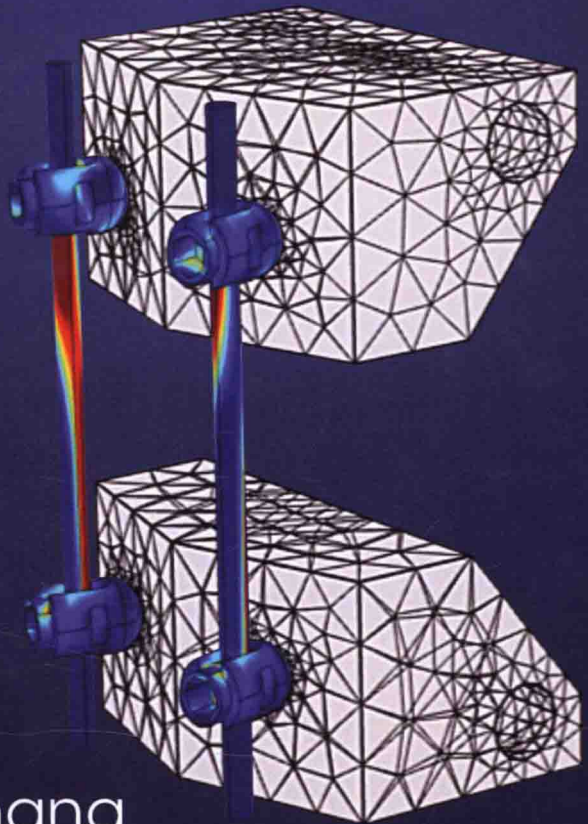




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Introduction to Integrative Engineering

A Computational Approach
to Biomedical Problems



Guigen Zhang

Introduction to **Integrative Engineering**

A Computational Approach to Biomedical Problems

This textbook is designed as an introductory course for junior and senior undergraduates and graduates alike. It aims to facilitate transdisciplinary learning through consolidation of commonalities in compartmentalized disciplines, develop deep understandings of how the "intricate machinery" of computational modeling operates, and pave the groundwork toward integrative engineering with the assistance of a computational investigative tool for problem-solving, inventing, hypothesis-testing, designing, prototyping, and testing.

Several special features:

- Highlights the connections among real-world problems, governing differential equations, computational ways of equation solving, and modeling implementation and practices
- Introduces basic concepts of multidiscipline-based computational modeling methods with detailed step-by-step techniques to build models with consideration of underlying multiphysics
- Discusses important aspects of a modeling approach including results interpretation, validation, and assessment
- Incorporates case studies of real-world relevance to biomedical care and regulatory science
- Suits both new and experienced researchers
- Text has been thoroughly class tested at appropriate courses at Clemson University



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INTRODUCTION TO INTEGRATIVE ENGINEERING

I would like to dedicate this book to my parents, from whom I learned the importance of learning how beyond learning that at a very young age (although I did not know the exact literary terms back then), and to my wife, for keeping me in check all these years whenever I wandered into foolishness.

Preface

This book has been developed based on my years of firsthand experiences in teaching *computational modeling of multidisciplinary problems* with the motivation to encourage transdisciplinary learning, integrative thinking, and holistic problem solving. The structure of this book is shaped by my philosophic views toward learning and teaching. These views include mainly that (1) an integrative transdisciplinary approach, rather than a reductive compartmentalized one, should be pursued in today's teaching and learning in order to equip students and engineers to take on the twenty-first-century challenges and (2) knowing how our minds function differently in *learning that* and *learning how*, it is feasible to devise ways to stimulate *learning how* besides *learning that* to cultivate and develop critical and creative minds in students within the time frame of current curricula.

With its sight set on encouraging *learning how*, this book introduces a systemic look into the blackbox of how the engineering world is linked to differential equations, and how these differential equations are solved by computer-based approximate methods through domain discretization, field quantity interpolations, weighted integral of residue evaluations, linearization of differential equations into matrix algebraic equations, Gauss quadrature and numerical integrations, and minimization of approximation errors, among other topics.

Through hands-on experiences in the process of *learning that* and developing crucial hard skills, students and readers will find it not only feasible but also practical to examine and solve engineering problems in a holistic way by taking advantage of a computational tool. With this approach, real-world problems exhibiting mechanical, electrical, thermal, electrochemical, and mass transport phenomena, either individually or combined, will be dealt with in a coupled multidisciplinary (i.e., transdisciplinary) way, rather than in the conventional single-discipline (i.e., compartmentalized disciplinary) way. I hope that this practice, in the long run, will help set future modelers and engineers on a journey of integrative learning and problem solving.

Although this book will discuss procedures used in the finite element method (FEM), it is not like any other books on FEM. It aims to introduce a computational modeling approach based on FEM for facilitating integrative learning through consolidation of commonalities in various compartmentalized disciplines, and for gaining a deep understanding of how this “intricate machinery” of computational modeling operates to encourage *learning how*

beyond *learning that*. It aims to pave some groundwork toward restructuring the engineering curriculum with the assistance of a computational modeling-based investigative tool, to promote integrative thinking and transdisciplinary reasoning in hypothesis testing, problem solving, inventing, designing, prototyping, and testing, among others, for the generation of novel solutions and cultivation of senses of unlimited possibilities in engineering research and industrial R&D activities. Such a journey is, of course, expected to be a long road. In its first edition, this book aims to lay the foundation. In future revisions, more and more integrated problems as case studies will be presented and discussed.

This book is designed for junior and senior undergraduate students in bioengineering and other related fields of engineering and applied sciences, and graduate students and practicing engineers in industry R&D labs and other consultancies. It was developed to suit the needs of not only novice modelers but also experienced ones. It is necessary that the reader has some basic understanding of elementary calculus and differential equations. Some knowledge with one or more of the following science and engineering disciplines would also be helpful: physics; chemistry; computer science; mechanical, electrical, chemical, biomedical, and materials science; and electrochemical, civil, and environmental engineering.

This book is structured in four parts. In Part I, the need for converting from a compartmentalized disciplinary to a transdisciplinary approach in education is argued for, for the purpose of promoting integrative rather than reductive learning. In Part II, a systemic discussion on the ins and outs of computational modeling procedures is presented, starting from the facts that the engineering world is linked to differential equations; where differential equations come from; how they are solved by computer-based approximate methods through domain discretization, field quantity interpolation, weighted integral of residue evaluations, and linearization of differential equations into matrix algebraic equations; how numerical integrations are performed using Gauss quadrature; and how minimization of approximation errors is ensured, among others. In Part III, the modeling environments of some common software, including COMSOL, ABAQUS, and ANSYS, are discussed, with the connections between software settings and the FEM fundamentals highlighted. Moreover, methods to develop hands-on practical skills in performing computational modeling and practical issues concerning image-based modeling, as well as the standardization and regulatory processes, are discussed. In Part IV, useful knowledge in the mechanics of materials and mathematics is provided as extra “just-in-time” learning and referencing materials.

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Acknowledgments

My interest in promoting *integrative engineering* did not come from any engineering textbooks. Instead, it came from my curious reading of articles in business, management, philosophy, history, and other engineering profession-related works over the years. For example, the writings by Mencius, Daisetz Suzuki, Gilbert Ryle, Peter Drucker, James March, Roger Martin, and Samuel Florman played certain roles in shaping my views toward learning and innovation in relation to engineering. Moreover, my active participation in *advancing engineering education in a liberal arts environment* at the University of Georgia, Athens, in the early 2000s (while I was on the faculty there) also helped shape my views.

My motivation for writing this textbook is to reflect the ideas I have developed over the years in my journey of searching for a practical strategy to update engineering curricula and make them relevant to our time. I developed it in the spirit of encouraging integrative learning, questioning, hypothesis testing, problem solving, inventing, designing, prototyping, and testing by linking commonalities across compartmentalized disciplines based on the underlying mathematics for the generation of novel solutions and cultivation of senses of limitless possibilities in engineering research and industrial R&D activities. Moreover, I structured it to promote transdisciplinary reasoning and encourage *learning how* besides *learning that*. It is my hope that such an integrative approach will also help make some curricular room for incorporating more relevant content of liberal arts and humanities in the engineering curricula.

As you will note from reading the book, iconic figures like Steve Jobs also had some influence on me, not just in the words I quoted from him, but also in his elegance to instill artistic beauty in whatever he touched. In my way of imitating, I pushed myself to learn and create my own graphic illustrations throughout the book to convey, with visualization, many of the mathematic and engineering concepts from a teacher's perspective. Of course, this is only possible thanks to the open-source codes of LaTeX and companion packages such as TikZ and PGF, allowing me to create illustrative graphics using mathematic equations (my way of linking math and engineering to graphic arts).

Many of the examples discussed in Chapters 14 through 16 are works of collaborations with many colleagues, associates, postdocs, graduate students, and undergraduate students. Although there are too many to list, I would particularly like to thank Mark Haidekker, Andrew Zhang, and Yutaka Takahashi

for their contributions and constructive discussions on the denture project; Walter Schmidt (the hip and knee projects); Samuel Bearden (the spine project); Mike Jaeggli (the stent project); Larry Alvord, Jordan Hall, David Keyes, Courtney Morgan, and Lynn Winterton (the cornea project); and all the students in my classes over the years for their constructive feedback and suggestions.

Author

Guigen Zhang, PhD, is a professor of bioengineering and a professor of electrical and computer engineering at Clemson University, South Carolina. He is also the executive director of the Institute for Biological Interfaces of Engineering, a research and education/training institute designated by the South Carolina Commission on Higher Education. Professor Zhang is a fellow of the American Institute for Medical and Biological Engineering. He has published extensively in the areas of biosensors, biomechanics, biomaterials, and computational modeling. Over the years, his research has been funded by diverse funding sources, ranging from federal agencies such as the National Institutes of Health and National Science Foundation, to private foundations like the Bill and Melinda Gates Foundation, to venture groups and state-level start-up funds, as well as industries in the health care, semiconductors, and data storage sectors. Professor Zhang holds numerous patents in nanotechnology-enhanced structures and biosensors. Aside from his services on the editorial boards of numerous scientific journals, Professor Zhang is active in leadership roles in professional societies. He is currently the executive editor of the Biomaterials Forum of the Society for Biomaterials, and president of the Institute of Biological Engineering, a professional society that supports the community of scientists and engineers who are at the forefront of creating new linkages between biology and engineering and seeking new opportunities through *biology-inspired* engineering.

