2006-1080: DEVELOPMENT OF EDUCATIONAL MATERIALS FOR A BIOENGINEERING FUNDAMENTALS COURSE

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Development of Educational Materials for a Bioengineering Fundamentals Course

Abstract

A significant effort has been made to develop educational materials for sophomore-level bioengineering and biomedical engineering students. The materials focus on the conservation laws and include: a textbook, a problem-based learning (PBL) module, a computer-based simulation, and a communications module.

The textbook, *Bioengineering Fundamentals,* which covers the conservation laws with applications in biological and medical systems, has been written. Its publication by Pearson-Prentice Hall is expected in 2006. The conservation laws of mass, energy, charge, and momentum form the foundation of engineering. Focusing on applications in biological systems to teach these conservation laws provides a new and unifying approach to the introductory, interdisciplinary fundamentals course in biomedical engineering departments.

Chapter 1 begins with a basic review of engineering calculations with an emphasis on elaborating physical variables, which are introduced in the context of different biomedical technologies. The fundamental framework of the conservation laws is described in Chapter 2. Chapters 3-6 cover conservation of mass, energy, charge, and momentum in biomedical systems. Each chapter begins with a challenge problem that presents a current bioengineering design challenge. Within each chapter, the accounting and conservation equations are restated and explicitly formulated for the property of interest. The derivation of Kirchhoff's current and voltage laws, Newton's laws of motions, Bernoulli's equation, and others from the key accounting and conservation equations are also presented. The text includes ten or more worked examples per chapter that span physiology, kinematics, biomaterials, cellular engineering, instrumentation, imaging, and biotechnology. Each chapter has 25-40 homework problems.

One unique feature of this textbook is the inclusion of three case studies in Chapter 7 that integrate the different conservation applications of mass, energy, charge, and momentum. The case studies include the heart, the lungs, and the kidneys. We developed a problem-based learning (PBL) module in conjunction with another university. We completed a computer simulation of the kidneys that supports the conservation concepts. Finally, we developed and implemented a communications module that improves students' communication skills, while simultaneously encouraging students to explore the emerging field of bioengineering.

The effectiveness of the textbook and students' progress toward established educational goals have been assessed over two year in several bioengineering departments across the country where the manuscript is currently being used. Based on a course impact surveys and pre- and post-tests focused on the conservation equations, statistically significant gains in acquired knowledge and problem-solving skills development were seen. The NSF Division of Undergraduate Education Course, Curriculum, and Laboratory Instruction (CCLI) program (DUE-0231313) funded this work.

Motivation

The U.S. Bureau of Labor predicts an increase of 26% by 2010 in the employment of biomedical engineers.[1] The influence of market trends as well as the increasing attention biotechnology has received in the mass media is attracting many students to the emerging, interdisciplinary field of bioengineering. The number of bioengineering and biomedical engineering departments in the United States has increased substantially during the last decade to support this growing interest. In 1995, fewer than 20 biomedical engineering departments in the U.S. were ABET accredited. In 2005, there are over 110 universities that teach courses in bioengineering or biomedical engineering to undergraduate students.[2]

At schools around the country, bioengineering is rapidly becoming a very desirable major. In 1990, less than 4,000 students were enrolled in undergraduate biomedical engineering programs; in 2003 there were over 12,000 students enrolled.[3] This increase in student interest and enrollment underscores the importance of creating excellent teaching materials for sophomore bioengineering students. The sophomore year is a critical and formative one for students as they transition from general courses in science and mathematics (chemistry, calculus) to upper-level, specialized courses in bioengineering (biomaterials, bioinstrumentation). The textbook, *Bioengineering Fundamentals*, makes a substantial and timely contribution to bioengineering and biomedical engineering undergraduate education.

The foundation courses in many engineering curricula are based on applications of conservation laws.[4] Conservation of mass and energy is typically the first course in a chemical engineering curriculum. Conservation of momentum including statics and dynamics is often the foundation course in mechanical engineering. Finally, conservation of charge provides the basis for an introduction to electrical circuits. Based on the same fundamental concepts and equations that unify all engineering curricula, *Bioengineering Fundamentals* focuses on these conservation laws and how they apply to biological and medical systems to lay a foundation for beginning bioengineers. Focusing on these applications to teach the conservation laws provides a novel approach to the sophomore-level fundamentals course in bioengineering and biomedical engineering.

Textbook: *Bioengineering Fundamentals*

The textbook is targeted to first or second semester sophomore students for use in a foundation course in a bioengineering or biomedical engineering department. Much of content of the textbook has been reported earlier.[5] College-level calculus, general chemistry, physics, biology, and some rudimentary computational skills are recommended as prerequisites. The educational goals of the textbook are designed to help bioengineering students:

1. Develop problem-formulation and problem-solving skills;
2. Develop and understand mass, momentum, charge, and energy conservation equations;
3. Apply the conservation equations to solve problems in the biological and medical sciences and to model biological and physiological systems;
4. Appreciate the types of technical challenges and opportunities in bioengineering and the rewards of an engineering approach in the life and medical sciences.

The outline of the textbook is given below.

Chapter 1	Introduction to Engineering Calculations
Chapter 2	Foundations of Conservation Principles
Chapter 3	Conservation of Mass
Chapter 4	Conservation of Energy
Chapter 5	Conservation of Charge
Chapter 6	Conservation of Momentum
Chapter 7	Case Studies

The seven chapters share many aspects in common. First, each chapter begins with a list of instructional objectives that highlight the knowledge and skills students should master during that chapter. The text contains 10-20 worked examples and 25-40 homework problems per chapter. The scope of the examples and problems covers the cellular level to the tissue level and span the breadth of modern bioengineering including physiology, biochemistry, tissue engineering, kinematics, biomaterials, biotechnology, cellular engineering, and instrumentation. While many problems have only one right answer, there are also many open-ended problems.

Chapter 1 provides motivation for a quantitative engineering approach and exposure to different bioengineering technologies and research topics. Physical variables used in accounting equation calculations are introduced in the context of bioengineering technologies and research topics. Intensive and extensive physical variables and their relevance to the conservation laws are explained. Used consistently throughout the textbook, a methodology or process for solving engineering problems is introduced. This method is similar to those found in other leading engineering textbooks.[6,7]

The fundamental framework for the conservation laws and system definitions are described in Chapter 2. Explicit discussion on isolating the system of interest and labeling the system boundary and surroundings is given. The system definitions of open, closed, isolated, reacting, non-reacting, steady-state and dynamic are illustrated with examples. The accounting equation models the movement, generation, consumption, and accumulation of an extensive property in a system of interest. Extensive properties that can be counted include mass, energy, charge, and momentum. The conservation equation is a specialized form of the accounting equation and can be applied to certain extensive properties.

The core of the textbook, Chapters 3-6, covers conservation of mass, energy, charge, and momentum, respectively, in biomedical systems. Each chapter opens with a challenge problem or focus that presents a current bioengineering research or design challenge to expose students to the many unanswered questions where further work could make an impact. Throughout Chapters 3-6, the system of interest is defined for each problem, appropriate assumptions are offered and critiqued, and the accounting or conservation equation is refined for the system of interest. A significant portion is devoted to applying these concepts to solve bioengineering problems and reducing the accounting and conservation equations to other key equations learned in previous courses. Although each of these chapters can stand alone, we highlight how the conservation laws are parallel across the four properties.

Conservation of mass is the topic of Chapter 3. The challenge problem is tissue engineering and its application for bone enhancement and replacement. The principles of mass balances are illustrated first for open, non-reacting, steady-state systems. Systems with multiple inlets and outlets and then systems with multicomponent mixtures are considered. More complex multiple-unit systems are illustrated by a two-compartment model of the kidney and by a wastewater treatment facility. Systems with chemical reactions, such as respiration, are explicitly covered. Terms such as reaction rate and fractional conversion are defined. Finally, dynamic systems such as drug delivery are addressed.

Conservation of energy is the topic of Chapter 4. The challenge problem explores different types of energy and how they may be harnessed, including renewable biomass resources. Energy balances are illustrated first for closed and isolated systems through classic thermodynamic examples such as the expansion of a gas. Significant attention is spent developing calculation strategies for changes in enthalpy due to changes in temperature, pressure and phase. Enthalpy changes associated with chemical reactions are calculated using heats of formation or combustion. Complete and incomplete respiration in the human body are given as examples. Dynamic systems include the start-up of a bioreactor and the use of basal metabolic rate to estimate weight gain.

Conservation of charge is the focus of Chapter 5. The challenge problem is neuroprosthetic devices. Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) are the reductions of the conservation of rate of charge and electrical energy for steady-state systems, respectively. Together with Ohm's law, classical examples in circuit analysis are used to illustrate KCL and KVL. Radioactive decay, acid and base dissociation, and electrochemical reactions illustrate reacting systems. The charging of a capacitor is given as an example of a dynamic system.

Conservation of linear momentum is the thrust of Chapter 6. The challenge problem is the kinematics of cycling. The derivation of equations for rigid-body statics and fluid statics from the conservation of linear momentum are shown. Example problems such as forces on the biceps and hydrostatic pressure differences between the shoulder and ankle are given. Systems with elastic and inelastic collisions are solved with Newton's third law of motion. Steady-state systems with mass flow and applied forces such as the flow through a total artificial heart are a more sophisticated application of the conservation of linear momentum. Dynamic systems, including reductions known as Newton's second law of motion and the impulse-momentum theorem, are presented. Finally, Bernoulli's equation is presented from the mechanical energy accounting equation. Friction loss and shaft work are introduced, and the application of friction losses in circulation is shown. Conservation of angular momentum is briefly reviewed in Chapter 6.

Chapter 7 contains three case studies—heart and blood circulation, lungs and a heart-lung bypass machine, and kidneys and dialysis—that are designed to bridge the applications of the mass, energy, charge, and momentum accounting and conservation equations in biomedical systems. We explicitly chose to include these systems since they had physical phenomena at both the cellular and tissue levels. Many of the problems are open-ended and require considerable research on the part of the students. This material could be used as a core or supplement material, as a project, or as the basis for large-scale problem-based learning problems.

Problem-based learning (PBL) module

Development of problem-based learning (PBL) modules using the case studies material is ongoing. Data will be presented at a later date.

Computer-based simulation

We developed a computer-based simulation module that supports the conservation concepts. Specifically, this module focuses on the kidneys and the transfer of specific chemical species such as urea through various modeled units in the kidneys. The computer models the kidney as a multi-unit system. The model shows how various parameters such as cardiac output and the size of the person affect the clearance of particular chemical species and the retention of water. This model is available at: http://www.ruf.rice.edu/~bioewhit/foundations.html .

Communications modules

The last goal was to develop communications modules that improve students' communication skills, while simultaneously encouraging students to explore the emerging field of bioengineering. In addition to attending classes and reading textbooks, bioengineering students need first-hand exposure to current engineering challenges in industrial and academic settings. They also need to explore different professional pathways. Students are encouraged to seek out internship opportunities to fulfill these needs early in their academic careers. We developed communication modules focused on these goals. The modules are available at: http://www.owlnet.rice.edu/~cainproj/courses/bioe252.html .

Module 1: For the Company Profile assignment students are prompted to select a bioengineering company or academic research program of interest and to write a one page description of its mission, products, research agenda, history, financial/management structure, and types of employment opportunities. In addition, they must provide contact information for the person they intend to write regarding an internship opportunity. Materials developed include the writing prompt and two examples of Company Profiles.

Module 2: Letters of application require students to summarize their relevant experience, define their goals, and persuade the reader of their strengths and potential as future colleagues. We have developed a sequence of materials designed to help students prepare for this task: PowerPoint lecture that explains what types of information to include and how to organize it, a mapping exercise, annotated examples of letters of application that point out strengths and weaknesses, and an editing exercise. Students submit a draft of their letter and revise it based on feedback from their instructor.

Module 3: Students explore different professional pathways through an Interviewing activity. Small groups of students interview bioengineers about their careers and educational backgrounds during a luncheon hosted on campus. The students then prepare written reports and oral presentations about the bioengineer they interviewed. Two example written profile reports have been annotated on the web with instructor comments.

Assessment

The effectiveness of the educational materials and students' progress toward the educational goals has been assessed during the 2003-2005 academic years at Rice University, Georgia Tech, and Washington State University. Two assessment tools have been used in addition to instructor comments. First, students completed a course impact survey. Second, technical problem-solving skills and the appropriate application of the conservation equations to solve problems were monitored through pre- and post-tests. The assessment has focuses largely on the textbook materials. Data from 5 semesters is presented.

One aspect of the impact survey assessed the student's perception of his/her ability to formulate and solve accounting and conservation equations in bioengineering. Students filled out part of the questionnaire during the first week of classes and completed the second part during the last week of classes. Specifically, two questions were asked:

1. Rate your overall understanding of the application of accounting and conservation equations to biological and medical problems and systems before and after this course.
   Responses ranged from 1 (highly knowledgeable) to 5 (mostly uniformed).
2. Rate your overall level of competence in engineering problem formulation and engineering problem-solving skills before and after this course.
   Responses ranged from 1 (highly competent) to 5 (mostly incompetent).

The response (mean $\pm$ standard deviation) of students to Questions 1 and 2 are shown in Tables 1 and 2, respectively. This data shows that the mean response of students before and after the course were statistically significantly different (t-test, 2-sided). Thus, students felt that their knowledge gains in the specific area of accounting and conservation equations as well as generic engineering problem-solving skills were improved during the course.

Table 1 Response to Survey Question 1

	Beginning of Semester	**End of semester**	**n**	**P value**
School 1, 2003	3.90 ± 0.62	1.45 ± 0.55	42	P<0.0001
School 2, 2003	4.22 ± 0.61	1.77 ± 0.68	22	P<0.0001
School 3, 2004	3.06 ± 0.93	2.00 ± 1.15	16	P<0.01
School 1, 2004	3.71 ± 0.86	1.69 ± 0.68	35	P<0.0001
School 3, 2005	3.25 ± 1.39	2.12 ± 0.83	8	P<0.1

Table 2 Response to Survey Question 2

	Beginning of Semester	**End of semester**	**n**	**P value**
School 1, 2003	3.86 ± 0.72	1.93 ± 0.51	42	P<0.0001
School 2, 2003	4.05 ± 0.79	2.14 ± 0.71	22	P<0.0001
School 3, 2004	3.27 ± 1.03	2.33 ± 1.04	15	P<0.05

School 1, 2004	3.83 ± 0.95	1.94 ± 0.68	35	P<0.0001
School 3, 2005	2.88 ± 0.99	1.88 ± 0.64	8	P<0.05

The second major area of assessment was the use of pre- and post-tests to evaluate technical problem-solving skills and the appropriate application of the conservation equations. In the pre- and post-test, the same two problems were given. The pre-test was administered as the first homework. The pre-test was graded for purposes of assessment; however, students received full credit for the assignment for a genuine attempt. The post-test was administered as either a homework or as an exam problem. The score of each problem is normalized to 1.0 and is reported as mean ± standard deviation. The difference in pre- and post-test values for each student was determined. A paired t-test (one-sided) was conducted to establish differences between student performance before and after the course.

The first question was the derivation of an equation describing the velocity of a fluid through a venturi meter. Students needed to apply Bernoulli's equation as well as the conservation of mass. The results of the pre- and post-tests for the first question are given in Table 3.

Table 3 Results of Technical Problem 1

	Pre-test	**Post-test**	**n**	**Post-test format**	**P value**
School 1, 2003	0.11 ± 0.09	0.84 ± 0.20	50	exam	<0.0005
School 2, 2003	0.05 ± 0.04	0.43 ± 0.27	32	exam	<0.0005
School 3, 2004	0.27 ± 0.39	0.50 ± 0.30	17	exam	<0.005
School 1, 2004	0.17 ± 0.20	0.84 ± 0.22	38	homework	<0.0005
School 3, 2005	0.35 ± 0.33	0.61 ± 0.27	11	exam	<0.0005

The second question involved a bioreactor and required the overall mass balance of material, use of the accounting equation to solve for the stoichiometric coefficients of a reaction, and the implementation of element balances to solve for the molecular weight of the produced biomass. The results of the pre- and post-tests for the second problem are given in Table 4.

Table 4 Results of Technical Problem 2

	Pre-test	**Post-test**	**n**	**Post-test format**	**P value**
School 1, 2003	0.19 ± 0.15	0.89 ± 0.18	50	homework	<0.0005
School 2, 2003	0.08 ± 0.06	0.66 ± 0.24	32	exam	<0.0005
School 3, 2004	0.36 ± 0.30	0.74 ± 0.30	17	homework	<0.0005
School 1, 2004	0.09 ± 0.05	0.90 ± 0.27	38	exam	<0.0005
School 3, 2005	0.19 ± 0.28	0.43 ± 0.29	11	homework	<0.0005

Even with the variability among post-test formats, this data clearly demonstrates that students' understanding of the application of conservation laws in biological and medical systems increased.

Summary

In summary, the textbook, *Bioengineering Fundamentals*, seeks to present the conservation laws as a new and unifying approach to the introductory, interdisciplinary fundamentals course in biomedical engineering and bioengineering departments. The development of a range of educational materials will allow for the widespread use of the materials in undergraduate programs. The National Science Foundation (NSF) under its Division of Undergraduate Education (DUE) Course, Curriculum, and Laboratory Instruction (CCLI) program has funded this work (NSF grant #DUE-0231313).

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