laboratory exercises. See Methods for additional details.

<sup>b</sup>See Methods regarding the principles behind the use of microbial pets in the class.

<sup>c</sup>Indicates laboratory exercises that used the students' microbial pets.

vide students with a general “biology common sense” that could be applied to work in any microbiology laboratory or project. The course was open only to fall-semester sophomore Chemical Engineering majors who had completed Advanced College Chemistry I (freshman chemistry).

The course was structured to meet three times each week, two sessions of 75 minutes each plus one 165-minute session. In principle the 75-minute sessions were to be used for lectures and the 165-minute sections were to be used for labs, but the session contents were often rearranged to accommodate the needs of the course. For example, sometimes 75-minute sessions were used for laboratory exercises (e.g., data collection). In other cases, 165-minute sessions were split up to include both lecture and laboratory components. There was also one week in which all sessions were used entirely for laboratory exercises.

Because of the sweeping scope of the BS&A syllabus, textbook selection was not easy. Taking students' limited budgets into account, it would have been ideal to choose a single text. Unfortunately, this was not possible because general biology texts do not place enough emphasis on applied microbiology nor do microbiology texts include enough general biology and eukaryotic biochemistry to meet the cur-

ricular goals of this course. Ultimately, it was decided to require two textbooks, the then-current editions of Campbell et al.'s *Biology* (2) and Madigan et al.'s *Brock Microbiology of Organisms* (7). The former was chosen because it is the text that is currently used in Rowan University's Biology I and II sequence; the latter was selected because of its emphasis on environmental and applied microbiology and its extensive discussions of unusual microbial physiology. Supplemental readings from other books were used to enhance discussions of eukaryotic signal transduction (11), eukaryotic gene regulation (12), and genomics (9).

Evaluations of student accomplishment took on a variety of forms. The final numerical grade consisted of four equally weighted exams, the lab grade average (weighted as one exam), the homework grade average (weighted as one half of one exam), and a semester-long class team project (weighted as one half of one exam). Conversion of numerical averages into letter grades was in part contingent on the instructor's assessment of individual student's classroom participation. For example, strong participation could raise a numerical grade up one “notch” (e.g., from B+ to A-), while poor participation could shift a grade down one notch and intermediate participation meant the grade was held in place.

Because classroom sessions were always conducted using a nearly Socratic method, participation by each student was usually intermediate to strong.

Grades for particular laboratory exercises consisted of either a series of written follow-up questions or a formal laboratory report written in the style of *Applied and Environmental Microbiology*. When calculating a student's lab grade average, formal lab reports were given twice as much weight as follow-up questions.

The class team project for the fall 2001 semester was the development of a website devoted to surveying the diversity and engineering applications of eukaryotic microbes. This particular topic was chosen in part because of the heavy emphasis on prokaryotic biology in the classroom. The class team project for the fall 2002 semester will be to flesh out portions of the existing eukaryote survey as well as to develop an analogous survey of the Archaea. Future semester projects will focus on groups of Eubacteria as well as specific engineering applications that utilize microbes.

**The use of "microbial pets" in the laboratory exercises.** During the first week of the course, each student in the class was assigned a microbial pet. Each pet was either a eubacterium (e.g., *Escherichia coli*, *Bacillus subtilis*, *Pseudomonas fluorescens*, *Micrococcus luteus*) or a single-celled fungus that forms discrete colonies (e.g., *Saccharomyces cerevisiae*, *Rhodoturulula rubra*). No two students received identical pets. Students were responsible for carrying out all culturing activities that their pets required during the entire semester. Pets were cultured at 30°C on Microbial Pet (MP) medium. MP medium contains per liter: 3.0 g beef extract, 5.0 g peptone, 15.0 g tryptone, 5.0 g papaic digest of soybean meal (soytone), and 5.0 g sodium chloride. For solid MP medium, agar was added to a final concentration of 15.0 g per liter. MP medium was selected to maximize the variety of pets capable of growing on a single type of medium.

The microbial pets served two purposes. First, they gave students direct experience in the proper aseptic upkeep of a microbial culture. In addition, these pets were used in several different laboratory exercises (Table 1). Follow-up questions or reports required the students to collect and compare the results obtained for all of the pets in the class. Thus, the microbial pets also provided an opportunity to demonstrate some aspects of microbial diversity.

The microbial pets in this course were not intended to be used as an "unknown bacterium." On the contrary, students were informed of the identity of their pet on the day that they received it, thereby enabling them to look up useful information regarding their pet which could then be used in analysis of their laboratory exercise data.

**September course content: laying the groundwork.** The first month of the course was devoted to establishing fundamental biological principles (Table 1). Topics that were presented during the initial weeks included discussions of biologically important molecules (carbohydrates, lipids, proteins, and nucleic acids), membrane structure and function, the basic structure and function of internal and external cellular organelles, the contrast between eukaryotic and prokary-

otic cells, DNA structure, replication, transcription, and translation. One of the fundamental principles introduced during this phase of the course is that proteins and other biological molecules do not function via "telepathy" or "radio waves;" instead, these molecules physically interact with substrates and other molecules. In particular, the principles of chemistry and physics dictate a protein's three-dimensional structure, and this in turn influences which molecules a protein may interact with and the consequences of that interaction. This was a theme repeated over and over again during the entire semester.

Fundamental laboratory skills were also established at this time. For example, students were introduced to the proper use of micropipettors. Using their microbial pets, students learned aseptic liquid and plate culturing techniques as well. Pipetting and culturing techniques were reinforced by having the students carry out a "dilution to extinction" titration of overnight cultures of their microbial pets. Students were also introduced to the use and care of brightfield compound microscopes.

Important principles regarding eukaryotic and prokaryotic cell biology were directly observed by the students during staining and antibiotic sensitivity experiments. Students carried out basic staining and Gram staining on their pets. As a result, students learned that eukaryotes are generally much larger than prokaryotes and that gross cell morphology (rods and cocci) is not necessarily indicative of a cell's envelope structure. All students were required to carry out a Gram stain on a mixed smear of *Escherichia coli* and *Bacillus subtilis*, so they all learned that particular technique even if their pet was a eukaryote. Students learned additional staining techniques (acid fast, endospore, and negative) using microbial cultures supplied by the instructor. Students used antibiotic disks to determine the sensitivity of their pets to a panel of ten different antibiotics. They observed that gram-positive and gram-negative cells have different sensitivity patterns and that eukaryotes are not susceptible to antibiotics. Follow-up questions asked the students to identify the targets for each of the antibiotics used during the laboratory, and this was used as a springboard during a classroom discussion to highlight the cellular differences between prokaryotes and eukaryotes and between gram-positive and gram-negative cells. During this month, students also assembled a large Winogradsky column, although the significance of this was not fully explained until much later in the course (see below).

**October course content: the dynamic behavior of organisms.** The underlying theme for the second month of the course was the concept that organisms are not static, as well as the contrast between individual behavior and population trends (Table 1). The discussion of prokaryotic regulatory systems focused mainly on control of gene expression in response to environmental changes, among the examples included were the *lac* operon of *E. coli*, bacteriophage lambda life cycle events, and quorum sensing. A laboratory exercise involving quorum sensing was carried out at this stage of the course. The experiment involved novel quorum sensing in-

teractions exhibited by the bacterium *Vibrio harveyi* (C. E. Mire, et al., unpublished data); the specific advantages of this exercise for this particular course will be presented in a later communication (G. B. Hecht, unpublished data). The topics regarding eukaryotic regulatory systems centered mainly on signal transduction, and examples included retinal rod cell function, cyclic AMP cascade events, and cell cycle regulation. This was followed up by a unit about the prokaryotic and eukaryotic cell cycle events and their control by cell cycle checkpoints. Mitosis was discussed as a “system of equitably dividing genetic material during cell division.” The other major component of this portion of the course was a discussion of prokaryotic genetic exchange and flux that are the consequence of processes such as mutation, conjugation, transformation, transduction, and transposition.

Some of the laboratory exercises during this portion of the course were not directly related to the lecture topics but nevertheless were very important. Students monitored the exponential growth of their microbial pets using a spectrophotometer, thus demonstrating that not all microbes grow at the same rate. More fundamentally, they also experimented on individual *Daphnia magnus*, assaying the change in heart rate in response to exposure to ethanol or caffeine. This experiment as originally designed and published (5) is intended to give students exposure to the scientific method and practice in data presentation in the format of graphs. Although those objectives were certainly in play during this particular exercise, a more fundamental purpose for this course was the demonstration that individual organisms may or may not display the behavior trends of a population as a whole. Engineers frequently deal with machines and computers that are intended to produce precisely repeatable outputs in response to perfectly identical inputs. Biological organisms cannot necessarily be assumed to behave in this manner, and the context of this exercise was designed to highlight this concept.

**November course content: introductions to biotechnology, genomics, and physiology.** The third phase of the course (Table 1) included the first major application unit, recombinant DNA and biotechnology. This directly led into a brief unit describing genomics and proteomics. A laboratory exercise involving detection of *V. harveyi* via PCR amplification of the *luxO* gene was conducted during this part of the semester.

The next unit focused on basic metabolism and physiology (aerobic metabolism, fermentation, oxygenic photosynthesis). This was followed up by discussions of microbial nutrition and growth, as well as “alternative” energy-harvest-

ing strategies employed by prokaryotes. Students conducted an array of simple qualitative physiological assays on their microbial pets in conjunction with this unit, including, but not limited to, Durham fermentation tube tests, growth on eosin-methylene blue plates, Simmons citrate agar tests, and catalase and urease detection. The lecture discussions were also enhanced by the use of the developing Winogradsky column as a visual aid.

**December course content: applications of November’s course topics.** The final section of the course was entirely devoted to the intellectual and industrial application of concepts presented during November (Table 1). For example, the environmental microbiology unit drew on many of the concepts of physiology and metabolism detailed previously. The importance of the Winogradsky column was brought forward at this time. The applied microbiology unit presented an array of industrial uses of microorganisms; one of many topics included the importance of genetically modified microbes for commercial applications. The unit also included a broad presentation of industrial water and sewage treatment coupled with a microscopic evaluation of activated sludge in the laboratory. A special unit (both lecture and laboratory) highlighted commercial use of microorganisms in food and beverage production as well as industrial strategies to limit microbially induced food spoilage.

**Procedures for assessment of course success.** The effectiveness of BS&A was evaluated by comparing the results of an entrance survey conducted during the first week of the course and an exit survey conducted during the last week of the course. The entrance survey consisted of a series of questions to assess student’s prior knowledge and comfort level in the areas of biology and microbiology. Questions were presented in a multiple-choice format as shown in Fig. 1.

The beginning portion of the exit survey had largely the same format as the entrance survey. Every question asked in the entrance survey was asked again in the exit survey, either verbatim or with only minor edits to account for changes in verb tense. Some additional questions were also added to the exit survey, primarily to obtain feedback regarding the course laboratory activities. In addition to the multiple-choice questions, students were presented with a list of every lab exercise from the semester and asked to indicate which labs “taught me a skill” and which ones “taught me something about microbiology and/or about science.”

Students completed both the entrance and exit surveys anonymously. Both surveys were completed by the entire class at the same time. The number of respondents for the

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“I have a good understanding of why Chemical Engineers should take a biology course.”

Strongly disagree		Neutral or not sure		Strongly agree
1	2	3	4	5

FIG. 1. Example of the format used to solicit responses to entrance and exit survey questions.

entrance survey was 14. During the semester, one student withdrew from Rowan University and another student went on a medical leave of absence, so the number of respondents for the exit survey was 12.

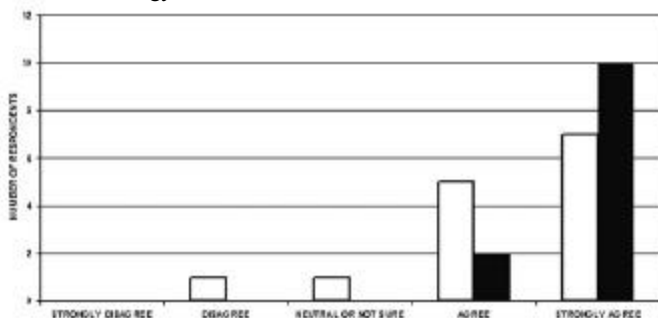
To determine whether observed differences in student responses on the entrance and exit surveys were significant, Fisher's Exact Test was performed on the results. The resulting  $P$  values are reported in Fig. 2 and 3 and are also given parenthetically in the text of the Results.  $P$  values less than 0.05 were deemed to be significant.  $P$  values between 0.05 and 0.1 in this study may represent marginally significant

differences between the entrance and exit data. In instances where  $P > 0.05$ , additional trials would be required to demonstrate strong significance.

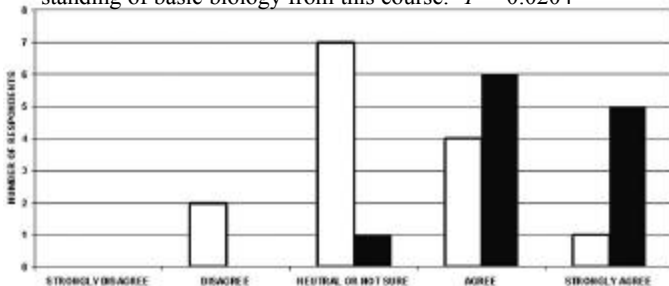
## RESULTS

**Assessment of student needs at the start of the semester.** The entrance survey indicated that at the beginning of the semester, approximately two-thirds of the students did not respond positively to a statement regarding their understanding of basic biology, and only 14% of the class felt comfortable with the notion of culturing microorganisms (Fig.

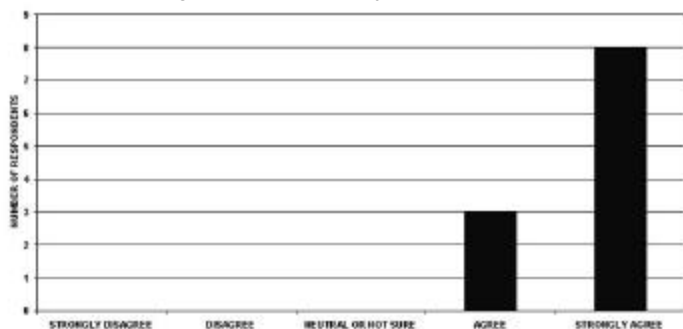
A. "I have a good understanding of why Chemical Engineers should take a biology course."  $P = 0.2327$





B. Entrance survey: "I have a solid understanding of basic biology from my previous experience." Exit survey: "I have a solid understanding of basic biology from this course."  $P = 0.0204$

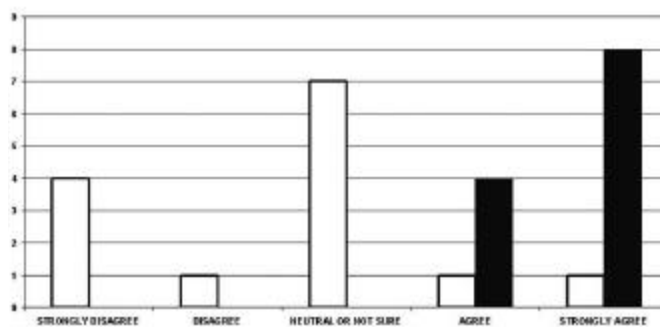


C. "I feel that I have some appreciation of microbial diversity because of things we did in lab, not just because of lecture material."



 Entrance survey results  
 Exit survey results

D. "If I were responsible for culturing a microorganism in a lab by myself, I would feel like I knew what I was doing."  $P = 8.563 \times 10^{-5}$



E. "The use of a 'microbial pet' in class helped me to learn about microbiology."

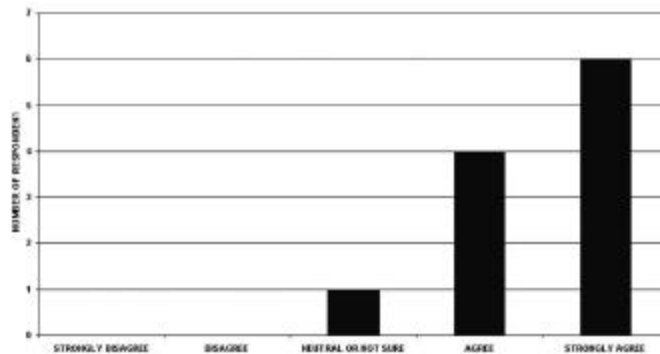
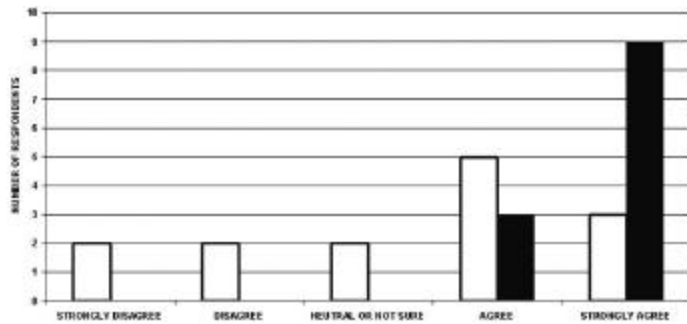
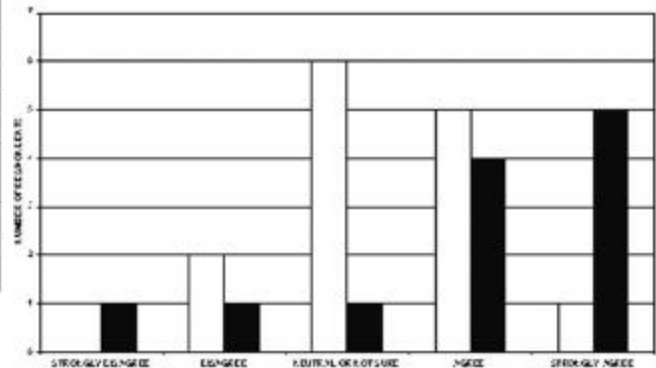


FIG. 2. Assessment of overall course success. Bar graphs indicate the number of respondents selecting a particular choice on the survey sheet. In those cases where only exit survey results are presented, the particular question was not asked on the entrance survey. Except where indicated, entrance and exit survey questions were identical. For the entrance survey,  $n = 14$ . For the exit survey,  $n = 12$  (except for panels C and D, where one of the participants elected not to respond to a particular question). In panel E, the one respondent who indicated "Neutral or Not Sure" added the following note to their answer for this question: "It made the class more interesting."  $P$  values shown indicate results of a Fisher's Exact Test performed on the entrance and exit results.  $P$  values  $< 0.05$  are significant. The  $P$  value reported in panel A may indicate marginal significance and additional trials would be required to demonstrate strong significance.

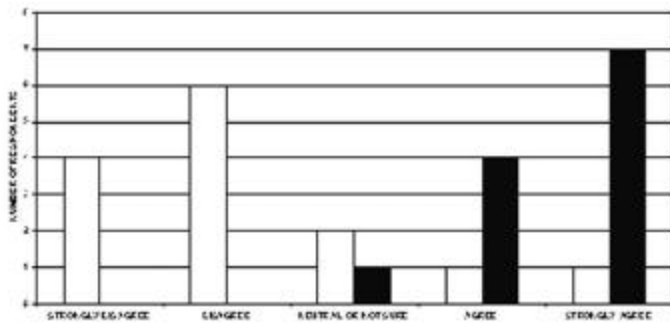
A. Entrance survey: "I know how to use a compound light microscope because I have used one in the past." Exit survey: "I know how to use a compound light microscope because I have used one."  $P = 0.0439$



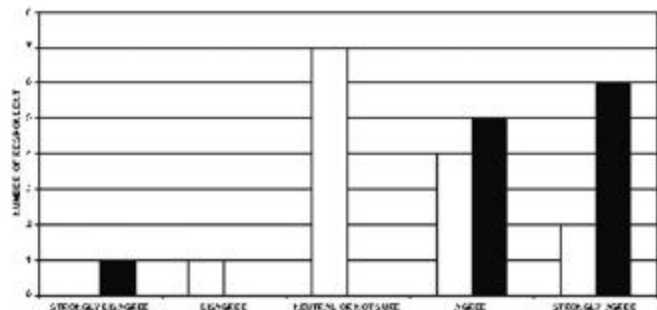
D. "Even though bacteria reproduce in a very simple fashion, it is fairly easy for bacteria in the natural world to change their genetic make-up on their own."  $P = 0.0932$



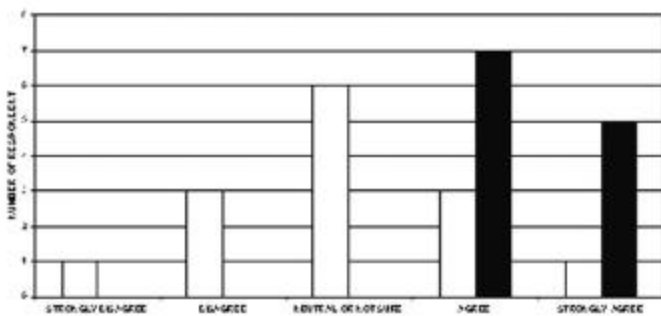
B. "I can clearly explain the difference between a yeast cell and a bacterium."  $P = 5.343 \times 10^{-4}$



E. "In the laboratory, existing technology gives scientists the capability to give bacteria new abilities by giving them genes from an entirely different species or organism."  $P = 0.0102$



C. "I can clearly explain what a gene is and how it works."  $P = 2.4 \times 10^{-3}$



F. "I can explain why organisms such as myself need to breathe oxygen."  $P = 0.0262$

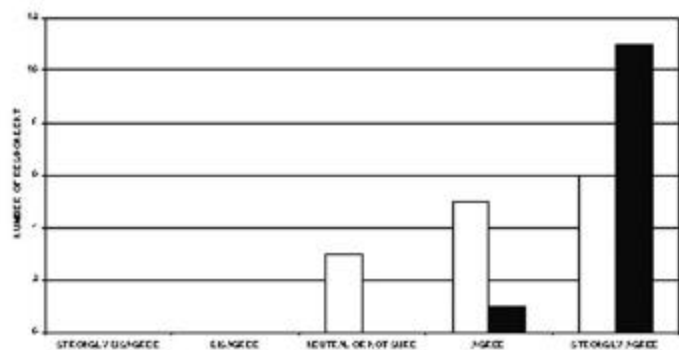
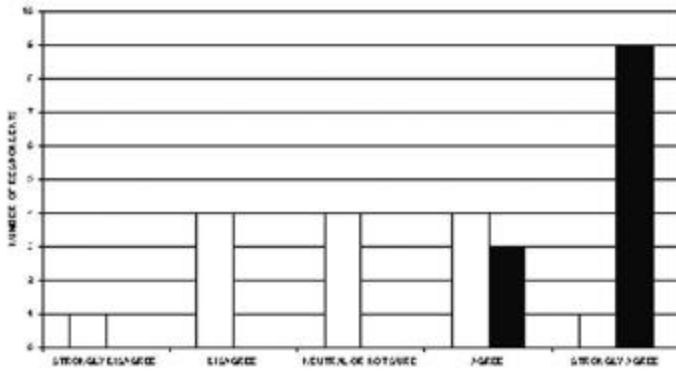
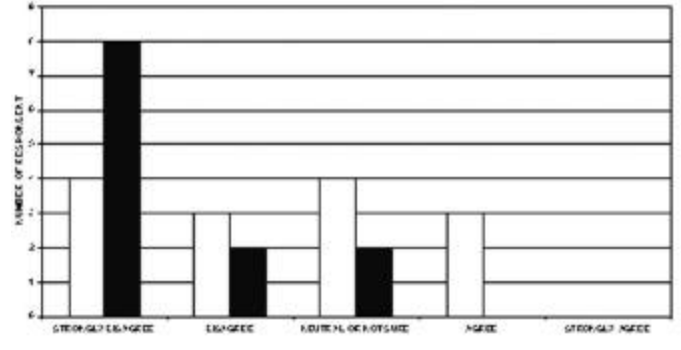


FIG. 3. Assessment of success of specific course components. Bar graphs indicate the number of respondents selecting a particular choice on the survey sheet. Entrance and exit survey questions were identical except where indicated. For the entrance survey,  $n = 14$ . For the exit survey,  $n = 12$ .  $P$  values shown indicate results of a Fisher's Exact Test performed on the entrance and exit results.  $P$  values  $< 0.05$  are significant. The  $P$  value reported in panel D may indicate marginal significance, and the values reported in panels I and J may indicate an important trend. Additional trials for these particular questions would be required to demonstrate strong significance.

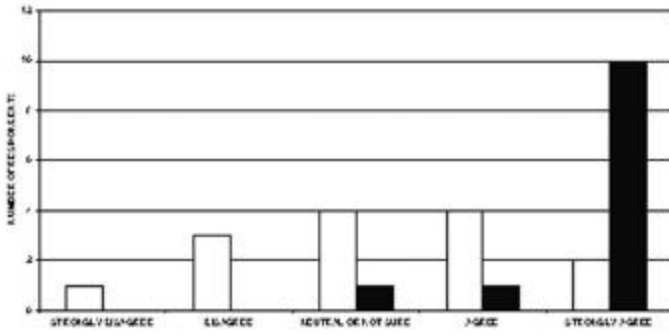
G. "I can explain why some organisms can live without oxygen in the air."  $P = 9.720 \times 10^{-4}$



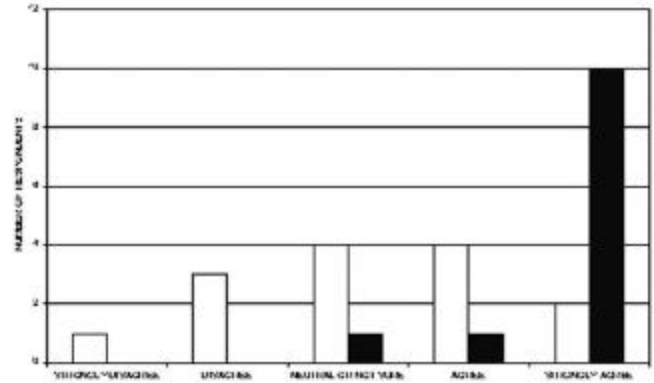
J. "The best way to get yeast to produce as much ethanol as possible is to make sure that it gets lots of oxygen for good growth."  $P = 0.2044$



H. "I can clearly explain the steps involved in soil bioremediation."  $P = 2.249 \times 10^{-4}$



K. "Other than alcoholic beverages, I can name five foods and/or drinks that require fermentation and/or other microbial activity as part of the production process."  $P = 3.0 \times 10^{-3}$



I. "I can name a type of organism that is a producer but which is not a plant."  $P = 0.1491$

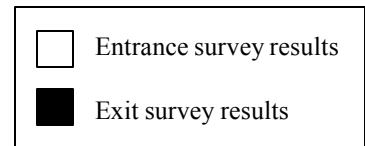
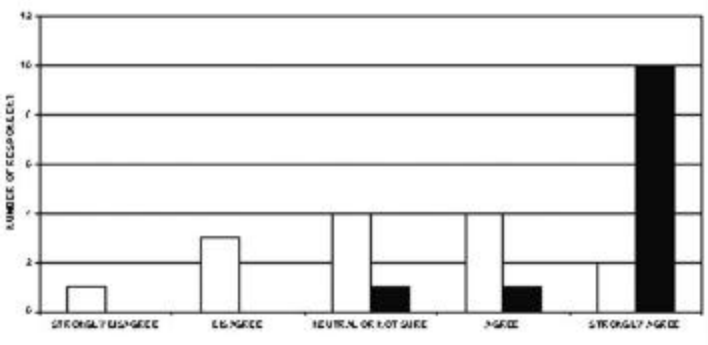


FIG. 3 - Continued.

2). Only 57% of the class stated that they knew how to use a compound microscope (Fig. 3).

Students conveyed a significant gap in their knowledge of fundamental cell biology, molecular genetics, and metabolic processes (Fig. 3). Only 29% felt that they could clearly explain what a gene is, and a meager 14% could describe the difference between a yeast cell and a bacterium. Forty-three percent of the students were comfortable with the idea that prokaryotic genotypes are not static in nature, and only 43% of the class agreed that bacteria could be genetically engineered in the laboratory. Although 79% of the class was not sure that they could explain why they needed to breathe oxygen, only 36% could explain why oxygen is not a requirement for all organisms.

Similar weaknesses were revealed in students' knowledge of environmental and applied microbiology (Fig. 3). Forty-three percent could name producers which are not a plant, and 43% could explain soil bioremediation. Forty-three percent could name five foods or drinks whose production was dependent upon microbes. Half of the students agreed or were not certain that aeration of a yeast culture would enhance ethanol production.

**Assessment of course effectiveness.** The exit survey results display significant shifts from the entrance survey responses. At the conclusion of the course, 92% of the students ( $P = 0.0204$ ) indicated that they had a solid understanding of basic biology and all of the students ( $P = 8.563 \times 10^{-5}$ ) indicated that they could culture microorganisms by themselves (Fig. 2).

The exit survey also shows that the use of microbial pets in the course was an effective learning tool for these students. Eighty-three percent of the students responded that the microbial pet was helpful, and 92% of the class agreed that they had "some appreciation for microbial diversity because of things [they] did in lab, not just because of lecture material" (Fig. 2). For all but two of the lab exercises, 50% or more of the respondents reported that the exercises taught them about microbiology and/or biology (data not shown). Labs that scored high marks in this category included Winogradsky column (83%), food microbiology (83%), quorum sensing (83%), activated sludge (92%), physiological microbiology tests (92%), and experimentation on individuals versus populations (100%). The only two labs that did not receive high ratings in this category were micropipetting and aseptic technique. This is not surprising since these exercises were dedicated exclusively to mechanical skill development and did not include an experimental component. For each of these labs, 100% of the class indicated that they learned a skill (data not shown).

Student responses regarding specific course topic areas also showed substantial changes in the exit survey (Fig. 3). The entire class indicated that they knew how to use a compound microscope ( $P = 0.0439$ ), explain what a gene is and how it works ( $P = 2.4 \times 10^{-3}$ ), why they required oxygen to live ( $P = 0.0262$ ), and why some organisms can live anaerobically ( $P = 9.720 \times 10^{-4}$ ). Ninety-two percent of the students could explain the difference between yeast and prokary-

otes ( $P = 5.343 \times 10^{-4}$ ). Seventy-five percent of the students agreed that prokaryotic genotypes can be altered by natural means ( $P = 0.0932$ ) and 92% agreed that this alteration was possible in the laboratory ( $P = 0.0102$ ). Ninety-two percent of the class agreed that not all producers are plants ( $P = 0.1491$ ). The exit survey also documented fundamental changes in students' knowledge regarding applied microbiology. Ninety-two percent could explain soil bioremediation ( $P = 2.249 \times 10^{-4}$ ), 83% were knowledgeable about the conditions necessary for fermentation ( $P = 0.2044$ ), and 92% could list a significant number of microbially produced foods or beverages ( $P = 3.0 \times 10^{-3}$ ).

The course as a whole was so successful that even though at the start of the semester 36% of the class agreed and 50% strongly agreed that chemical engineers should take a biology course, a shift to 17% agreement and 83% strong agreement was observed at the semester's conclusion ( $P = 0.2327$ ; Fig. 2).

## DISCUSSION

A comparison of the student entrance and exit data clearly demonstrates that the BS&A course accomplished its objectives. We suggest that two reasons for this success include the special attention paid to its interdisciplinary nature and the project-based learning approach.

The heart of this particular course is its interdisciplinary nature, engaging the faculty that designed the course in a community of learners, giving them opportunities to learn from each other. It has been demonstrated that interdisciplinary courses increase course completion rates and strengthen learning, making it more connected and meaningful. This type of course deepens faculty development and teacher vitality, responds to larger integrative societal trends, and encourages the development of communication and collaborative skills amongst students and faculty (6). The establishment and enrichment of these sorts of collaborations was key to the success of this course. BS&A was not developed to deliver the same content as a routine Biology I or Microbiology course to a segregated group of students. To the contrary, the course content was always prepared with an eye toward basic biology skill development and linkage to engineering applications. The fact that students were responsive to this course on numerous levels derives partly from the interactivity between themselves and the Biology department and partly from the collaborations between faculty in the Biology and the Chemical Engineering departments.

One of the hallmarks of both the engineering and the biology programs at Rowan University is an emphasis on hands-on design and experimentation through project-based learning. The use of the microbial pets throughout the semester is very representative of this type of curricular approach and was a keystone to the BS&A course. Learning from a project base as part of the classroom curriculum engages students in a range of activities: logical thinking, communication skills, acquisition of information, problem solving, data analysis, and oral and written presentation design and delivery. It requires the instructor to focus on how well

learners acquire, integrate, and internalize information and skills. In essence, it allows students to learn how to learn. Students are better prepared for work after graduation, developing greater productivity more quickly because they have acquired teamwork abilities needed in the workplace. This curricular approach also enables students to retain a greater portion of the course content since that content is valued and required to solve problems. In short, students appreciate and value the curricular knowledge for what it enables them to do (8).

The experience gained during the creation of this course serves as a model for other schools to follow in interdisciplinary cooperation between microbiology and engineering. Through joint cooperation and innovative design, an optimum course was developed and implemented. The experiences reported here show that what could have been a lackluster "service course" was instead conceived and developed as a much richer education experience for both faculty and students. The philosophies that were the driving force behind the development of this course are applicable to other kinds of cross-disciplinary curricular components, including those that do not involve microbiology or engineering, e.g., physics, chemistry, mathematics, and computer science.

The impact of BS&A also goes beyond its short-term semester goals and significantly enhances broader aspects of the chemical engineering curriculum. As the chemical engineering faculty are challenged with incorporating new experiments, projects, or curricular content that reflects topics in the life sciences and related fields into the program, the BS&A course provides the fundamental background for these experiences. The Sophomore Engineering Clinic recently incorporated a project on the development of a microbial-fuel-cell-powered robot (4); Junior and Senior Engineering Clinic projects on bioengineering, food processing, and biochemical separations will also benefit (10). Courses in Reaction Engineering and Separation Processes taught in the junior year will be able to use examples relevant to bioprocessing because of the fundamental knowledge students have gained through the BS&A curriculum. The chemical engineering department offers electives in the senior year, which can also be enhanced because of the prior biology knowledge that students have gained. For example, a course in Food Engineering would devote less coverage to microbial fundamentals and therefore could spend more time on processing issues.

Further assessment of the Biological Systems and Applications course will be done in future years, comparing the different cohorts and their accomplishments within their specific engineering courses and clinics. Furthermore, future development of the course will incorporate any enhancements in the applied lab component to meet the needs of the engineering students.

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