Organizing the engineering curriculum with biomedically related learning modules

Dr. Stephanie Farrell, Rowan University

Dr. Stephanie Farrell is an Associate Professor of Chemical Engineering at Rowan University (USA). She obtained her PhD in Chemical Engineering from New Jersey Institute of Technology in 1996. Prior to joining the faculty at Rowan in 1998, she was an Assistant Professor of Chemical Engineering and Adjunct Professor of Biomedical Engineering at Louisiana Tech University until 1998. Dr. Farrell has made contributions to engineering education through her work in experiential learning, focusing on areas of pharmaceutical, biomedical and food engineering. She has been honored by the American Society of Engineering Education with several teaching awards such as the 2004 National Outstanding Teaching Medal and the 2005 Quinn Award for experiential learning. She was also awarded an honorary degree in International Engineering Education by IGIP.

Prof. Jennifer Vernengo, Rowan University

Dr. Tom Merrill, Rowan University

Dr. Jennifer Kadlowec, Rowan University

Dr. Mary M. Staehle, Rowan University

Dr. Robi Polikar, Rowan University

Robi Polikar is a Professor of Electrical and Computer Engineering at Rowan University, in Glassboro, NJ. He has received his B.Sc. degree in electronics and communications engineering from Istanbul Technical University, Istanbul, Turkey in 1993, and his M.Sc and Ph.D. degrees, both co-majors in electrical engineering and biomedical engineering, from Iowa State University, Ames, IA in 1995 and 2000, respectively. His current research interests within computational intelligence include ensemble systems, incremental and nonstationary learning, and various applications of pattern recognition in bioinformatics and biomedical engineering. He is a member of IEEE, ASEE, Tau Beta Pi and Eta Kappa Nu. His recent and current works are funded primarily through NSF’s CAREER and Energy, Power and Adaptive Systems (EPAS) programs.
Organ-izing the curriculum with hands-on, biomedically-related learning modules

ABSTRACT

The relatively new discipline of biomedical engineering emerged from informal collaborations between engineers, physicians and life scientists, and is the fastest growing engineering discipline at most universities. Chemical, mechanical, and electrical engineers play an important and expanding role in this burgeoning field because the fundamental core principles of each discipline are critical to biomedical mainstays such as the design of artificial organs. This project introduces hands-on, biomedically-related experiments and course materials into the engineering curriculum, with a focus on artificial organs. Several modules are being developed and integrated throughout Rowan’s engineering curriculum, into the multidisciplinary freshman engineering course, core engineering courses, and senior electives. The modules will be highly transferrable to other traditional engineering programs such as chemical, mechanical and electrical as well as biomedical engineering programs. Our evaluation plan will examine specific learning outcomes in core engineering areas as well as effect on retention, student attitudes, and career choices. This paper presents descriptions of the proposed and completed modules, and results of our assessment of learning outcomes to date.

INTRODUCTION

The relatively new discipline of biomedical engineering emerged from informal collaborations between engineers, physicians and life scientists, and is the fastest growing engineering discipline at most universities. As a result of the aging of the population and a growing focus on health issues which increase the demand for better medical equipment, devices, and pharmaceutical products, the biomedical engineering industry has demonstrated explosive growth in recent years. According to the Department of Labor Statistics, Biomedical engineers are expected to have employment growth of 72 percent in the decade between 2008 and 2018, in comparison with the average of 7-13% for all occupations.

Chemical, mechanical, and electrical engineers play an important and expanding role in this burgeoning field because the fundamental core principles of each discipline are critical to biomedical mainstays such as the design of artificial organs. While the number of biomedical engineering degrees granted annually is increasing, many biomedical engineers have a background in chemical, mechanical, or electrical engineering with some specialized biomedical training. Engineering programs in these disciplines struggle to squeeze bio-related topics into their already-crowded curricula, yet undergraduate engineering students are rarely exposed to real biomedical topics through their coursework. To provide students with the skills directly relevant to the evolving needs of the biomedical industry, this project will develop and integrate applied biomedical course content and experiments throughout the Rowan Engineering curriculum.

A plan is presented to introduce hands-on, biomedically-related experiments and course materials into the engineering curriculum, with a focus on artificial organs. These biomedical modules will be integrated throughout Rowan’s engineering curriculum, into the multidisciplinary freshman engineering course, core engineering courses, and senior electives. Exposure to biomedical topics will provide excellent preparation for interested students to pursue graduate studies in related disciplines such as biomedical engineering or medicine. Because the modules are rooted in fundamental engineering principles, they will be equally valuable to students who pursue careers in other engineering areas. Once developed, our modules could be adopted by classic engineering programs such as Chemical, Electrical and Mechanical Engineering, as well as specialized Biomedical Engineering programs, and could be implemented by fac-
ulty who do not have specialized biomedical expertise. This paper focuses on the description of the course modules, which has been the primary activity during this first year of the project.

GOALS AND OBJECTIVES

The goals and objectives of this project are outlined below.

- To develop scalable and transferrable biomedical course modules that enhance learning in the core disciplines.
- To increase student retention and participation in biomedical education.
- To increase participation and retention of underrepresented minorities and persons with disabilities.

PROJECT PLAN

The project comprises seven modules that introduce students to multidisciplinary engineering principles through application to artificial organs. This project adapts and implements research equipment and methodology used by medical and engineering researchers, to teach engineering principles. At the freshman level, students will be engaged in the scientific discovery process using exciting hands-on design challenges to analyze artificial organs. In more advanced core engineering courses and laboratories, students will explore the function of artificial organs in the laboratory and investigate the variables affecting their performance.

The engineering goals of this project are: (1) to explore the function of human and artificial organs; (2) to apply current research methodology state-of-the-art medical devices for a hands-on investigation of artificial organs; and (3) to introduce fundamental engineering principles through experiments with artificial organs; (4) to investigate the factors affecting artificial organ performance and design criteria; and (5) to explore the complicated ethical issues regarding the technological advances that blur the boundaries between machines and organisms.

The development of the undergraduate modules began in year one and was performed by summer interns and teams of students in the Junior/Senior Engineering Clinic, under the supervision of the investigators. Piloting the modules in undergraduate courses began in year two (the current year of the project), and they will be refined based on our formative evaluation. In the second half of year two and year three, we will continue to use the modules at Rowan while also focusing on dissemination activities such as beta-testing at other institutions and G6-12 teacher-training workshops.

Artificial Blood - Rheology

The rheology of blood is very complex because it is a suspension of cells in a solution of proteins and salts. Sickle cell anemia represents the loss of normal blood rheology due to the distortion and decreased flexibility of red blood cells (RBCS), causing pathologies such as tissue infarction and organ failure. Understanding the flow characteristics of normal and sickle cell blood is critical for finding treatments for the disease. In this module, students determine the rheological behavior of single-phase and two-phase blood analogs. The influence of fluid composition and hematocrit are explored and related to effects of sickle cell anemia on the body. The overall objectives of this module are to 1) give students hands-on exploration with the rheological characterization of Newtonian and non-Newtonian fluids, 2) To learn to quantify fluid viscosity and Casson parameters as a function of hematocrit content and RBC deformability, and 3) relate the physiological significance of these flow parameters to sickle cell anemia.

We implemented a blood rheology experiment into the Freshman Engineering course. In this experiment, the rheological behavior of single phase and two-phase analogs was analyzed using the Casson model, a constitutive relation that describes the rheological behavior of two-phase fluid.
A single phase, 80% glycerol solution was used to simulate blood plasma. Chitosan particles in 80% glycerol was used to simulate healthy blood, with chitosan concentration between 25-75% representing different hematocrit levels. Glutaraldehyde-crosslinked chitosan particles were used to simulate the sickle-cell blood analog. The flow characteristics were analyzed using a rotational viscometer.

Sample student results are shown in Figure 1. The square root of shear rate is plotted on the ordinate to facilitate linear regression for the determination of the parameters a and b in the Casson model.

![Graph showing the effect of varying hematocrit level on the viscosity of the healthy two-phase blood analog.](image)

**Figure 1.** The effect of varying hematocrit level on the viscosity of the healthy two-phase blood analog.

To evaluate the impact of this experiment on student learning, a quiz was administered to students before and after the lab. The quiz comprised 7 multiple choice questions which were mapped to lab objectives and measureable skills associated with each outcome. The average score on the pre-test was 42%±9%, and the average score on the post-test was 92%±5%, for n=17 students. The specific quiz questions are shown in Table 1. More detail on the learning module and learning outcomes is provided in the paper by Vernengo et al. [6].
Table 1. Quiz questions for the rheology module. Original questions were multiple choice. For brevity, this table shows the quiz questions phrased as true statements.

<table>
<thead>
<tr>
<th>Question #</th>
<th>Correct statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rheology is defined as the study of how liquids and soft solids flow under a force.</td>
</tr>
<tr>
<td></td>
<td>In the following, indicate the depiction that best represents a shear force.</td>
</tr>
<tr>
<td>3</td>
<td>Shear stress is defined as the application of force across a fluid.</td>
</tr>
<tr>
<td>4</td>
<td>The units of shear strain are: unitless.</td>
</tr>
<tr>
<td>5</td>
<td>In the following figure, indicate the data that represents a fluid with a yield stress (line A or B?)</td>
</tr>
<tr>
<td></td>
<td>In the above figure, line A represents a fluid where there is a linear relationship between shear rate and shear stress. This means the fluid is a Newtonian fluid.</td>
</tr>
<tr>
<td>7</td>
<td>Sickle cell anemia is a blood disorder where red blood cells become crescent-shaped and lose flexibility. This causes blood viscosity to increase.</td>
</tr>
</tbody>
</table>

The Lungs - Blood Oxygenation

Blood oxygenators are used during open-heart surgery when a patient’s lungs cannot function properly. In comparison with their direct-contact predecessors, the membrane blood oxygenators used today offer several advantages due to engineering improvements: a lower blood priming volume reduces the need for donated blood transfusion, and enhanced mass transfer allows lower blood flow rates and therefore less damage to blood components. Blood oxygenators are used in more than one million procedures annually, and their total market is over $500 million per year.

An adult blood oxygenator must deliver about 250 ml/min (STP) oxygen and remove about 200 ml/min (STP) carbon dioxide. The limited solubility of these gases in blood poses a challenge, which is addressed by using high flow rates of blood. As a result, high mass transfer rates and low pressure drops are crucial design considerations, and there remains a great need for further design improvement. Characterization of mass and momentum transfer in blood oxygenators therefore important to the design of these devices. The blood oxygenation (BO) module explores BO design and performance evaluation through a series of hands-on experiments that are integrated from freshman through senior level engineering courses.

In the fall 2013 semester, the experiment was implemented in the Freshman Engineering course. Students measured gas and liquid flow rates and oxygen concentrations, and they applied a mass balance to determine the oxygen transfer rate. Students varied the gas and liquid flow rates to investigate their effect.
on the mass transfer rate. Sample student results are shown in Figure 2. In the spring semester, a team of junior and senior engineering students re-designed the system and introduced an additional dissolved oxygen meter. This has resulted in even better mass balance agreement. The new system will be used by freshman students in the fall of 2014.

![Figure 2. Mass transfer rates for high and low gas and liquid flow rates. Error bars are 95% confidence intervals. Students are expected to conclude that mass transfer rate is significantly affected by liquid flowrate.](image)

To evaluate student learning, a pre-test and a post-test was given to the class. The test comprised a combination of multiple choice and open-answer questions that were designed to address both lower and higher levels of Bloom’s Taxonomy. Each question was mapped to the objectives of the activity and to ABET objectives. At this time only the multiple choice questions have been analyzed. These questions covered concepts related to mass balances, mass transfer and design of blood oxygenators. The phrasing of some of the questions was modified slightly between pre-test and post-test, while covering the same concepts, so that the test could more reliably test student understanding. The class average gain between pre-test and post-test was 43% for n=21 students.

**Skin – Barrier Properties**

As the largest organ in the human body, the primary function of skin is to serve as a barrier between the body and the surrounding environment. The large area of the skin, convenient accessibility, and proximity to blood vessels and systemic circulation make skin an obvious candidate for a route of drug administration. In this module, students will explore the permeability of porcine skin, easily obtainable at a grocery store and cost-effective. Porcine skin has been shown to be histologically and biochemically similar to human skin, and have a similar permeability\(^9\). In parallel, students will measure mass transfer across
biomaterials using artificial skin and also determine the effects of various permeation enhancers on the mass transfer.

In this module, the permeability of a model drug, caffeine, across porcine skin is determined experimentally using passive transdermal delivery, chemically enhanced delivery, and iontophoresis. The objectives of this module are (1) to determine the release kinetics from a transdermal delivery system, (2) to apply a mass balance to the membrane system, and (3) to investigate the effects of permeation enhancers and dermal substitute composition on the transdermal rate of drug delivery.

The experiment uses a modified Franz Diffusion Cell constructed of inexpensive plastic syringe barrels forming the donor and receiver compartments. Porcine skin is used as the dermal membrane between the donor and receiver. The chemical enhancement technique used was a 30 minute skin pre-treatment of 50 vol% EtOH, followed by a 28 hour data acquisition period. The physical enhancement technique used was a 2 hour continuous treatment of iontophoresis using a commercially available iontophoresis delivery device. Caffeine is initially present in aqueous solution in the donor compartment, and samples are removed periodically from the receiver for spectrophotometric analysis. Chemical enhancement resulted in a 218% increase in the rate of drug delivery. Iontophoresis increased the rate by 95%. This module will be piloted in the Fall 2014 Freshman Engineering course.

**Skin - Thermoregulation**

Students often struggle with conceptualizing heat and energy, limiting their ability to enhance heat transfer. In this module, are exploring the thermoregulatory properties of skin as an example of efficient heat transfer. The skin provides a physical, albeit penetrable, barrier between the internal and external environments. As discussed above, this barrier serves to protect the internal environment of the body and to regulate bidirectional transfer of both heat and mass. This module explores the properties of heat transfer in artificial skin.

Researchers at Cornell have developed a method of generating elastomer-encapsulated networks of small channels using cotton candy[10]. We have adapted this process to mimic the capillary networks that facilitate heat transfer across the skin. Briefly, we spin cotton candy from JollyRanchers™ and then encapsulate the cotton candy “networks” into an elastomer (Sylgard 184, Dow Corning). To facilitate flow through the network, we insert caramel-filled plastic tubing into opposite sides of the elastomer. After the composite sets, we dissolve the cotton candy and caramel in a low-heat water bath. We have found that this step can be prohibitively time-consuming without the addition of heat, but we have found that an inexpensive coffee warmer and a beaker of water work well to dissolve the sugars. We are currently developing a laboratory activity for incorporation into the Fall 2014 Freshman Engineering course that will involve measuring the temperature change of heated water pumped through the artificial skin. We expect that the outcomes of this module will be to increase students’: (1) ability to explain, interpret, and classify topics in heat transfer, particularly regarding the relationships between surface area and volume in heat exchange; (2) ability to enhance heat exchange and recognize resistances to heat exchange in various systems; and (3) aptitude for modeling and simulation of heat exchange processes with complex geometries.
Despite significant advances in neurosciences, the brain remains the least understood organ, with its cognitive abilities, such as learning and recalling information, as its least understood functions. While we may need to wait for further advances in neuroscience to better understand its remarkable structure, advances in computational intelligence do allow us to mathematically model various functions of the brain. The objectives of this module are therefore to introduce the students to 1) cognitive and memory functions of the central nervous system (CNS); 2) mathematical modeling and optimization approaches, by designing artificial neural network (ANN) models that can mimic – albeit very modestly – the learning, associative memory and decision making functionality of the brain; 3) demonstrate the challenges, benefits and applications of representing complex (biological) systems with simple mathematical models, including over- and under-representing a system with such a model.

The design challenge presented to the students will include using a technical computing environment (e.g. Matlab), to design appropriate ANN models for such applications as face recognition, fingerprint identification, speech recognition, and handwritten character recognition. We will choose a different application in each offering (or for each different section) of the course. To further motivate and inspire students, the data will come from the students themselves (photos taken under different lighting conditions or obstructions, such as sunglasses, hat, etc.; their own speech while they purposely change the tone of their voice, their own handwriting, etc.).

This topic lends itself naturally to create design challenges for a variety of different applications, as well as different levels. At the lower levels, for example, the students will be taught that certain functionalities of the brain – with many interconnected neurons – can be modeled as interconnected nodes each of which simply computes a weighted sum of its inputs (see Figure 4), which constitutes the basis of an artificial neural network (ANN). They will also learn that objects (or patterns) that look alike usually belong to the same class / category, which is the essence of pattern recognition and machine learning.

Perhaps one of the most well-known, easily understood, yet surprisingly effective pattern recognition algorithms is the k-nearest neighbor model, where each unknown object that needs to be identified is labeled as the most commonly observed category of the k other known objects that are most similar to the unknown object in the Euclidean sense. The Euclidean distance metric is easy to understand and provides a mathematical mechanism of measuring similarity.

We have implemented this approach – teaching fundamentals of machine learning as a way to mimic brain’s decision making ability – through k-nearest neighbor model, with a real-world application of automated recognition of hand-written characters in Fall 2013 of our Freshman Engineering Clinic I class. The data used for this exercise consisted of over 5000 hand written characters (digits between 0 and 9), digitized on a rather crude 8-by-8 grid (Figure 6). Students were provided with a skeleton code and worked on calculating the distances between characters, finding the k-nearest neighbors of any given character (those that are most similar with respect to Euclidean distance), determine the labels of those k-neighbors, obtain their majority vote and finally declare the label to be assigned to the unknown character.
At the end of the class, students were provided with a survey that was designed to measure their level of interest in the intersection of biomedical and computational concepts. The survey asked them which fields – from a list of 10 engineering fields one of which was biomedical engineering / biotechnology - they would be interested studying now that they had one engineering class, which electives – from a list of courses that included 19 different topics, 6 of which were in the intersection of biomedical engineering, and machine learning – they would like to take as an elective, as well as which fields – from the same list above - they would be interested for a career or graduate school. There were 18 students in this class.

Of the 18 students in the class, 10 students indicated that based on the material they have seen in this class, they are now interested in biomedical fields. Presumably this number was very small or zero before students took this class, since all students came to a program that is fundamentally not biomedically oriented. On a list of 19 courses that included 6 courses that are related to biomedical engineering, artificial neural network or machine learning, 14 of the 18 students picked 3 or more such biomedical classes as the electives that they would like to take. Finally, seven of these 18 students indicated that they now consider biomedical engineering as a potential career or graduate school option. Again, since all of these students came to a non-biomedical engineering program, we conjecture that all of them got interested in this field largely in-part because of this one exercise. More insight will be provided by a survey on attitudes and interests that was taken by all freshmen students before and after their first semester. These surveys are still being analyzed.

Based on this preliminary analysis, we believe that this simple experiment had a significant impact on students, and opened a field of study that they previously did not consider, or perhaps were not even aware of.

**Muscles - Movement and Control of Movement**

Birth defects, illnesses, and injuries can lead to the loss of muscle or muscular control. The objectives of this module are: (1) to introduce students to force generation in muscles at a macroscopic level and thereby build an understanding of the mechanical advantage afforded by complementary pairing of muscles in the human body; (2) to examine the mechanical properties arising from the microscopic structure of muscle, namely the parallel organization of sarcomeres; and (3) to investigate the nervous system control of muscle movement as an example of a physiological control system.

In this module, students will be assigned an open-ended challenge to design and build an artificial arm that is capable of lifting and lowering an object of a given mass a given distance. This problem-based-learning opportunity enables the students to discover the compensatory forces in muscle extension and contraction, to assess the effect of moving the insertion point on force generation, and to compare the effective forces generated by components in series to those in parallel (like muscle fibers). These introductory investigations into the mechanics of muscle movement will be used for freshman level students, and the topic will also be incorporated into upper-level elective courses in process control. Movement is coordinated precisely by the nervous system, which acts as a controller to achieve fluid motion. Therefore, with the addition of an arm angle sensor and a computer interface to control the input, the system becomes an artificial example of a physiological control system.

**EVALUATION PLAN**

A systematic project evaluation will be carried out in a manner consistent with current recommended practices as described by NSF[11]. An external evaluator to the project will work with the PI on preparation of survey instruments to assess and evaluate the project. To date, we have begun to perform assessment of the short-term outcomes of the project.
Table 2. Logic Map for evaluation of the project

<table>
<thead>
<tr>
<th>Resources</th>
<th>Activities</th>
<th>Outputs</th>
<th>Outcomes</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Director &amp; Co-PIs</td>
<td>Develop 7 course modules</td>
<td>College faculty prepared to deliver new curricula</td>
<td>Integration across the curriculum</td>
<td># of students enrolled, retained, graduated and employed.</td>
</tr>
<tr>
<td>Module Developers</td>
<td>Incorporate Biomedical engineering into core engineering</td>
<td>Trained middle/high school teachers ready to implement engineering into their STEM curricula</td>
<td>Development plan for new faculty</td>
<td># of teachers trained level of satisfaction and competency with training</td>
</tr>
<tr>
<td>Module Teachers</td>
<td>Collect and analyze evaluation data</td>
<td># of students enrolling into single courses of the concentration</td>
<td>Increase middle/high school teachers capacity to integrate engineering</td>
<td># of students reached through teachers and lesson plans employed</td>
</tr>
<tr>
<td>Rowan students</td>
<td>Workshop material for secondary school teachers</td>
<td># of students of students showing interest in bio-engineering concentration</td>
<td>Increase retention and interest of engineering students in bioengineering concentration</td>
<td>Measurement of Self efficacy for STEM and Career aspirations (for secondary and post-secondary students)</td>
</tr>
<tr>
<td>Middle/High school teachers</td>
<td></td>
<td>Improved and newly developed STEM camps and outreach</td>
<td>Increase secondary students understanding and interest in STEM careers</td>
<td></td>
</tr>
<tr>
<td>Evaluators</td>
<td></td>
<td></td>
<td>Plan to replicate or scale regionally or nationally</td>
<td></td>
</tr>
<tr>
<td>Funding from NSF</td>
<td></td>
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</table>

A logic map for evaluation of the project is presented in Table 1. Formative evaluation will be conducted using an assessment that maps student work directly to the individual learning outcomes. The learning outcomes specifically address ABET Criteria, AIChe and program-specific goals. This will be done through pre-tests and post-tests as well as instruments such as team laboratory reports, individual in-class quizzes, oral presentations, and interactive poster presentations. Through surveys, students will assess their interest level, background preparation, level of difficulty, usefulness of the reference materials, and any suggestions they have for improvement. The formative evaluation will be used to determine whether the project is meeting its goals, and to perform continuous improvement of the project.

A summative evaluation will also be conducted. Faculty will evaluate the learning outcomes and impact of vertical integration using rubrics, students will assess the lasting impact of the modules and the effectiveness of vertical integration in a survey given with the senior exit interviews. The faculty and their department chairs will evaluate whether the project assisted in professional development, based on conference proceedings, publications and potential collaborations. A final measure of success of the project will be whether the project has been successfully adapted into other STEM programs in other colleges, universities, and G6-12 programs across the country. Broader impact of the project will be assessed via surveys of educators at G6-12 schools and universities where the materials are adopted and used.

ACKNOWLEDGEMENT

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