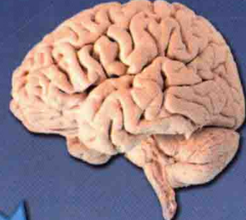
SECOND EDITION

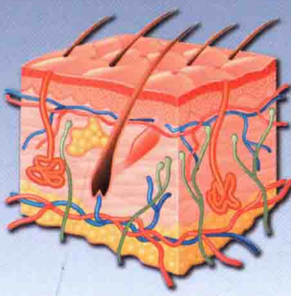
HEAT AND MASS TRANSFER

A Biological Context

Defining the Problem



Selecting the Appropriate Approach



Implementing the Solution

Interpreting the Solution

ASHIM K. DATTA

CRC Press
Taylor & Francis Group

BIOMEDICAL SCIENCE

SECOND EDITION

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A Biological Context

ASHIM K. DATTA

This is a major revision of a highly regarded primary text that incorporates a practical and easy to follow overview of heat and mass transfer principles and concepts. These are illustrated within a broad context, including medicine, drug development, food, plant, soil, earth and the environment. While these applications are captured in over 300 problems derived from important, real-world scenarios, the focus is on the principles of heat and mass transfer and on engineering problem solving that is even more broadly applicable. Consequently, key benefits of this new edition are as follows:

- This book takes on the challenge of providing a systematic approach to learning problem solving; a template that is useful not just in heat and mass transfer, but in other areas of engineering and science.
- Provides 300+ interesting application problems over a broad biological context (biomedical, bioenvironmental and bioprocessing) which the author has mostly created from scratch based on published research papers, which he has developed over the past 15 years.
- Solved examples are added for each subsection that follow the same template for problem solving throughout, serving two purposes: 1) taking the student deeper into the physical understanding and 2) providing more practice with the templates for problem solving.
- Answers to every problem included, something students have consistently requested.
- Additional items that help the student review the material—types of problems possible, short questions that test conceptual understanding.

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HEAT AND MASS TRANSFER
A Biological Context

SECOND EDITION

To my parents

Atindra Nath Dutta
and
Bela Rani Dutta

the topics of a chapter relate to each other and step-by-step instructions for solving various types of problems should improve the students' problem solving ability significantly and cross over to other subjects.

- While having many more application problems is a good idea, students need to see more solved problems following the problem solving template. This makes the problem solving process less abstract, shows a range of problem types and their nuances and also provides practice in using the problem solving template so that students internalize it. Over 25 solved problems have been developed that use the problem solving template—this covers almost every topic in the book. The template includes an "Evaluating and Interpreting the Solution" step that takes the student deeper into what we learn from the solution.
- Helping the typical (as opposed to the gifted) student excel guided the changes. In addition to assistance with approaches to problem solving, the students also want ways to verify their skills. Answers to all problems are now included at the back—to help the student do problems on his/her own. To help the student develop an eye for problem solving, the contents of each chapter also have been organized in a "Problem Solving" section in terms of the types of problems one can expect to solve in each chapter.
- Problem formulation—making connections between mathematics and the physical problem—is another challenge. Without making this connection, the learner may be doing just the math problem and not the engineering problem. Detailed step-by-step instructions, along with examples, have been developed for problem formulation that show how to take a physical (biological) process and simplify it to a domain with its governing equation and boundary conditions.

Using this book: The solved examples show not just the solution but the logic behind approaching the solution. For every such solved example, the student should pay particular attention to step 2, "Generating and selecting among alternate solutions," and the related problem solving map provided in the chapter. In addition, the section at the end of every chapter dedicated to problem solving discusses all the possible types of problems that can be solved using the contents of the chapter and how to approach each type of problem. The student is strongly encouraged to apply the problem solving logic to try the many problems provided at the end of each chapter. Additional pointers on using the book can be found on page xxiii.

I have been able to significantly enhance teaching and learning in my course using the developments mentioned in the above paragraphs that led me to incorporate them in the text. I sincerely wish the same will be true for others using the book.

Ashim K. Datta, Ithaca, New York

PREFACE

It is very important to give the undergraduate engineer a fundamental education in the context of his/her likely application areas. Transport of energy and mass is fundamental to many biological and environmental processes (see pages xxix to xxxv). Areas from food processing to thermal design of buildings to biomedical devices to pollution control and global warming require knowledge of how energy and mass can be transported through materials. These wide-ranging applications have become part of emerging curricula in biological engineering, and societies such as the Institute of Biological Engineering and the American Society of Agricultural Engineers have recognized the need for a course (and a text) that presents fundamentals while integrating the diverse subject matter.

The basic transport mechanisms of many of these processes are diffusion (or diffusion-like, such as capillary and dispersion) and bulk flow. Additionally, there is radiative heat transfer. It is crucial for the student to see these concepts as comprehensive and unified subject matter (much like fluid mechanics); they are the building blocks for lifelong learning in many of their interest areas. Such a fundamentals-based approach will replace the more empirical and ad hoc teaching that sometimes exists.

Although the concept of teaching transport processes as a unified subject has existed for over forty years in some engineering disciplines, only in recent years have we seen adequate quantitative studies to make such teaching possible in biological and bioenvironmental processes. This book attempts to bring together under one umbrella the unique content, contexts, and parameter regimes of biologically related processes and to emphasize principles and not just mathematical analysis. *Content*, such as bioheat transfer, thermoregulation, freezing, global warming, capillary flow, and dispersion, are some of the topics not typically included in the undergraduate-level teaching of transport phenomena. *Context*, such as plants, animals, water, soil, and air, is important at this level, because without this information students have an unnecessarily hard time relating to real physical processes. Context also helps students learn about the physical processes themselves in a quantitative way. For example, studying convective transfer of water vapor over a leaf includes a quantitative introduction to transpiration.

(The present text was created by distilling the content of hundreds of research papers and textbooks on similar biological and environmental applications.) The *parameter regimes* of biological processes are also different from those of typical mechanical and chemical processes. For example, biological processes often involve a source term of heat generation or oxygen consumption. The presence of the source or sink term changes the nature of the solution and is emphasized in this text.

How This Book Fits in a Biological Engineering Curriculum

This text is intended for a junior-level engineering science course in curricula that emphasize biology and the environment. The course would build on the prerequisites of partial differential equations and fluid mechanics. Prior knowledge of biological and environmental science, although not required, would be useful. For example, this course can readily build on a course such as Thermodynamics of Biological Systems that has been discussed in the context of a biological engineering curriculum. Mass and heat transfer, much like fluid flow, are just as much building blocks for many of the upper-level courses. Thus, specialized design courses and advanced courses such as bioprocessing, biomedical engineering, food process engineering, environmental processes and their control, and waste management can build on a course that uses this text, greatly reducing the need to teach basic engineering science of mass and heat transfer in these upper-level courses. This text was developed at Cornell University for a junior-level engineering science course.

Approach and Organization of the Book

The overall organization of the book follows the well-tested transport phenomena approach. The chapters and their content on heat and mass transfer are made to follow an almost exact parallel, as shown in the table below. The first two chapters in each part (Part I, "Energy Transfer" and Part II, "Mass Transfer") develop the two building blocks of conservation laws and rate laws, and the next chapter (Chapters 3 and 11) combines them to build the general governing equations and boundary conditions. The next two chapters in each part (as shown in the table below) cover steady-state or transient diffusion, without any flow, while the last one adds the effect of flow. Chapter 7 covers heat transfer with change of phase, and Chapter 8 covers radiative energy transfer. Porous media flow and simple kinetics of zero and first order are included for completeness as they relate to transport. An effort has been made to clarify important processes such as dispersion. Different application areas in biology and environment are included within this framework of chapters, when they are relevant.

	Chapter number	
	Energy	Mass
Conservation	1	9
Rate laws	2	10
Governing equation	3	11
Diffusion, steady-state	4	12
Diffusion, transient	5	13
Diffusion (and dispersion) with bulk flow	6	14

How to Use This Book

Students frequently follow individual topics well but have difficulty seeing their relatedness, i.e., the big picture. Thus, a major effort has been made to distill the concepts presented here and to show the connections among chapters. Each chapter begins with a small list of major concepts to be covered, together with important terminologies introduced in that chapter, and each chapter has a map showing how all chapters are interconnected in terms of the topic under consideration. Each chapter has a summary at the end that puts every major concept and equation at the reader's fingertips, providing page numbers for easy access, and a set of descriptive questions checks the reader's understanding of concepts and facts. Summary maps in Appendix A (pages 544–547) show the integration of all the scenarios covered in the text. The first-time reader of the subject is strongly encouraged to use these features.

As curricula in biological and related engineering programs evolve, the core of such curricula will include mass and heat transfer as essential building blocks in students' instruction in a natural and obvious way. The author sincerely hopes that this text will serve the needs of these curricula. He also believes that the text must evolve with the curricula. Additional materials helpful for teaching this subject matter can be seen on the Internet at www.ashimdatta.net. Please do not hesitate to contact the author if you have comments on any aspect of the book.

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INTRODUCTION

Problem Solving in the Transport Processes

This book centers around solving problems in energy and mass transfer in a biological (Biomedical/Plant/Bioprocessing/Bioenvironment) context. Starting from a biological process (Figure 1), after making sufficient assumptions, we formulate it as a mathe-

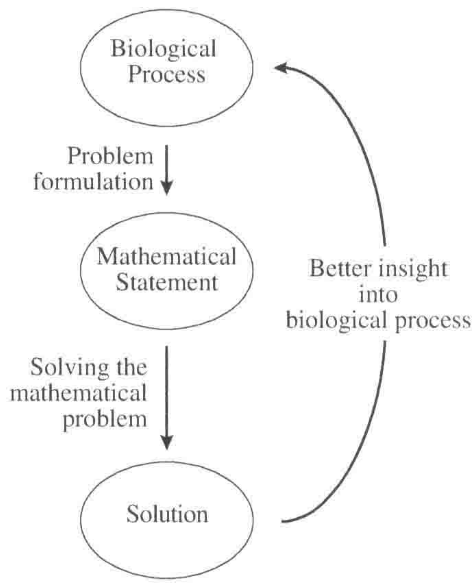

Figure 1: Schematic showing the steps of problem formulation and solution.