APPLICATIONS OF CLASSICAL PHYSICS

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Preface

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This book is an introduction to the fundamentals and 21st-century applications of all the major branches of classical physics except classical mechanics, electromagnetic theory, and elementary thermodynamics (which we assume the reader has already learned elsewhere).

Classical physics and this book deal with physical phenomena on macroscopic scales: scales where the particulate natures of matter and radiation are secondary to the behavior of particles in bulk; scales where particles' statistical as opposed to individual properties are important, and where matter's inherent graininess can be smoothed over. In this book, we shall take a journey through spacetime and phase space, through statistical and continuum mechanics (including solids, fluids, and plasmas), and through optics and relativity, both special and general. In our journey, we shall seek to comprehend the fundamental laws of classical physics in their own terms, and in relation to quantum physics. Using carefully chosen examples, we shall show how the classical laws are applied to important, contemporary, 21st-century problems and to everyday phenomena, and we shall uncover some deep connections among the various fundamental laws, and connections among the practical techniques that are used in different subfields of physics.

Many of the most important recent developments in physics—and more generally in science and engineering—involve classical subjects such as optics, fluids, plasmas, random processes, and curved spacetime. Unfortunately, many young physicists today have little understanding these subjects and their applications. Our goal, in writing this book, is to rectify that. More specifically:

- We believe that every masters-level or PhD physicist should be familiar with the basic concepts of all the major branches of classical physics, and should have had some experience in applying them to real-world phenomena; this book is designed to facilitate that.
- A large fraction of physics, astronomy and engineering graduate students in the United

States and around the world use classical physics extensively in their research, and even more of them go on to careers in which classical physics is an essential component; this book is designed to facilitate that research and those careers.

In pursuit of these goals, we seek, in this book, to *give the reader a clear understanding of the basic concepts and principles of classical physics.* We present these principles in the language of modern physics (not nineteenth century applied mathematics), and present them for physicists as distinct from mathematicians or engineers — though we hope that mathematicians and engineers will also find our presentation useful. As far as possible, we emphasize theory that involves general principles which extend well beyond the particular subjects we study.

In this book, we also seek to *teach the reader how to apply classical physics ideas.* We do so by presenting contemporary applications from a variety of fields, such as

- fundamental physics, experimental physics and applied physics;
- astrophysics and cosmology;
- geophysics, oceanography and meteorology;
- engineering, optical science & technology, radio science & technology, and information science & technology.

Why is the range of applications so wide? Because we believe that physicists should have at their disposal enough understanding of general principles to attack problems that arise in unfamiliar environments. In the modern era, a large fraction of physics students will go on to careers away from the core of fundamental physics. For such students, a broad exposure to non-core applications will be of great value; for those who wind up in the core, such an exposure is of value culturally, and also because ideas from other fields often turn out to have impact back in the core of physics. Our examples will illustrate how basic concepts and problem solving techniques are freely interchanged between disciplines.

Classical physics is defined as the physics where Planck's constant can be approximated as zero. To a large extent, it is the body of physics for which the fundamental equations were established prior to the development of quantum mechanics in the 1920's. Does this imply that it should be studied in isolation from quantum mechanics? Our answer is, most emphatically, "No!". The reasons are simple. *First*, quantum mechanics has primacy over classical physics: classical physics is an approximation, often excellent, sometimes poor, to quantum mechanics. *Second*, in recent decades many concepts and mathematical techniques developed for quantum mechanics have been imported into classical physics and used to enlarge our classical understanding and enhance our computational capability. An example that we shall discuss occurs in plasma physics, where nonlinearly interacting waves are treated as quanta ("plasmons"), despite the fact that they are solutions of classical field equations. *Third*, ideas developed initially for "classical" problems are frequently adapted for application to avowedly quantum mechanical subjects; examples (not discussed in this book) are found in supersymmetric string theory and in the liquid drop model of the atomic nucleus. Because of these intimate connections between quantum and classical physics, quantum physics will appear frequently in this book, in a variety of ways.

The amount and variety of material covered in this book may seem overwhelming.

If so, please keep in mind the key goals of the book: to teach the fundamental concepts, which are not so extensive that they should overwhelm, and to illustrate those concepts. Our goal is not to provide a mastery the many illustrative applications contained in the book, but rather to convey the spirit of how to apply the basic concepts of classical physics.

This book will also seem much more manageable and less overwhelming when one realizes that the same concepts and problem solving techniques appear over and over again, in a variety of different subjects and applications. *These unifying concepts and techniques are listed in Appendix B, in outline form, along with the specific applications and section numbers in this book, where they arise.* The reader may also find Appendix A useful. It contains an outline of the entire book based on concepts — an outline complementary to the Table of Contents.

This book is divided into six parts; see the Table of Contents:

I. Statistical physics — including kinetic theory, statistical mechanics, statistical thermodynamcs, and the theory of random processes. These subjects underly some portions of the rest of the book, especially plasma physics and fluid mechanics. Among the applications we study are the statistical-theory computation of macroscopic properties of matter (equations of state, thermal and electric conductivity, viscosity, ...); phase transitions (boiling and condensation, melting and freezing, ...); the Ising model and renormalization group; chemical and nuclear reactions, e.g. in nuclear reactors; Bose-Einstein condensates; Olber's Paradox in cosmology; the Greenhouse effect and its influence on the earth's climate; noise and signal processing, and the relationship between information and entropy; entropy in the expanding universe and the entropy of black holes.

II. Optics, by which we mean classical waves of all sorts: light waves, radio waves, sound waves, water waves, waves in plasmas, and gravitational waves. The major concepts we develop for dealing with all these waves include geometrical optics, diffraction, interference, and nonlinear wave-wave mixing. Some of the applications we will meet are gravitational lenses, caustics and catastrophes, Berry's phase, phase-contrast microscopy, Fourier-transform spectroscopy, radio-telescope interferometry, gravitational-wave intereferometers, holography, frequency doubling and phase conjugation in nonlinear crystals, squeezed light, and how information is encoded on DVD's and CD's.

III. Elasticity — elastic deformations, both static and dynamic, of solids. Here some of our applications are bifurcations of equilibria and bifurcation-triggered instabilities, stress-polishing of mirrors, mountain folding, buckling, seismology and seismic tomography.

IV. Fluid Dynamics, with the fluids including, for example, air, water, blood, and interplanetary and interstellar gas. Some of the fluid concepts we study are vorticity, turbulence, boundary layers, subsonic and supersonic flows, convection, sound waves, shock waves and magnetohydrodynamics. Among our applications are the flow of blood through constricted vessels, the dynamics of a high-speed spinning baseball, convection in stars, helioseismology, supernovae, nuclear explosions, sedimentation and nuclear winter, the excitation of ocean waves by wind, salt fingers in the ocean, tornados and water spouts, the Sargasso Sea and the Gulf Stream in the Atlantic

Ocean, nonlinear waves in fluids (solitons and their interactions), stellerators, tokamaks, and controlled thermonuclear fusion.

V. Plasma Physics, with the plasmas including those in earth-bound laboratories and technological devices, the earth's ionosphere, stellar interiors and coronae, and interplanetary and interstellar space. In addition to magnetohydrodynamics (treated in Part IV), we develop three other physical and mathematical descriptions of plasmas: kinetic theory, two-fluid formalism, and quasi-linear theory which we express in the quantum language of weakly coupled plasmons and particles. Among our plasma applications are: some of the many types of waves (plasmons) that a plasma can support—both linear waves and nonlinear (soliton) waves; the influence of the earth's ionosphere on radio-wave propagation; the wide range of plasma instabilities that have plagued the development of controlled thermonuclear fusion; and wave-particle (plasmon-electron and plasmon-ion) interactions, including the two-stream instability for fast coronal electrons in the solar wind, isotropization of cosmic rays via scattering by magnetosonic waves, and Landau damping of electrostatic waves.

VI. General Relativity, i.e. the physics of curved spacetime, including the laws by which mass-energy and momentum curve spacetime, and by which that curvature influences the motion of matter and influences the classical laws of physics (e.g., the laws of fluid mechanics, electromagntic fields, and optics). Here our applications include, among others, gravitational experiments on earth and in our solar system; relativistic stars and black holes, both spinning (Kerr) and nonspinning (Schwarzschild); the extraction of spin energy from black holes; interactions of black holes with surrounding and infalling matter; gravitational waves and their generation and detection; and the large-scale structure and evolution of the universe (cosmology), including the big bang, the inflationary era, and the modern era. Throughout, we emphasize the physical content of general relativity and the connection of the theory to experiment and observation.

Each of the six parts is semi-independent of the others. It should be possible to read and teach the parts independently, if one is willing to dip into earlier parts occasionally, as needed, to pick up an occasional concept, tool or result from earlier. We have tried to provide enough cross references to make this possible. The full book has been designed for a full-year course at the first-year graduate level; and that is how we have used it, covering one chapter per week. (Many fourth-year undergraduates have taken our course successfully, but not easily.)

In most of this book, we adopt a **geometrical view of physics**; i.e., we express the laws of physics in geometric, frame-independent language (the language of vectors and tensors), and we use geometric reasoning in our applications. Because our geometric viewpoint is so fundamental and will be unfamiliar to many readers, we begin this book with a chapter that lays out that viewpoint carefully and pedagogically, both in 3-dimensional flat space (Newtonian physics) and in 4-dimensional, flat spacetime (special relativistic physics). In Parts I – V we focus largely on nonrelativistic, Newtonian physics, with some major exceptions (for example, we develop kinetic theory relativistically and explore relativistic as well as Newtonian applications of it; and we study relativistic, high-speed fluids, though most of our fluid studies are Newtonian.) Part VI is fully relativistic, including, of course, the warping of 4-dimensional spacetime by the mass-energy and momentum that it contains.

Exercises are a major component of this book. There are five types of exercises:

1 *Practice.* Exercises that give practice at mathematical manipulations (e.g., of tensors).

2 *Derivation.* Exercises that fill in details of arguments or derivations which are skipped over in the text.

3 *Example.* Exercises that lead the reader step by step through the details of some important extension or application of the material in the text.

4 *Problem.* Exercises with few if any hints, in which the task of figuring out how to set the calculation up and get started on it often is as difficult as doing the calculation itself.

5 *Challenge.* An especially difficult exercise whose solution may require that one read other books or articles as a foundation for getting started.

We urge readers to try working many of the exercises, and to *read and think about all of the Example exercises.* The Examples should be regarded as continuations of the text; they contain many of the most illuminating applications.

A few words on **units:** In this text we will be dealing with practical matters and will frequently need to have a quantitative understanding of the magnitude of various physical quantities. This requires us to adopt a particular unit system. Students we teach are about equally divided in preferring cgs/Gaussian units or MKS/SI units. Both of these systems provide a complete and internally consistent set for all of physics and it is an often-debated issue as to which of these is the more convenient or aesthetically appealing. We will not enter this debate! One's choice of units should not matter and a mature physicist should be able to change from one system to another without thinking. However, when learning new concepts, having to figure out "where the 4π's go" is a genuine impediment to progress. Our solution to this problem is as follows: We shall use the units that seem most natural for the topic at hand or those which, we judge, constitute the majority usage for the subculture that the topic represents. We shall not pedantically convert cm to m or *vice versa* at every juncture; we trust that the reader can easily make whatever translation is necessary. However, where the equations are actually different, for example as is the case in electromagnetic theory, we shall often provide, in brackets or footnotes, the equivalent equations in the other unit system and enough information for the reader to proceed in his or her preferred scheme. As an aid, we also give some unit-conversion information in Appendix C, and values of physical constants in Appendix D.

We wrote this book in connection with a full-year course that we and others have taught at Caltech nearly every year since the early 1980s. We conceived that course and this book in response to a general concern at Caltech that our PhD physics students were being trained too narrowly, without exposure to the basic concepts of classical physics beyond electricity & magnetism, classical mechanics, and elementary thermodynamics. Courses based on parts of this book, in its preliminary form, have been taught by various physicists, not only at Caltech but also at a few other institutions in recent years, and since moving to Stanford in 2003, Blandford has taught from it there. Many students who took our Caltech course, based on early versions of our book, have told us, with enthusiasm, how valuable it was in their later careers. Some were even enthusiastic during the course.

Many generations of students and many colleagues have helped us hone the book's presentation and its exercises through comments and criticisms, sometimes caustic, usually helpful; we thank them. Most especially:

For helpful advice about presentations and/or exercises in the book, and/or material that went into the book, we thank Professors Steve Koonin, Steven Frautschi, Peter Goldreich, Sterl Phinney, David Politzer, and David Stevenson at Caltech (all of whom taught portions of our Caltech course at one time or another), and XXXXX [ROGER: WHO ELSE SHOULD WE BE LISTING?]

Over the years, we have received extremely valuable advice about this book from the teaching assistants in our course: XXXXXXX[WE MUST ASSEMBLE A COMPLETE LIST] We are very indebted to them.

We hope that, in its published form, this book will trigger a significant broadening of the training of physics graduate students elsewhere in the world, as it has done at Caltech.

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Stanford University and Caltech, September 2004

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[For an alternative overview of this book, See *Appendix A. Concept-Based Outline.*]

II. OPTICS

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VI. GENERAL RELATIVITY

APPENDICES