PHYSICS of the Life Sciences

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About the Author

Jay Newman is the R. Gordon Gould Professor of Physics at Union College where he has taught for 30 years. While studying for his PhD in physics at New York University, he developed a keen interest in biophysics and did a three-year postdoctoral fellowship in the Biophysics Department of Johns Hopkins University. Since joining the faculty at Union College, Professor Newman has taught and developed more than 15 different courses, led student terms abroad in science research in Italy, and also spent a year at Stanford University. The experiences abroad with students stemmed from his previous stays as a Visiting Professor in Italy, once in Pavia and six times in Palermo.

His research has been on the structure, dynamics and interactions of biomolecules using laser light scattering and other physical methods. He has 60 publications, many co-authored with some of the 30 plus undergraduate students who have done research projects in his laboratory, and has received two grants from the Research Corporation and five multiyear grants from the National Science Foundation for both research and teaching.

About 15 years ago, he developed a special introductory physics course for life science students at Union College, which was the basis for this text. The idea behind the course and this book is to show the essential connections between physics and modern life sciences. Motivating this new approach to an introductory course was Professor Newman's firm belief, developed over his early training and now reinforced by almost daily news reports, that modern biology and medicine are becoming ever more quantitative and dependent on an understanding of physics fundamentals, methodology, technology, and modes of thinking. Building this bridge is the purpose and goal of *Physics of the Life Sciences*.

Preface

This textbook has its origins in a course that I began developing at Union College in the mid-1980s to teach physics to life science students in a way that would interest them and show the connections of fundamental physics to modern biology and medicine. From my own research experiences and interests in biophysics, I know that almost all areas of modern life sciences integrally involve physics in both experimental techniques and in basic understanding of process or function. However, I and many colleagues with whom I have spoken have been unhappy over the years with published attempts to direct a textbook to this audience. Most such texts are watered down engineering physics books with occasional added sections on related biology topics that are easy to skip over or assign students to read on their own.

As I set out to write this textbook, I had certain definite goals in mind. I wanted to write a book that was truly directed at life science students, one that integrated modern biology, biophysics, and medical techniques into the presentation of the material. Believing in the *less is more* credo, I chose to omit certain standard topics that are usually included in texts for this audience, while expanding on topics that have more relevance to the life and biomedical sciences. From my experience teaching to these students, I also wanted a book that would be shorter and could be fully covered in a two-semester course. Although students at Union College and comparable institutions taking this introductory course have all had some calculus, only algebra and trigonometry are used in the main body of the text. At this level, I believe that calculus adds little to the understanding of the material and can detract from focusing on the basic physical ideas. However, I have sprinkled in optional boxed calculations that do use some calculus where I felt they truly added to the discussion (averaging less than one box per chapter). These "sidebars" can be omitted without any loss of continuity.

The order of topics for this text follows a more or less traditional sequence. An exception to this is the presentation of one-dimensional mechanics through forces and energy before introducing vectors and generalizing to motion in more than one dimension. This allows students to focus on the physics concepts of kinematics, forces, and energy without being distracted by the ideas of vector analysis.

Beyond the order of topics, the presentation of material is unique in that, wherever possible, themes from biology or medicine are used to present the physics material. The material speaks to life science students. Rather than optional sections at the end of occasional chapters, life science themes are plentiful and integral to the text. The role of these topics here is more fundamental, as can be gleaned from a list of some examples.

- The early introduction of diffusion as an example of motion (full section in Chapter 2).
- The early introduction of motion in a viscous fluid as an example of one-dimensional motion, development of Hooke's law and elasticity with applications to biomaterials and viscoelasticity, protein structure, and molecular dynamics calculations (all in Chapter 3).
- Discussion of centrifugation in Chapter 5.

- Examples of rotational motion kinematics of a bacteria and of a rotary motor protein, the atomic force microscope, rotational diffusion, and cell membrane dynamics (all in Chapter 7).
- A chapter (9) on viscous fluids with discussions of blood, other complex fluids, the human circulatory system, surface tension, and capillarity.
- A chapter (11) on sound with extensive discussions on the ear and on ultrasound.
- A chapter (13) with a molecular discussion of entropy, a section on Gibbs free energy, a section on biological applications of statistical thermodynamics, and a section on biological applications of nonlinear dynamics.
- Chapters (14–15) on electric forces, fields, and energy with sections on electrophoresis, macromolecular charges in solution, modern electrophoresis methods, electrostatic applications to native and synthetic macromolecules, an introduction to capacitors entirely through a discussion of cell membranes, and sections on membrane channels and electric potential mapping of the human body: heart, muscle, and brain.
- A chapter (16) on electric current and cell membranes covering circuits through membrane models: included are sections on membrane electrical currents, an overview of nerve structure and function including measurement techniques such as patch-clamping, the electrical properties of neurons, and a second section on membrane channels with a discussion of single-channel recording.
- Chapters on electromagnetic induction and waves (18–19) that include discussion of MEG (magnetoencephalography) using SQUIDs, an entire section on NMR, and sections on magnetic resonance imaging, laser tweezers, the quantum theory of radiation concepts (revisited later), and the interaction of radiation with matter, the last a primer on spectroscopy, including absorption spectroscopy, scattering, and fluorescence.
- Four chapters (20–23) on optics include a section on optical fibers and their applications in medicine, a section on the human eye, sections on the new light microscopies (dark field, fluorescence, phase contrast, DIC, confocal and multiphoton methods), discussion of polarization in biology, including birefringence and dichroism techniques, and sections on the transmission electron microscope, scanning EM and scanning transmission EM, and x-rays and computed tomography (CT) methods.
- Three chapters (24–26) on modern physics (many of these ideas have been introduced and used throughout the book) include discussions of the scanning tunneling microscope, a section on the laser and its applications in biology and medicine, including holography. The chapter on nuclear physics and medical applications (26) includes sections on dosimetry and biological effects of radiation, radioisotopes, and nuclear medicine, and the medical imaging methods SPECT (single photon emission computer tomography) and PET (positron emission tomography).

As mentioned above, we've chosen to omit some standard topics that are either not central to the life science themes or that students find very opaque. Omitted are such topics as Kepler's laws, heat engines, induction and LR/LRC circuits, AC circuits, special relativity kinematics, particle physics, and astrophysics; Gauss's law and Ampere's law are presented in optional sections at the end of appropriate chapters.

Each chapter contains three types of learning aides for the student: open-ended questions, multiple-choice questions, and quantitative problems. In about 60 of these per chapter, we have tried to include a wide selection related to the life sciences. Complete solutions to all of the multiple choice and other problems are available to instructors. There are also a number of worked examples in the chapters, averaging over six per chapter, and about 900 photos and line drawings to illustrate concepts in the text, with many in full color.

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Acknowledgments

First I'd like to thank the American Institute of Physics Press and both Maria Taylor and Elias Greenbaum for suggesting this project and providing a grant that gave me most of a year free from teaching to start writing this textbook. I've benefited greatly from collaborations with three colleagues on its development. David Peak, a former Union College colleague now at Utah State, edited portions of the manuscript and made many suggestions on the presentation of the material. Larry Brehm, formerly at IBM and now at SUNY Potsdam, contributed to the end-of-chapter problems for a number of the chapters, particularly in the mechanics and optics portions. Scott LaBrake, at Union College, checked and solved all the problems in the book, and wrote the solutions manual, as well as taught from preliminary editions of the book.

Thanks also to the many students who learned their introductory physics from preliminary versions of this text and put up with typographical errors and occasional unsolvable problems. Some of these students worked through essentially all the problems in the book helping to find errors as well. I also thank my colleagues at Union College for their interest and support in this project and for numerous discussions about physics pedagogy.

The staff at Springer, including David Packer, Anushka Hosain, and all the production team, has been most helpful in seeing this project to fruition.

Finally, I thank my extended family for their support, encouragement, and love over these many years, especially my wife, Maia.

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1. SCIENCE, PHYSICS, AND BIOLOGY

If one examines the course catalog of a large, contemporary, university in the United States for fields of instruction in science, one can find such titles as animal science, astronomy, atmospheric science, biochemistry, biology, botany, chemistry, computer science, geology, ecology, mathematical science, meteorology, physics, psychology, toxicology, and zoology, to name but a few. Each of these is a field of study in its own right consisting of many subtopics. On the other hand, a catalog from a U.S. college that existed in the early 19th century probably would show at most only two "sciences": natural history (the progenitor of geology and biology) and natural philosophy (physics and chemistry). Over the years, there has been an explosion of speciation in science, resulting in what appears at first sight to be a technological Tower of Babel.

Although the factual content of the many branches of modern science may serve to differentiate one from the other, all branches share certain common characteristics and concepts. Most important, all of the sciences share a way of thinking. Science is a search for truth predicated on the belief that there is an absolute physical reality; things aren't just figments of our imaginations. Science is based on observation. Unlike the observations of creative art or religion, for example, which tend to be private and highly personal, scientific observations are made, as best as can be done, in a public way, that is, in a way that anyone, in principle, could repeat them.

Scientific truth is couched in *models*. A model is not the thing itself, but a representation of the thing, much like a metaphor. A model is a guess about how the thing works based on a set of empirical data. (If the dataset is very large and the model appears to be especially useful, it is called a *theory*. In science, the colloquially pejorative phrase, "That's only a theory," would never be used because in science a theory is the best kind of guess one can have.) A model can be physical or pictorial or verbal. Often in science, models are mathematical. Mathematics is an incredibly economical way of expressing an idea. One equation can encapsulate tomes of empirical data. Better yet, an equation can be used to predict outcomes of experiments performed under conditions never seen before. In fact, prediction is the heart of science. Science is a relentless series of predictions designed to identify the limitations of previously established "truths." By tearing down and supplanting prior knowledge, science aspires to produce an ever-clearer picture of physical reality. In this sense, science can be said to be an insatiable pursuit of *provisional* truth.

Physics is the most elemental of all the sciences. It attempts to explain the most fundamental phenomena with the fewest assumptions and in the simplest terms. In a sense, physics strives to identify and attack the "easiest" of nature's problems. Despite its pursuit of the fundamental, however, physics has been extraordinarily successful in understanding a vast array of practically important questions such as how

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to build a better steam engine, how to place a satellite in orbit, and how energy stored in atomic nuclei can be used to light cities, to cite just a few examples. Indeed, physics is the basis for a huge portion of the world's economy.

The subfields of physics bear such names as classical mechanics, thermodynamics, electricity and magnetism, optics, relativity, and quantum mechanics. Of these, classical mechanics is usually studied first because it deals with the ideas of mass, motion, force, and energy, concepts that underlie not only the other areas of physics, but also astronomy, biology, chemistry, and geology, as well as all of engineering.

Like physics, biology is a study of matter and energy. The systems of matter and energy that are of biological interest, however, are vastly more complex than those that are the focus of physics. Biology deals with *living* matter, collections of atoms and molecules that manage to harness energy to perform such extraordinary tasks as locomotion, reproduction, and computation ("thinking"). On the most primitive, microscopic level, the rules obeyed by living matter are just the fundamental laws of physics. These, as far as we can tell, are immutable. They have persisted since the origin of the universe. On a higher level of organization, however, at the level of cells and organisms, living matter obeys rules that can change. Mutation and evolution are the cornerstones of biological diversity. How the immutable, microscopic rules of physics are knit together into the macroscopic fabric of life, where matter is capable of adaptive and evolving behavior, is one of the great unsolved mysteries of contemporary scientific inquiry.

Until the 1950s or so, relatively few direct connections between physics and biology had been recognized. Up to that point, most research in biology had been descriptive, a kind of cataloging of similarities and differences. Since then, strong linkages between biology and physics have emerged. These connections have revolutionized our understanding of how life works and led to profound improvements in pharmaceuticals and clinical procedures. The impact of physics on modern biology and medical science is due, in part, to the introduction of new technologies used to study biological systems and, in part, to direct applications of physics to the detailed understanding of macromolecular processes.

Examples of new technology based on physics and used in the study of biology and medicine abound. A huge array of new microscopies (transmission electron, scanning electron, fluorescence, interference, polarization, scanning tunneling, atomic force) and spectroscopies (nuclear magnetic resonance (NMR), electron spin resonance (ESR), x-ray, neutron, and many laser-based methods such as Raman scattering) have been developed and are now routinely used to study macromolecular structure and functioning. New methods in electromagnetic sensing (e.g., superconducting quantum interference devices (SQUIDS) for measuring extremely small magnetic fields, such as those due to nerve activity, and single-membrane channel recording of electrical activities), laser and electronic instrumentation to better image events both spatially and temporally (allowing studies of extremely fast kinetics, down to 10^{-14} s, and submillimeter spatial resolutions using ultrasound, x-rays, or magnetic resonance methods), and, of course, dramatic improvements in computers, made possible by new physics, have all led to major advances in our knowledge.

In conjunction with this technological progress, has come a marked increase in the description of biological processes using fundamental physics. Detailed molecular models of the structure and functioning of many significant biological processes are now in hand. Most of this progress has been at the subcellular or single-cell level but even areas of biology involving cell–cell interactions, functioning of entire organs, developmental biology, physiology, and the ecology of plant and animal communities are now being approached with physical models and fundamental physics approaches. The rate at which new ideas in physics find application in biology is astonishing. Recent developments in nonlinear dynamics in physics, for example, have already been applied to a large variety of complex biological systems, especially in understanding how electrical activity in the heart and brain changes from health to a state of disease.

To summarize, it is fair to say that no student of today's life sciences will be adequately educated without a firm understanding of the fundamental principles of physical science. It is to that aspect of the life scientist's education that the remainder of this book is dedicated.

2. PLAN OF THIS BOOK

Physics of the Life Sciences is designed to teach fundamental physics to students of the life sciences. Our approach is to use modern biophysical themes as much as possible to introduce the physics and to illustrate the wide variety of applications of physics in the life sciences. Indeed today's doctors, scientists, nurses, and medical and health technicians constantly use a vast array of modern technology in their work. A working knowledge of these devices and their basic functioning is a necessity. Our scientific knowledge base also is growing at an ever-increasing pace. Science is rapidly becoming interdisciplinary. Scientists from many different backgrounds, including biology, chemistry, physics, medicine, and engineering, study a vast array of diverse biological problems. What they all have in common is the use of physics and modern technology in attempts to understand particular biological phenomena. Understanding involves observing, quantifying, and developing a good model that has some predictive ability. The better our understanding of a system or phenomenon, the better is our model in making predictions about its behavior under a larger variety of conditions. As already mentioned, the best models are called theories, the pinnacles of our understanding.

This book is organized into three major parts. After an introduction and an overview of some fundamental themes in this chapter, we begin the first portion of this book, classical mechanics and thermodynamics, in Chapters 2–13. There we learn how to apply a few basic laws of motion for particles to understand the much more complex motion of real macroscopic objects and fluids. Many of the fundamental concepts we learn in the first few of those chapters are used throughout the book in our studies of a variety of biological systems and many important tools used in their study. The second major topic of study is electricity and magnetism and their synthesis in electromagnetism, found in Chapters 14–18. Aside from gravity, these are the sources of the interactions between all objects in our daily experience as well as between biological macromolecules. We introduce much of the physics through biophysical topics such as electrophoresis, biological membranes and channels, nerve conduction, and magnetic resonance imaging (MRI). After having introduced the general properties of waves in Chapter 10, and applied those ideas to sound in Chapter 11, waves are a unifying theme of the third and last major topic of this book. In Chapter 19 electromagnetic waves are discussed, which leads into light waves in optics and matter waves in quantum physics (Chapters 20–23 and 24–25); we conclude, in Chapter 26, with topics on nuclear physics, nuclear medicine, and imaging methods.

Throughout, we emphasize understanding the fundamental concepts of physics and their importance in the study of biology. To help in this, major themes and concepts are developed from specific examples and problems whenever possible. Using descriptive English to explain physical concepts can sometimes lead to confusion because many of the words used in physics have specific meanings that differ from those used in ordinary speech. Mathematics is the natural language of physics, allowing a huge body of knowledge to be expressed in compact equations. However, without an understanding and appreciation of the meanings of the variables, or letters, used in equations, readers often view them as simply a means to obtain a numerical answer to a problem by inserting values for the other letters, rather than as summaries of vast amounts of knowledge. Equations are de-emphasized in this text by keeping the most important, numbered, equations to a minimum. In addition, each chapter has a variety of nonmathematical questions at its end designed to make the reader think about key ideas in the chapter.

On the other hand, without mathematics it would be much more difficult to present a complete picture of our knowledge of science and to make predictions about the behavior of a system. As we show, Newton's second law equation and Maxwell's four equations of electromagnetism together are equivalent to an enormous body of knowledge. Without those equations, we could not easily express the same information content in words, nor would we be able to approach the tremendous variety of problems these equations can solve. Facility with algebra and trigonometry is assumed here; an appendix is provided for readers to review some basics in algebra and trigonometry as well as in scientific notation, and a few other issues. For those readers who have had some elementary calculus, there are occasional boxed discussions that use some calculus to either derive a particular result or enhance the presentation. This material is not integral to the text and can be skipped over. Each chapter also has a variety of short-answer and open-ended problems to help in learning the material. These should be viewed as integral to the text and a fair number should be attempted to probe understanding of the material and to develop problem-solving skills that will be of benefit in all areas of a life-long education.

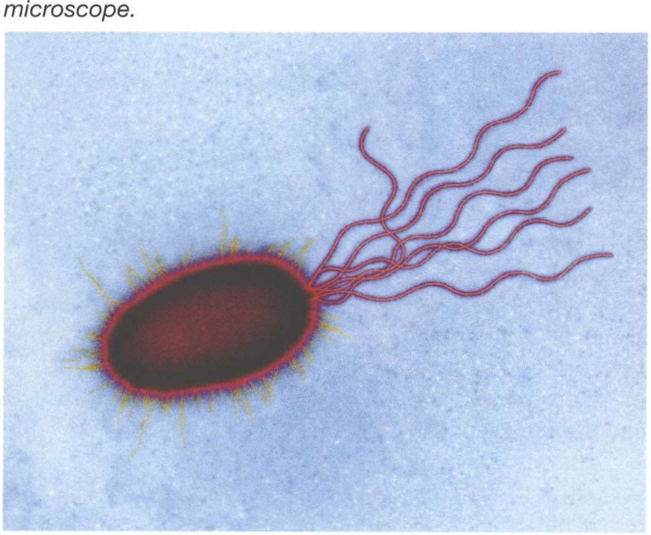
Problem solving involves some extremely useful skills, such as the ability to extract information from a written paragraph, to find the key issue or unknown, to develop solution strategies, and to be able to describe those methods and your solutions to others. Just as critical reading skills will help throughout one's life, problem-solving skills are valuable tools to have in whatever one chooses to do later in life, whether related to science or not.

A major goal of this text is for the reader to develop an appreciation of physics as a discipline that has led to tremendous advances in our civilization. We now have a basic, if incomplete, understanding of our world, ranging from the constituents of atoms to biological cells to galaxies. Although our scientific knowledge has grown explosively over the last 50 years, particularly in the life sciences, the general public's awareness and appreciation of science has declined. *Physics of the Life Sciences* hopes to show many of the interrelationships among the sciences, particularly the physical basis of our understanding of biology.

3. TWO EXAMPLES OF BIOPHYSICAL SYSTEMS: THE SINGLE CELL *E. COLI* BACTERIA AND THE HUMAN HEART

Biological systems are extremely complex, much more so than standard physical systems traditionally studied by physicists. With the tremendous growth of technological methods have come interdisciplinary laboratories and scientific collaborations with a focus on particular biological systems and questions. A glance at a list of topics discussed at various international scientific meetings with a biological focus will show the huge array of systems that are currently studied, including macromolecules, subcellular components, cells, organs, whole organisms, and even interactions between organisms. In the course of this text we show how physics and physical technologies have been applied to many of these. Here we briefly discuss two particularly important systems, one a cell and one an organ, to indicate the range of questions that have been addressed by biophysicists and other scientists.

FIGURE 1.1 *E. coli bacteria as seen using a scanning electron microscope.*



The bacterium, *Escherichia coli* (*E. coli*), is the most studied and well-characterized single-cell organism known. Discovered in 1885, these bacteria are several micrometers long rod-shaped cells (Figure 1.1), a convenient size for optical microscopy, and can be easily, cheaply, and rapidly grown in large quantities. The fact that huge numbers of these organisms can be rapidly grown has led to a number of significant biochemical discoveries including the genetic code, glycolysis, and protein synthesis regulation, and has made these organisms the powerhouse of genetic engineering. *E. coli* bacteria reappear in some of our later discussions as a prototype cell in learning some areas of physics.