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Organizing the curriculum: introducing engineering principles through biomedically related experiments: Module Development

Dr. Stephanie Farrell, Rowan University

Dr. Stephanie Farrell is an associate professor of Chemical Engineering at Rowan University. She obtained her Ph.D. 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. Dr. Farrell has made significant contributions to engineering education through her work in experiential learning. She focuses 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. Dr. Farrell has conducted workshops on a variety of topics including effective teaching, inductive teaching strategies, and the use of experiments and demonstrations to enhance learning.

Prof. Jennifer Vernengo, Rowan University
Dr. Mary Staehle, Rowan University
Dr. Jennifer Kadlowec, Rowan University
Dr. Tom Merrill, Rowan University
Dr. Robi Polikar, Rowan University
Dr. Johannes Strobel, Purdue University, West Lafayette

Dr. Johannes Strobel is director of the Institute for P-12 Engineering Research and Learning (INSPIRE), and assistant professor of engineering education and learning design and technology at Purdue University. NSF and several private foundations fund his research. His research and teaching focuses on the policy of P-12 engineering, the support for teachers and students' academic achievements through engineering learning, the measurement and support of change of "habits of mind" particularly in regards to sustainability, and the use of cyber-infrastructure to sensitively and resourcefully provide access to and support learning.

Organizing the Curriculum - Introducing Core Engineering Concepts through Biomedically-related Experiments: Module Development

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.

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.[1] 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.[2]

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 faculty 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 proposed 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 undergraduate modules are being developed in year one by summer interns and teams of students in the Junior/Senior Engineering Clinic, under the supervision of the investigators. The modules will be piloted in courses at ROWAN during year two, 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.

Module 1: 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 [3]. Understanding the flow characteristics of normal and sickle cell blood is critical for finding treatments for the disease[4]. In this module, students will determine the rheological behavior of single-phase and two-phase blood analogs. The influence of fluid composition and hematocrit will be 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) explore flow parameters as a function of fluid composition and hematocrit content, and 3) relate the physiological significance of these flow parameters to sickle cell anemia.

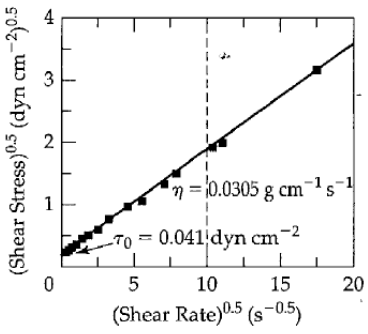

Figure 1. Shear stress versus shear rate for blood, plotted according to equation 1. Adapted from (1).

At the freshman level, students will be introduced to viscosity measurement techniques using a rotational viscometer. Blood analogs such as water/glycerol mixtures, with and without added polymeric components, have been studied previously[5] and will be explored here. Students will prepare fluids with a range of compositions and determine the power law coefficients, *m* and *n*, using a log-log plot of appar-

ent viscosity versus shear rate[6] Results can be compared to previously reported literature values for actual blood [5] and sickle cell blood[7]. As a result of this experiment, students understand the rheological behavior of macromolecules and, in particular, the phenomenon of sheer thinning, which is characteristic of blood.

In the junior-year fluid mechanics course, students will explore behavior of two-phase fluids. The presence of the cellular components of blood, predominantly RBCs, complicates its rheological behavior. The sheer thinning behavior of blood is attributed to the deformability of RBCs at high shear rates, which causes the viscosity to not only decrease, but also be less than what is obtained if rigid spherical particles are present[8]. In this activity, students can generate particles of varying rigidity using glutaraldehyde and chitosan[9], which will substitute for RBCs. The particles will be suspended in blood analog fluids and the viscosity characterized using a rotational viscometer. The Casson equation is a constitutive relation that describes the rheological behavior of two-phase fluid systems and can be applied to whole blood[10]:

$$\tau_w^{1/2} = \tau_o^{1/2} + \eta_N^{1/2}\left(-\dot{\gamma}_r\right)^{1/2}$$

where τ_o is the yield stress, $\dot{\gamma}$ is the shear rate, τ_w is the shear stress and η_N is the viscosity at high shear rates. Students will explore the effects of particle deformability and concentration by plotting data according to equation 1 and solving for τ_o and η_N. The deformability of healthy blood cells at high shear rates enables the heart to pump with less work. Through this experiment, students will relate their findings to changes in blood viscosity due to decreased flexibility of sickle cells. The body's inability to compensate for these changes is what ultimately leads to clinical manifestations of sickle cell disease.

Module 2: 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[11]. 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[12]. 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. Non-Newtonian blood analog fluids (described in Module 1) will be used in this module to simulate the shear-thinning behavior of blood.

The objectives of this hands-on module are to (1) introduce the basic function of a BO; (2) perform a material balance on the device; (3) determine the friction factor from pressure drop measurements; (4) analyze mass transfer in the membrane separator using standard performance criteria; and (5) develop mass transfer (*Sh-Re-Sc*) and friction factor (*f-Re*) correlations using parametric studies. The key engineering concepts explored in this module are: measurement of flow, pressure, and concentration; calibration; mass balances; rheology of non-Newtonian fluids, friction factor determination; evaluation of membrane performance; and mass transfer correlations. The experimental methods and analysis will be adopted from Wickramasinghe *et al.* [13]. Comsol Multiphysics, a finite element analysis tool, will be used to explore fine details regarding hollow fiber membrane performance and oxygen concentration distributions.

At the Freshman level, students will perform a mass balance on an oxygenator. In a sophomore material balances course, students will perform mass balances on the oxygenator, deoxygenator, and the overall system. In a junior fluid mechanics course, students will characterize the rheology of the blood analogue (see blood module), measure the pressure drop across the oxygenator and compare it to the predicted for a shear-thinning fluid. In the same course, students will determine the friction factor and compare it to that for water. In a ChE mass transfer course or a ME transport course, students will obtain a correlation for the mass transfer coefficient in the form

$$Sh = a\mathrm{Re}^{b}\, Sc^{c}$$

Post processing of hollow fiber membrane finite element models will explore how input variables such as flow rate, membrane thickenss, and diffusivity impact overall mass transfer coefficients.

Module 3: The Heart and Circulatory System

The heart is a double pump that circulates blood through two major pipe networks, the pulmonary and systemic circulatory systems. Unfortunately, heart failure is the leading cause of death in this country. Of the 40-50,000 people per year who might need a heart transplant, only 2,200 human hearts are available[14], and an artificial heart might be the only means for survival. The first totally artificial heart, the Jarvik heart, was received by an Israeli patient in 2000[15]. The first totally implantable artificial heart, the AbioCor, was received in 2001[16]. While most of the patients did not survive for a long time after receiving their blood pumps, these were great milestones and research to improve the artificial heart continues at a furious pace. These medical advances are complicated by ethical issues regarding intellectual property and public health policy. [17,18]

This module will introduce fluid mechanics and principles of pumps and pipe flow using a physical model of the cardiovascular system adapted from Anderson's medical teaching model. [19] The objectives of this module are (1) to explore pressure drops and frictional losses in pipes, (2) to investigate the interconversion of kinetic energy and pressure, described by the Bernoulli Equation, using a stenosis (constriction) and an aneurysm (bulge) as examples (3) to determine the significance of hydrostatic pressure effects (4) to generate pump curves for flow vs. pressure, (5) to determine the work of the heart, and (6) to simulate the cardiovascular system using HYSYS process simulator.

At the freshman level, students will investigate the flow characteristics of different pumps and design a cost-effective pulsatile flow system. They will perform a mechanical energy balance on an artificial heart using water and blood analog fluids. In a junior fluids mechanics course, students will generate pump curves for the artificial heart using experimental measurements of pressure and flow rate. In the same course, students will explore the effect of an aneurysm and stenosis on pressure and velocity. A flow visualization technique using AQ-1000 fluid and an inexpensive high speed digital camera will enable students to visualize flow patterns in aneurysms and stenoses. Using Comsol Multiphysics students will simulate aneurysms and stenoses inside simple vascular structures. This modeling will reveal high and low shear stress regions where blockages form.

Module 4: 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[20]. 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 will be determined experimentally using a vertical Franz diffusion cell as described previously[21,22]. The skin or dermal substitute will be clamped between the donor and receptor chambers. Donor phase will be composed of caf-

feine in 0.1 M phosphate buffer, and the receptor phase will be buffer alone, stirred at 400 rpm. The drug concentration as a function of time in the receptor chamber will be quantified spectrophotometrically by reading absorbance values at 273 nm. Students will construct a plot of cumulative drug concentration over time. The efficacy of known permeation enhancers, polyethylene glycol, polypropylene glycol, and mineral oil[21] will be tested. Freshman students will compare these diffusion rates to commonly used dermal substitutes, such as silicone elastomer[11]. Upper level students in the Biomedical Processes elective will design their own artificial dermis, from currently investigated materials such as gelatin-alginate blends[23] and poly(hydroxyethylmethacrylate) gels[24].

The objectives of this module are (1) to determine the release kinetics from a transdermal delivery system, (2) to apply an unsteady-state mass balance to a pseudo-steady-state membrane system, (3) to investigate the effects of permeation enhancers and dermal substitute composition on the transdermal rate of drug delivery, (4) to investigate the hydrodynamic effects on the release rate and to develop a mass transfer correlation for the system.

Module 5: Skin - Thermoregulation

Students often struggle with conceptualizing heat and energy, limiting their ability to enhance heat transfer. In this module, we will explore 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. This barrier serves to protect the internal environment of the body and to regulate bidirectional transfer of both heat and mass. This module will explore the properties of heat transfer in artificial skin; mass transfer across the skin is described in Module 4: Skin – Barrier Properties.

Figure 3. Polymer-encapsulated networks made using cotton candy

Researchers at Cornell have developed a method of generating polymer-encapsulated networks of small channels using cotton candy[25].In this module, we will adapt this process to mimic the capillary networks that facilitate heat transfer across the skin. The students will make cotton candy, encapsulate cotton candy "networks" into flat polymer sheets (Sylgard 184, Dow Corning), dissolve the cotton candy to leave a branched network of capillaries, and then measure the temperature change of heated water pumped through the artificial skin. The rate of heat transfer is proportional to the exposed surface area ($q=hA\Delta T$). Yet, students tend to equate surface area with volume, limiting their ability to enhance heat transfer by increasing surface area. Therefore, in addition to studying the heat transfer across the artificial skin, the students will also create a second skin with an unbranched channel of an approximately equal volume, and then compare the resulting heat exchange. At this level, the module can be completed by lowerclassmen in our lower-level Engineering Clinic sequence. In specialized heat transfer courses (e.g. junior-level Heat Transfer Processes), we will also incorporate: mathematical modeling and simulation of heat exchange processes, an additional source of heat under the skin to mimic the heat generated by underlying organs, and an additional surface layer of polymer that increases the resistance to heat exchange and approximates a thickened adipose layer separating the capillary vasculature and the external environment.

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.

Module 6: The Brain - Cognition and Decision Making

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 freshman and K-12 level, 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). The students will then be provided with a previously compiled ANN model, as well as properly extracted data features based on the application. They would determine the appropriate parameters of the model (number of nodes, error goal, etc.), such that once trained on a set of training examples, the ANN can identify the correct person (for face / speech recognition) or the character (for handwritten character recognition) on previously unseen validation / field data. In a senior course on Advanced Pattern Recognition, the students will learn the actual optimization techniques for designing the ANN model. They will design their own ANN models, using different types of automated classifiers, different optimization algorithms used to train the models, and generating their own data features as appropriate for the given application. The ANN models, once designed and trained on Matlab based environment, will then be implemented in hardware using simple microcomputer development kits to allow students a complete hands-on design, development and implementation experience. Once designed, an ANN implementation essentially involves a series of matrix multiplication, addition and thresholding operations, which can be easily realized with very basic programming knowledge that will also be provided within the module.

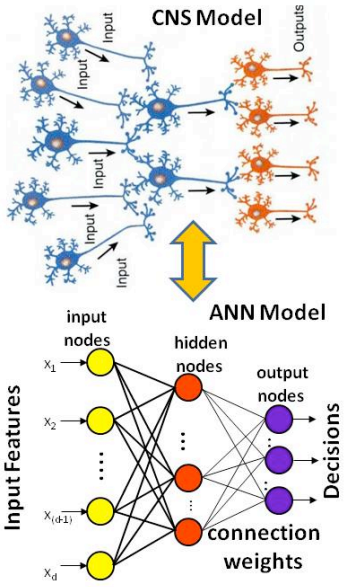

Figure 4. Comparison of central nervous system and artificial neural network decision making

Module 7: 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[26]. An external evaluator to the project will work with the PI on preparation of survey instruments to assess and evaluate the project.

Table 1. Logic Map for evaluation of the project

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

A logic map for evaluation of the project is presented in Table 1. Formative evaluation will be conducted using an assessment plan based on the rubrics developed by Newell et al. [27] will be developed to map student work directly to the individual learning outcomes. The learning outcomes specifically address ABET Criteria, AIChE and program-specific goals. Several instruments will be evaluated by faculty, including 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.

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