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Kerry Kuehn

A Student's Guide Through the Great Physics Texts

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For Cindy.

Preface

What is the Nature of This Book?

This four-volume book grew from a four-semester general physics curriculum which I developed and taught for the past decade to undergraduate students at Wisconsin Lutheran College in Milwaukee. The curriculum is designed to encourage a critical and circumspect approach to natural science while at the same time providing a suitable foundation for advanced coursework in physics. This is accomplished by holding before the student some of the best thinking about nature that has been committed to writing. The scientific texts found herein are considered classics precisely because they address timeless questions in a particularly honest and convincing manner. This does not mean that everything they say is true—in fact many classic scientific texts contradict one another—but it is by the careful reading, analysis and discussion of the most reputable observations and opinions that one may begin to discern truth from error.

Who is This Book For?

Like fine wine, the classic texts in any discipline can be enjoyed by both the novice and the connoisseur. For example, Sophocles' tragic play *Antigone* can be appreciated by the young student who is drawn to the story of the heroine who braves the righteous wrath of King Creon by choosing to illegally bury the corpse of her slain brother, and also by the seasoned scholar who carefully evaluates the relationship between justice, divine law and the state. Likewise, Galileo's *Dialogues Concerning Two New Sciences* can be enjoyed by the young student who seeks a clear geometrical description of the speed of falling bodies, and also by the seasoned scholar who is amused by Galileo's wit and sarcasm, or who finds in his *Dialogues* the progressive Aristotelianism of certain late medieval scholastics.¹

¹ See Wallace, W. A., The Problem of Causality in Galileo's Science, *The Review of Metaphysics*, 36(3), 607–632, 1983.

Having said this, I believe that this book is particularly suitable for the following audiences. First, it could serve as the primary textbook in an introductory discussion-based physics course at the university level. It was designed to appeal to a broad constituency of students at small liberal arts colleges which often lack the resources to offer the separate and specialized introductory physics courses found at many state-funded universities (e.g. *Physics for poets*, *Physics for engineers*, *Physics for health-care-professionals*, *Physics of sports*, etc.). Indeed, at my institution it is common to have history and fine arts students sitting in the course alongside biology and physics majors. Advanced high-school or home-school students will find in this book a physics curriculum that emphasizes reading comprehension, and which can serve as a bridge into college-level work. It might also be adopted as a supplementary text for an advanced placement course in physics, astronomy or the history and philosophy of science. Many practicing physicists, especially those at the beginning of their scientific careers, may not have taken the opportunity to carefully study some of the foundational texts of physics and astronomy. Perhaps this is because they have (quite understandably) focused their attention on acquiring a strong technical proficiency in a narrow subfield. Such individuals will find herein a structured review of such foundational texts. This book will also likely appeal to humanists, social scientists and motivated lay-readers who seek a thematically-organized anthology of texts which offer insight into the historical development and cultural significance of contemporary scientific theories. Finally, and most importantly, this book is designed for the benefit of the teaching professor. Early in my career as a faculty member, I was afforded considerable freedom to develop a physics curriculum at my institution which would sustain my interest for the foreseeable future—perhaps until retirement. Indeed, reading and re-reading the classic texts assembled herein has provided me countless hours of enjoyment, reflection and inspiration.

How is This Book Unique?

Here I will offer a mild critique of textbooks typically employed in introductory university physics courses. While what follows is admittedly a bit of a caricature, I believe it to be a quite plausible one. I do this in order to highlight the unique features and emphases of the present book. In many university-level physics textbooks, the chapter format follows a standard recipe. First, accepted scientific laws are presented in the form of one or more mathematical equations. This is followed by a few example problems so the student can learn how to plug numbers into the aforementioned equations and how to avoid common conceptual or computational errors. Finally, the student is presented with contemporary applications which illustrate the relevance of these equations for various industrial or diagnostic technologies.

While this method often succeeds in preparing students to pass certain standardized tests or to solve fairly straightforward technical problems, it is lacking in important respects. First, it is quite bland. Although memorizing formulas and

learning how to perform numerical calculations is certainly crucial for acquiring a working knowledge of physical theories, it is often the more general questions about the assumptions and the methods of science that students find particularly stimulating and enticing. For instance, in his famous *Mathematical Principles of Natural Philosophy*, Newton enumerates four general rules for doing philosophy. Now the reader may certainly choose to reject Newton's rules, but Newton himself suggests that they are necessary for the subsequent development of his universal theory of gravitation. Is he correct? For instance, if one rejects Rules III and IV—which articulate the principle of induction—then in what sense can his theory of gravity be considered universal? Questions like “is Newton's theory of gravity correct?” and “how do you know?” can appeal to the innate sense of inquisitiveness and wonder that attracted many students to the study of natural science in the first place. Moreover, in seeking a solution to these questions, the student must typically acquire a deeper understanding of the technical aspects of the theory. In this way, broadly posed questions can serve as a motivation and a guide to obtaining a detailed understanding of physical theories.

Second, and perhaps more importantly, the method employed by most standard textbooks does not prepare the student to become a practicing scientist precisely because it tends to mask the way science is actually done. The science is presented as an accomplished fact; the prescribed questions revolve largely around technological applications of accepted laws. On the contrary, by carefully studying the foundational texts themselves the student is exposed to the polemical debates, the technical difficulties and the creative inspirations which accompanied the development of scientific theories. For example, when studying the motion of falling bodies in Galileo's *Dialogues*, the student must consider alternative explanations of the observed phenomena; must understand the strengths and weaknesses of competing theories; and must ultimately accept—or reject—Galileo's proposal on the basis of evidence and reason. Through this process the student gains a deeper understanding of Galileo's ideas, their significance, and their limitations.

Moreover, when studying the foundational texts, the student is obliged to thoughtfully address issues of language and terminology—issues which simply do not arise when learning from standard textbooks. In fact, when scientific theories are being developed the scientists themselves are usually struggling to define terms which capture the essential features of their discoveries. For example, Oersted coined a term which is translated as “electric conflict” to describe the effect that an electrical current has on a nearby magnetic compass needle. He was attempting to distinguish between the properties of stationary and moving charges, but he lacked the modern concept of the magnetic field which was later introduced by Faraday. When students encounter a familiar term such as “magnetic field,” they typically accept it as settled terminology, and thereby presume that they understand the phenomenon by virtue of recognizing and memorizing the canonical term. But when they encounter an unfamiliar term such as “electric conflict,” as part of the scientific argument from which it derives and wherein it is situated, they are tutored into the original argument and are thus obliged to think scientifically, along with the great

scientist. In other words, when reading the foundational texts, the student is led into *doing* science and not merely into memorizing and applying nomenclature.

Generally speaking, this book draws upon two things that we have in common: (i) a shared conversation recorded in the foundational scientific texts, and (ii) an innate faculty of reason. The careful reading and analysis of the foundational texts is extremely valuable in learning how to think clearly and accurately about natural science. It encourages the student to carefully distinguish between observation and speculation, and finally, between truth and falsehood. The ability to do this is essential when considering the practical and even philosophical implications of various scientific theories. Indeed, one of the central aims of this book is to help the student grow not only as a potential scientist, but as an educated person. More specifically, it will help the student develop important intellectual virtues (*i.e.* good habits), which will serve him or her in any vocation, whether in the marketplace, in the family, or in society.

How is This Book Organized?

This book is divided into four separate volumes; volumes I and II were concurrently published in the autumn of 2014, and volumes III and IV are due to be published approximately a year later. Within each volume, the readings are centered on a particular theme and proceed chronologically. For example, Volume I is entitled *The Heavens and the Earth*. It provides an introduction to astronomy and cosmology beginning with the geocentrism of Aristotle's *On the Heavens* and Ptolemy's *Almagest*, proceeding through heliocentrism advanced in Copernicus' *Revolutions of the Heavenly Spheres* and Kepler's *Epitome of Copernican Astronomy*, and arriving finally at big bang cosmology with Lemaître's *The Primeval Atom*. Volume II, *Space, Time and Motion*, provides a careful look at the science of motion and rest. Here, students engage in a detailed analysis of significant portions of Galileo's *Dialogues Concerning Two New Sciences*, Pascal's *Treatise on the Equilibrium of Fluids and the Weight of the Mass of Air*, Newton's *Mathematical Principles of Natural Philosophy* and Einstein's *Relativity*.

Volume III traces the theoretical and experimental development of the electromagnetic theory of light using texts by William Gilbert, Benjamin Franklin, Charles Coulomb, André Marie Ampère, Christiaan Huygens, James Clerk Maxwell, Heinrich Hertz, Albert Michelson, and others. Volume IV provides an exploration of modern physics, focusing on the mechanical theory of heat, radio-activity and the development of modern quantum theory. Selections are taken from works by Joseph Fourier, William Thomson, Rudolph Clausius, Joseph Thomson, James Clerk Maxwell, Ernest Rutherford, Max Planck, James Chadwick, Niels Bohr, Erwin Schrödinger and Werner Heisenberg.

While the four volumes of the book are arranged around distinct themes, the readings themselves are not strictly constrained in this way. For example, in his *Treatise on Light*, Huygens is primarily interested in demonstrating that light can be

best understood as a wave propagating through an aethereal medium comprised of tiny, hard elastic particles. In so doing, he spends some time discussing the speed of light measurements performed earlier by Ole Rømer. These measurements, in turn, relied upon an understanding of the motion of the moons of Jupiter which had recently been reported by Galileo in his *Sidereal Messenger*. So here, in this *Treatise on Light*, we find references to a variety of inter-related topics. Huygens does not artificially restrict his discussion to a narrow topic—nor does Galileo, or Newton or the other great thinkers. Instead, the reader will find in this book recurring concepts and problems which cut across different themes and which are naturally addressed in a historical context with increasing levels of sophistication and care. Science is a conversation which stretches backwards in time to antiquity.

How Might This Book be Used?

This book is designed for college classrooms, small-group discussions and individual study. Each of the four volumes of the book contains roughly thirty chapters, providing more than enough material for a one-semester undergraduate-level physics course; this is the context in which this book was originally implemented. In such a setting, one or two 50-min classroom sessions should be devoted to analyzing and discussing each chapter. This assumes that the student has read the assigned text before coming to class. When teaching such a course, I typically improvise—leaving out a chapter here or there (in the interest of time) and occasionally adding a reading selection from another source that would be particularly interesting or appropriate.

Each chapter of each volume has five main components. First, at the beginning of each chapter, I include a short introduction to the reading. If this is the first encounter with a particular author, the introduction includes a biographical sketch of the author and some historical context. The introduction will often contain a summary of some important concepts from the previous chapter and will conclude with a few provocative questions to sharpen the reader's attention while reading the upcoming text.

Next comes the reading selection. There are two basic criteria which I used for selecting each text: it must be *significant* in the development of physical theory, and it must be *appropriate* for beginning undergraduate students. Balancing these criteria was very difficult. Over the past decade, I have continually refined the selections so that they might comprise the most critical contribution of each scientist, while at the same time not overwhelming the students by virtue of their length, language or complexity. The readings are not easy, so the student should not feel overwhelmed if he or she does not grasp everything on the first (or second, or third. . .) reading. Nobody does. Rather—like classic literature—these texts must be “grown into” (so to speak) by returning to them time and again.

I have found that the most effective way to help students successfully engage foundational texts is to carefully prepare questions which help them identify and

understand key concepts. So as the third component of each chapter, I have prepared a study guide in the form of a set of questions which can be used to direct either classroom discussion or individual reading. After the source texts themselves, the study guide is perhaps the most important component of each chapter, so I will spend a bit more time here explaining it.

The study guide typically consists of a few general discussion questions about key topics contained in the text. Each of these general questions is followed by several sub-questions which aid the student by focusing his or her attention on the author's definitions, methods, analysis and conclusions. For example, when students are reading a selection from Albert Michelson's book *Light Waves and their Uses*, I will often initiate classroom discussion with a general question such as "Is it possible to measure the absolute speed of the earth?" This question gets students thinking about the issues addressed in the text in a broad and intuitive way. If the students get stuck, or the discussion falters, I will then prompt them with more detailed follow-up questions such as: "What is meant by the term absolute speed?" "How, exactly, did Michelson attempt to measure the absolute speed of the earth?" "What technical difficulties did Michelson encounter while doing his experiments?" "To what conclusion(s) was Michelson led by his results?" and finally "Are Michelson's conclusions then justified?" After answering such simpler questions, the students are usually more confident and better prepared to address the general question which was initially posed.

In the classroom, I always emphasize that it is critical for participants to carefully read the assigned selections before engaging in discussion. This will help them to make relevant comments and to cite textual evidence to support or contradict assertions made during the course of the discussion. In this way, many assertions will be revealed as problematic—in which case they may then be refined or rejected altogether. Incidentally, this is precisely the method used by scientists themselves in order to discover and evaluate competing ideas or theories. During our discussion, students are encouraged to speak with complete freedom; I stipulate only one classroom rule: any comment or question must be stated publicly so that all others can hear and respond. Many students are initially apprehensive about engaging in public discourse, especially about science. If this becomes a problem, I like to emphasize that students do not need to make an elaborate point in order to engage in classroom discussion. Often, a short question will suffice. For example, the student might say "I am unclear what the author means by the term *inertia*. Can someone please clarify?" Starting like this, I have found that students soon join gamely in classroom discussion.

Fourth, I have prepared a set of exercises which test the student's understanding of the text and his or her ability to apply key concepts in unfamiliar situations. Some of these are accompanied by a brief explanation of related concepts or formulas. Most of them are numerical exercises, but some are provocative essay prompts. In addition, some of the chapters contain suggested laboratory exercises, a few of which are in fact field exercises which require several days (or even months) of observations. For example, in Chap. 3 of Volume I, there is an astronomy field exercise which involves charting the progression of a planet through the zodiac over the

course of a few months. So if this book is being used in a semester-long college or university setting, the instructor may wish to skim through the exercises at the end of each chapter so he or she can identify and assign the longer ones as ongoing exercises early in the semester.

Finally, I have included at the end of each chapter a list of vocabulary words which are drawn from the text and with which the student should become acquainted. Expanding his or her vocabulary will aid the student not only in their comprehension of subsequent texts, but also on many standardized college and university admissions exams.

What Mathematics Preparation is Required?

It is sometime said that mathematics is the “language of science.” This sentiment appropriately inspires and encourages the serious study of mathematics. Of course if it were taken literally then many seminal works in physics—and much of biology—would have to be considered either unintelligible or unscientific, since they contain little or no mathematics. Moreover, if mathematics is the *only* language of science, then physics instructors should be stunned whenever students are enlightened by verbal explanations which lack mathematical form. To be sure, mathematics offers a refined and sophisticated language for describing observed phenomena, but many of our most significant observations about nature may be expressed using everyday images, terms and concepts: heavy and light, hot and cold, strong and weak, straight and curved, same and different, before and after, cause and effect, form and function, one and many. So it should come as no surprise that, when studying physics *via* the reading and analysis of foundational texts, one enjoys a considerable degree of flexibility in terms of the mathematical rigor required.

For instance, Faraday’s *Experimental Researches in Electricity* are almost entirely devoid of mathematics. Rather, they consist of detailed qualitative descriptions of his observations, such as the relationship between the relative motion of magnets and conductors on the one hand, and the direction and intensity of induced electrical currents on the other hand. So when studying Faraday’s work, it is quite natural for the student to aim for a conceptual, as opposed to a quantitative, understanding of electromagnetic induction. Alternatively, the student can certainly attempt to connect Faraday’s qualitative descriptions with the mathematical methods which are often used today to describe electromagnetic induction (*i.e.* vector calculus and differential equations). The former method has the advantage of demonstrating the conceptual framework in which the science was actually conceived and developed; the latter method has the advantage of allowing the student to make a more seamless transition to upper-level undergraduate or graduate courses which typically employ sophisticated mathematical methods.

In this book, I approach the issue of mathematical proficiency in the following manner. Each reading selection is followed by both study questions and homework exercises. In the study questions, I do not attempt to force anachronistic concepts or

methods into the student's understanding of the text. They are designed to encourage the student to approach the text in the same spirit as the author, insofar as this is possible. In the homework exercises, on the other hand, I often ask the student to employ mathematical methods which go beyond those included in the reading selection itself. For example, one homework exercise associated with a selection from Hertz's book *Electric Waves* requires the student to prove that two counter-propagating waves superimpose to form a standing wave. Although Hertz casually mentions that a standing wave is formed in this way, the problem itself requires that the student use trigonometric identities which are not described in Hertz's text. In cases such as this, a note in the text suggests the mathematical methods which are required. I have found this to work quite well, especially in light of the easy access which today's students have to excellent print and online mathematical resources.

Generally speaking, there is an increasing level of mathematical sophistication required as the student progresses through the curriculum. In Volume I students need little more than a basic understanding of geometry. Euclidean geometry is sufficient in understanding Ptolemy's epicyclic theory of planetary motion and Galileo's calculation of the altitude of lunar mountains. The student will be introduced to some basic ideas of non-Euclidean geometry toward the end of Volume I when studying modern cosmology through the works of Einstein, Hubble and Lemaitre, but this is not pushed too hard. In Volume II students will make extensive use of geometrical methods and proofs, especially when analyzing Galileo's work on projectile motion and the application of Newton's laws of motion. Although Newton develops his theory of gravity in the *Principia* using geometrical proofs, the homework problems often require the student to make connections with the methods of calculus. The selections on Einstein's special theory of relativity demand only the use of algebra and geometry. In Volume III, mathematical methods will, for the most part, be limited to geometry and algebra. More sophisticated mathematical methods will be required, however, in solving some of the problems dealing with Maxwell's electromagnetic theory of light. This is because Maxwell's equations are most succinctly presented using vector calculus and differential equations. Finally, in Volume IV, the student will be aided by a working knowledge of calculus, as well as some familiarity with the use of differential equations.

It is my feeling that in a general physics course, such as the one being presented in this book, the extensive use of advanced mathematical methods (beyond geometry, algebra and elementary calculus) is not absolutely necessary. Students who plan to major in physics or engineering will presumably learn more advanced mathematical methods (e.g. vector calculus and differential equations) in their collateral mathematics courses, and they will learn to apply these methods in upper-division (junior and senior-level) physics courses. Students who do not plan to major in physics will typically not appreciate the extensive use of such advanced mathematical methods. And it will tend to obscure, rather than clarify, important physical concepts. In any case, I have attempted to provide guidance for the instructor, or for the self-directed student, so that he or she can incorporate an appropriate level of mathematical rigor.

Figures, Formulas, and Footnotes

One of the difficulties in assembling readings from different sources and publishers into an anthology such as this is how to deal with footnotes, references, formulas and other issues of annotation. For example, for any given text selection, there may be footnotes supplied by the author, the translator and the anthologist. So I have appended a [K.K.] marking to indicate when the footnote is my own; I have not included this marking when there is no danger of confusion, for example in my footnotes appearing in the introduction, study questions and homework exercises of each chapter.

For the sake of clarity and consistency, I have added (or sometimes changed the) numbering for figures appearing in the texts. For example, Fig. 16.3 is the third figure in Chap. 16 of Volume I; this is not necessarily how Kepler or his translator numbered this figure when it appeared in an earlier publication of his *Epitome Astronomae Copernicanae*. For ease of reference, I have also added (or sometimes changed the) numbering of equations appearing in the texts. For example, Eqs. 31.1 and 31.2 are the equations of the Lorentz and Galilei transformations appearing in the reading in Chap. 31 of Volume II, extracted from Einstein's book *Relativity*. This is not necessarily how Einstein numbered them.

In several cases, the translator or editor has included references to page numbers in a previous publication. For example, the translators of Galileo's *Dialogues* have indicated, within their 1914 English translation, the locations of page breaks in the Italian text published in 1638. A similar situation occurs with Faith Wallis's 1999 translation of Bede's *The Reckoning of Time*. For consistency, I have rendered such page numbering in bold type surrounded by slashes. So **/50/** refers to page 50 in some earlier "canonical" publication.

Acknowledgements

I suppose that it is common for a teacher to eventually mull over the idea of compiling his or her thoughts on teaching into a coherent and transmittable form. Committing this curriculum to writing was particularly difficult because I am keenly aware how my own thinking about teaching physics has changed significantly since my first days in front of the classroom—and how it is quite likely to continue to evolve. So this book should be understood as a snapshot, so to speak, of how I am teaching my courses at the time of writing. I would like to add, however, that I believe the evolution of my teaching has reflected a maturing in thought, rather than a mere drifting in opinion. After all, the classic texts themselves are formative: how can a person, whether student or teacher, not become better informed when learning from the best thinkers?

This being said, I would like to offer my apologies to those students who suffered through the birth pains, as it were, of the curriculum presented in this book. The countless corrections and suggestions that they offered are greatly appreciated; any and all remaining errors in the text are my own fault. Many of the reading selections included herein were carefully scanned, edited and typeset by undergraduate students who served as research and editorial assistants on this project: Jaymee Martin-Schnell, Dylan Applin, Samuel Wiepking, Timothy Kriewall, Stephanie Kriewall, Cody Morse, Michaela Otterstatter, and Ethan Jahns deserve special thanks. My home institution, Wisconsin Lutheran College, provided me with considerable time and freedom to develop this book, including a year-long sabbatical leave, for which I am very grateful. During this sabbatical, I received support and encouragement from my trusty colleagues in the Department of Mathematical and Physical Sciences. Also, the Higher Education Initiatives Program of the Wisconsin Space Grant Consortium provided generous funding for this project, as did the Faculty Development Committee of Wisconsin Lutheran College. Greg Schulz has been an invaluable intellectual resource throughout this project. Aaron Jensen conscientiously translated selections of the *Almagest*, included in Volume I of this book, from Heiberg's edition of Ptolemy's Greek manuscript. And Glen Thompson was instrumental in getting this translation project initiated. Starla Siegmann and Jenny

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Milwaukee, 2015

Kerry Kuehn

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