

Development of the Textbook, *Conservation Principles in Bioengineering*

Ann Saterbak,¹ Ka-Yiu San,¹ Larry V. McIntire²

¹ **Department of Bioengineering, Rice University, Houston TX 77005**

² **Department of Biomedical Engineering, Georgia Tech, Atlanta GA 30332**

Summary

The textbook, *Conservation Principles in Bioengineering*, which covers the conservation laws with applications in biological and medical systems, has been written. Its publication by Prentice Hall is expected in 2005. 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.

Chapters 1 and 2 provide exposure to bioengineering problems and motivation for a quantitative engineering approach. The manuscript begins with a basic review of engineering calculations with an emphasis on elaborating the 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 present a current bioengineering design challenge. Within each chapter, basic concepts are reviewed, and the accounting and conservation equations are restated and explicitly formulated for the property of interest. Open, closed, steady-state, dynamic, reacting and non-reacting systems are covered. 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 deliberately includes ten or more worked examples per chapter that span physiology, kinematics, biomaterials, cellular engineering, instrumentation, imaging, and biotechnology. Presently, 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. Problem-based learning (PBL) modules on these systems are being developed as part of a NSF Division of Undergraduate Education grant.

The effectiveness of the textbook and students' progress toward established educational goals are being assessed in several bioengineering departments across the country where the manuscript is

currently being used. Assessment evaluates knowledge acquisition and problem-solving skills development.

Motivation

The U.S. Bureau of Labor predicts a 31% increase in the employment of biomedical engineers between 2000 and 2010 [1]. The influence of market trends as well as the increasing attention biotechnology has received in the mass media are 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, only 19 Biomedical Engineering Departments in the U.S. were ABET accredited [2]. In 2004, there are over 100 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 2002 there were over 10,000 students enrolled [3]. In the next five years, it is estimated that two to three times more students per year will take bioengineering and biomedical engineering courses [4]. A substantial number of these departments are in the process of developing curriculum and course materials. This increase in student interest and enrollment underscores the importance of creating excellent teaching materials. Despite the increase in student enrollment, there are limited educational materials available to teach sophomore bioengineering students [4-5]. 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, *Conservation Principles in Bioengineering*, will make a substantial and timely contribution to bioengineering and biomedical engineering undergraduate education.

The conservation laws of mass, energy, charge and momentum form the foundation of engineering [6]. The first semester foundation courses in many engineering curricula are based on applications of conservation laws. 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. With the support of a NSF grant (1988-1994), a team of educators at Texas A&M University developed the textbook, *Conservation Principles and the Structure of Engineering* [6]. This text presents the application of the conservation equations across all engineering disciplines and is used in a cornerstone, sophomore-level course in their unified engineering curriculum. The textbook that we have written is based on the same fundamental concepts and equations. However, our text focuses on biological and medical applications that are relevant to bioengineering students. Focusing on these applications to teach the conservation laws provides a novel approach to the sophomore-level fundamentals course in bioengineering and biomedical engineering.

Several excellent textbooks that are appropriate for undergraduate students in bioengineering have been written and are used widely. A number of these focus on areas of specialization such

as bioinstrumentation, biomechanics, biochemical engineering, or biomaterials. Many of these textbooks present a form of an accounting or conservation equation as a basis for study or in the derivation of other governing equations. For example, the conservation of momentum is often presented in biomechanics and transport texts. While textbooks and educational materials are available in these specialized fields, to the best of our knowledge, no textbooks or educational materials are available that explicitly and broadly present conservation principles with applications to biology and medicine, which we feel is the most appropriate foundation for the diverse areas of study in bioengineering.

Content of the Textbook

The textbook is targeted to first or second semester sophomore students for use in a foundation course in a Bioengineering or Biomedical Engineering Department. College-level calculus, general chemistry, physics, biology, and some rudimentary computational skills are recommended as prerequisites. The engineering principles, problem-solving approach, and technical rigor make the use of these course materials a good foundation for junior- and senior-level engineering courses in transport, bioinstrumentation, biomechanics, cellular engineering, and biotechnological processes.

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. Currently, the length of the manuscript is 600 pages, including figures.

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. Finally, student misperceptions are addressed in each chapter [7].

Chapter 1 provides motivation for a quantitative engineering approach and exposure to different bioengineering technologies and research topics. First, units, dimensions, and unit conversion are reviewed. Intensive and extensive physical variables and their relevance to the conservation laws are explained. Thirty physical variables are introduced in the context of five bioengineering technologies and research topics plus one environmental system. The topics and a subset of the elaborated physical variables are listed below:

- Drug delivery for Parkinson's disease (mass, moles, mass fraction, concentration)
- Mars surface conditions (temperature, density, saturation)
- Gene transfer technology (momentum, kinetic energy, current, charge)
- Getting to and life on Mars (force, weight, pressure, heat, work)
- Microsurgical assistant (flow rates, pressure)
- Victoria Falls (rate of momentum, rate of potential energy)

A methodology or process for solving engineering problems is introduced in Chapter 1. This method is similar to those found in other leading engineering textbooks [7-8]. The four main steps in the problem-solving methodology are as follows:

1. Assemble (diagram, problem statement, selection of units)
2. Analyze (make appropriate assumptions, collect extra data, set a basis if needed)
3. Calculate (apply and simplify governing equations, calculate unknown quantities)
4. Finalize (check if answers are reasonable, state answer clearly)

This methodology for solving problems is used throughout the textbook for about 70% of the worked example problems.

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. Algebraic, differential and integral forms of the accounting and conservation equations and the rationale for using each are presented. The generic form of the accounting equation is as follows:

$$\text{Input} - \text{Output} + \text{Generation} - \text{Consumption} = \text{Accumulation} \quad [1]$$

and the generic form of the conservation equation is as follows:

$$\text{Input} - \text{Output} = \text{Accumulation} \quad [2]$$

Since a conserved property can neither be created nor destroyed, conservation equations can be written for total mass, elemental mass, linear momentum, angular momentum, net charge, and total energy. Real-life examples such as balancing a checkbook, population growth, and the drainage of water from a bathtub are given. In addition, several biomedical examples are given.

The system definitions of open, closed, isolated, reacting, non-reacting, steady-state and dynamic are illustrated with examples.

Chapters 3-6 cover 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. The challenge problem presents current work and also exposes students to the many unanswered questions where further work could make an impact. Within each chapter, basic concepts are reviewed, and the accounting and conservation laws are restated and explicitly formulated for the property of interest. Highlighted are how the conservation laws are parallel across the four properties. Throughout Chapters 3-6, explicit problem-solving strategies are presented. 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. Reinforcing the method for solving engineering problems is critical to developing problem-formulation and problem-solving skills.

Conservation of mass is the topic of Chapter 3. The challenge problem is tissue engineering and its application for bone enhancement and replacement; worked example problems include flow through a bone graft, oxygen consumption in bone, and toxin accumulation in a laboratory bone implant. 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; worked example problems include enthalpy change during photosynthesis, hydroelectric power, and photosynthesis in green plants. Potential, kinetic and internal energy and enthalpy and their rates are defined and illustrated. The movement of energy as heat and work is discussed. 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. With these tools, open, steady-state systems such as heat loss during breathing are illustrated. 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; worked example problems include a transistor sensor that converts a chemical signal to an electrical signal and modeling a neuron. Kirchhoff's Current Law is the reduction of the conservation of rate of charge for a steady-state system. Classical examples in circuit analysis are used to illustrate Kirchhoff's Current Law. 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. The electrical energy accounting statement is then developed.

The concept of resistance and Kirchhoff's Voltage Law are illustrated in several circuit examples. Analogous sections to those described above delineate examples of reacting systems and dynamic systems such as those including inductors.

Conservation of linear momentum is the thrust of Chapter 6. The challenge problem is the kinematics of cycling; worked example problems include the linear momentum of a bicycle, forces on the ankle and knee while cycling, and forces on a helmet during a crash. Different types of forces that can act on a system are noted. 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. Bernoulli's equation is given in this chapter since it is used to describe flowing systems, often in conjunction with the conservation of linear momentum equation. Friction loss and shaft work are introduced, and applications such as friction losses in circulation and bioremediation pump-and-treat are shown. Conservation of angular momentum is briefly reviewed in Chapter 6.

One unique feature of this manuscript is the inclusion of three case studies in Chapter 7 that are designed to bridge the applications of the mass, momentum, charge, and energy accounting and conservation equations in biomedical systems. The case studies include the following:

- The heart and blood circulation
- The lungs and a heart-lung bypass machine
- The kidneys and dialysis

We explicitly chose to include these systems since they had physical phenomena at both the cellular and tissue levels. Three worked examples are included in each case study in addition to appropriate physiological background. Each has 10-20 homework problems; many of the homework problems are very open-ended and require considerable research on the part of the students.

Assessment

The effectiveness of the educational materials and students' progress toward the educational goals are being assessed at three universities - Rice University, Georgia Tech, and Washington State University - during the 2003-2004 academic year. Two assessment tools are being used in addition to instructor comments. First, students are completing a course impact survey. Second, technical problem-solving skills and the appropriate application of the conservation equations to solve problems are being monitored through pre- and post-tests. Data from fall 2003 from Rice University are presented in this paper; data from Georgia Tech and Washington State University will be presented later.

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. At Rice University, the course using this textbook is BIOE 252. Students filled out part of the questionnaire during the first week of classes and completed the second part during the last week of classes. Forty-two responses were received. 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 BIOE 252.
Responses ranged from 1 (highly knowledgeable) to 5 (mostly unformed).
2. Rate your overall level of competence in engineering problem formulation and engineering problem-solving skills before and after BIOE 252.
Responses ranged from 1 (highly competent) to 5 (mostly incompetent).

The response (mean \pm stdev) of students to Question 1 at the beginning of the semester was 3.9 ± 0.7 . The response of students at the end of the semester was 1.4 ± 0.6 . This data shows that the mean response of students before and after the course were statistically significantly different (t-test, $p < 0.0001$). In all cases, student's perception of his/her understanding of the application of accounting and conservation equations increased. Most students (37 of 42) felt the understanding increased by two or three levels.

The response (mean \pm stdev) of students to Question 2 at the beginning of the semester was 3.9 ± 0.7 . The response of students at the end of the semester was 2.0 ± 0.6 . This data shows that the mean response of students before and after the course were statistically significantly different (t-test, $p < 0.0001$). Forty of the 42 students felt their level of competence in engineering problem formulation and engineering problem-solving skills increased. Students recognized that while competence in both areas had increased, knowledge gains in the specific area of accounting and conservation equations was greater than in generic engineering problem-solving skills (t-test, $p < 0.0001$).

A second aspect of the impact survey was to evaluate the effectiveness of the various teaching materials and tools. This aspect of the survey was completed the end of the course. Specifically, two questions were asked:

3. How effective were the following materials and activities in teaching the application of accounting and conservation equations in biological and medical systems?
Responses ranged from 1 (very effective) to 6 (very ineffective).
4. How effective were the following materials and activities in building engineering problem formulation and engineering problem-solving skills?
Responses ranged from 1 (very effective) to 6 (very ineffective).

The students assessed nine different teaching materials and learning modes. The mean response of the effectiveness of each of the teaching materials in relation to the two questions above is summarized in Table 1.

Table 1

Range of Mean Response	Question 3	Question 4
<1.5	Homework problems	
>1.5-2.0	Lectures	Homework problems Design project
>2.0-2.5	Interaction with course instructor Design project Example problems in textbook Textbook (course notes)	Example problems in textbook Lectures Interaction with course instructor Interaction with other students Textbook (course notes)
>2.5-3.0	Challenge problems Case studies Interaction with other students	
>3.0		Challenge problems Case studies

These results show that well-written homework problems, effective lectures and meaningful design projects have the greatest impact on student learning in BIOE 252. The textbook (course notes) and its example problems as well as interactions with fellow classmates and the instructors were of moderate value in student learning in BIOE 252. Finally, the challenge problems and the case studies were not as effective for student learning. Either the developed material is poor or, as instructors, we are not using this material effectively. Certainly these results point to areas for improvement.

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 first test 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. On the pre-test, none of the students correctly solved this problem, although a few did have the correct process for several of the parts. On the post-test (final exam), 28 of 53 students earned full credit on this problem. Eighteen students earned 75-99% credit, while only seven students earned less than 75%. The second test 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. On the pre-test, one student correctly solved the problem. On the post-test (final homework), 25 of 51 students correctly solved this problem; 21 others had the essence of the problem correct but made a sign or algebra mistake. This data demonstrates that students learned the basic concepts regarding the application of conservation laws in biological and medical systems.

Future Directions

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). The major deliverables of that grant are as follows:

- Completion of the textbook, including the homework and example problems, and a solutions manual.
- Development of problem-based learning (PBL) modules using the case studies material.
- Development of a computer-based simulation module that support the conservation concepts.
- A communications module that improves students' communication skills, while simultaneously encouraging students to explore the emerging field of bioengineering.

Work will continue along these lines with a goal to complete the textbook by August 2004. Publication of the textbook is expected by January 2005. The PBL modules will be developed during the summer of 2004 and will be utilized in the 2004-2005 academic year. Other materials including the computer-based simulations and the communications module will be available on the web by August 2004.

In summary, the textbook, *Conservation Principles in Bioengineering*, 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.

References

- [1] www.whitaker.org/glance/outlook.html
- [2] <http://www.whitaker.org/academic/>
- [3] www.whitaker.org/glance/enrollments.html#undergraduate
- [4] Dorothy Marrero, Acquisitions Editor for Prentice Hall (Upper Saddle River, NJ). Personal communication: May 27, 2002.
- [5] www.whitaker.org/grants/textbook.html
- [6] Glover, C., K.M. Lunsford, J.A. Fleming *Conservation Principles and the Structure of Engineering*, 4th Edition. McGraw-Hill Inc., New York, 1994, 751 pp.
- [7] Slotta, J.D., M.T.H. Chi, E. Joram. "Assessing Students' Misclassification of Physics Concepts: An Ontological Basis for Conceptual Change." *Cognition and Instruction*, 1995, **13(3)**:373-400.
- [8] Doran, P.M. *Bioprocess Engineering Principles*. Academic Press Inc., San Diego, CA, 1999, 439 pp.
- [9] Felder, R.M., R.W. Rousseau. *Elementary Principles of Chemical Processes*, 3rd Edition. John Wiley and Sons, Inc., New York, 2000, 675 pp.

Biographical Information

ANN SATERBAK

Ann Saterbak is Director of Laboratory Instruction and Lecturer in the Bioengineering Department at Rice University. She received her B.A. in Chemical Engineering and Biochemistry from Rice University in 1990 and her Ph.D. in Chemical Engineering from the University of Illinois in Urbana-Champaign in 1995. She conducted research and provided technical support within Shell Development Company from 1995 to 1999.

KA-YIU SAN

Dr. San is a professor in the Departments of Bioengineering and Chemical Engineering at Rice University. Dr. San received his B.S. degree in chemical engineering from Rice University in 1978 and his M.S. and Ph.D. degrees in chemical engineering from the California Institute of Technology in 1981 and 1984, respectively. His research interests include genetic and metabolic engineering of microbial and plant cells, and modeling and optimization of bioreactors.

LARRY V. MCINTIRE

Dr. McIntire is Professor and Chair of the Biomedical Engineering Department at Georgia Institute of Technology. Dr. McIntire received his B.Ch.E. and M.S. degrees in chemical engineering from Cornell University in 1966 and his Ph.D. degree in chemical engineering from Princeton University in 1970. Dr. McIntire has edited two texts: *Biotechnology - Science, Engineering and Ethical Challenges for the Twenty-First Century* [Joseph Henry Press (NAS), 1996] and *Frontiers in Tissue Engineering* [Pergamon-Elsevier Science Ltd., 1998].