An Introduction to Mechanics

For 40 years, Kleppner and Kolenkow's classic text has introduced students to the principles of mechanics. Now brought up-to-date, this revised and improved Second Edition is ideal for classical mechanics courses for first- and second-year undergraduates with foundation skills in mathematics.

The book retains all the features of the first edition, including numerous worked examples, challenging problems, and extensive illustrations, and has been restructured to improve the flow of ideas. It now features

- New examples taken from recent developments, such as laser slowing of atoms, exoplanets, and black holes
- A "Hints, Clues, and Answers" section for the end-of-chapter problems to support student learning
- A solutions manual for instructors at www.cambridge.org/kandk

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Robert Kolenkow

AN INTRODUCTION TO MECHANICS

SECOND EDITION

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PREFACE

An Introduction to Mechanics grew out of a one-semester course at the Massachusetts Institute of Technology—Physics 8.012—intended for students who seek to understand physics more deeply than the usual freshman level. In the four decades since this text was written physics has moved forward on many fronts but mechanics continues to be a bedrock for concepts such as inertia, momentum, and energy; fluency in the physicist's approach to problem-solving—an underlying theme of this book—remains priceless. The positive comments we have received over the years from students, some of whom are now well advanced in their careers, as well as from faculty at M.I.T. and elsewhere, reassures us that the approach of the text is fundamentally sound. We have received many suggestions from colleagues and we have taken this opportunity to incorporate their ideas and to update some of the discussions.

We assume that our readers know enough elementary calculus to differentiate and integrate simple polynomials and trigonometric functions. We do not assume any familiarity with differential equations. Our experience is that the principal challenge for most students is not with understanding mathematical concepts but in learning how to apply them to physical problems. This comes with practice and there is no substitute for solving challenging problems. Consequently problem-solving takes high priority. We have provided numerous worked examples to help provide guidance. Where possible we try to tie the examples to interesting physical phenomena but we are unapologetic about totally pedagogical problems. A block sliding down a plane is sometimes mocked as the quintessentially dull physics problem but if one allows the plane to accelerate, the system takes on a new complexion.

The problems in the first edition have challenged, instructed, and occasionally frustrated generations of physicists. Some former students have volunteered that working these problems gave them the confidence to pursue careers in science. Consequently, most of the problems in the first edition have been retained and a number of new problems have been added. We continue to respect the wisdom of Piet Hein's aphoristic ditty[1]

Problems worthy of attack,
Prove their worth by hitting back.

In addition to this inspirational thought, we offer students a few practical suggestions: The problems are meant to be worked with pencil and paper. They generally require symbolic solutions: numerical values, if needed, come last. Only by looking at a symbolic solution can one decide if an answer is reasonable. Diagrams are helpful. Hints and answers are given for some of the problems. We have not included solutions in the book because checking one's approach before making the maximum effort is often irresistible. Working in groups can be instructional for all parties. A separate solutions manual with restricted distribution is however available from Cambridge University Press.

Two revolutionary advances in physics that postdate the first edition deserve mention. The first is the discovery, more accurately the rediscovery, of chaos in the 1970's and the subsequent emergence of chaos theory as a vital branch of dynamics. Because we could not discuss chaos meaningfully within a manageable length, we have not attempted to deal with it. On the other hand, it would have been intellectually dishonest to present evidence for the astounding accuracy of Kepler's laws without mentioning that the solar system is chaotic, though with a time-scale too long to be observable, and so we have duly noted the existence of chaos. The second revolutionary advance is the electronic computer. Computational physics is now a well-established discipline and some level of computational fluency is among the physicist's standard tools. Nevertheless, we have elected not to include computational problems because they are not essential for understanding the concepts of the book, and because they have a seductive way of consuming time.

Here is a summary of the second edition: The first chapter is a mathematical introduction to vectors and kinematics. Vector notation is standard not only in the text but throughout physics and so we take some care to explain it. Translational motion is naturally described using familiar Cartesian coordinates. Rotational motion is equally important but its natural coordinates are not nearly as familiar. Consequently, we put special emphasis on kinematics using polar coordinates. Chapter 2 introduces Newton's laws starting with the decidedly non-trivial concept of inertial systems. This chapter has been converted into two, the first (Chapter 2) discussing principles and the second (Chapter 3) devoted to applying these to various physical systems. Chapter 4 introduces the concepts of momentum, momentum flux, and the conservation of

[1] From *Grooks 1* by Piet Hein, copyrighted 1966, The M.I.T. Press.

momentum. Chapter 5 introduces the concepts of kinetic energy, potential energy, and the conservation of energy, including heat and other forms. Chapter 6 applies the preceding ideas to phenomena of general interest in mechanics: small oscillations, stability, coupled oscillators and normal modes, and collisions. In Chapter 7 the ideas are extended to rotational motion. Fixed axis rotation is treated in this chapter, followed by the more general situation of rigid body motion in Chapter 8. Chapter 9 returns to the subject of inertial systems, in particular how to understand observations made in non-inertial systems. Chapters 10 and 11 present two topics that are of general interest in physics: central force motion and the damped and forced harmonic oscillator, respectively. Chapters 12–14 provide an introduction to non-Newtonian physics: the special theory of relativity.

When we created Physics 8.012 the M.I.T. semester was longer than it is today and there is usually not enough class time to cover all the material. Chapters 1–9 constitute the intellectual core of the course. Some combination of Chapters 9–14 is generally presented, depending on the instructor's interest.

We wish to acknowledge contributions to the book made over the years by colleagues at M.I.T. These include R. Aggarwal, G. B. Benedek, A. Burgasser, S. Burles, D. Chakrabarty, L. Dreher, T. J. Greytak, H. T. Imai, H. J. Kendall (deceased), W. Ketterle, S. Mochrie, D. E. Pritchard, P. Rebusco, S. W. Stahler, J. W. Whitaker, F. A. Wilczek, and M. Zwierlein. We particularly thank P. Dourmashkin for his help.

Daniel Kleppner
Robert J. Kolenkow

TO THE TEACHER

This edition of *An Introduction to Mechanics*, like the first edition, is intended for a one-semester course. Like the first edition, there are 14 chapters, though much of the material has been rewritten and two chapters are new. The discussion of Newton's laws, which sets the tone for the course, is now presented in two chapters. Also, the discussion of energy and energy conservation has been augmented and divided into two chapters. Chapter 5 on vector calculus from the first edition has been omitted because the material was not essential and its presence seemed to generate some math anxiety. A portion of the material is in an appendix to Chapter 5.

The discussion of energy has been extended. The idea of heat has been introduced by relating the ideal gas law to the concept of momentum flux. This simultaneously incorporates heat into the principle of energy conservation, and illustrates the fundamental distinction between heat and kinetic energy. At the practical end, some statistics are presented on international energy consumption, a topic that might stimulate thinking about the role of physics in society,

The only other substantive change has been a recasting of the discussion of relativity with more emphasis on the spacetime description. Throughout the book we have attempted to make the math more user friendly by solving problems from a physical point of view before presenting a mathematical solution. In addition, a number of new examples have been provided.

The course is roughly paced to a chapter a week. The first nine chapters are vital for a strong foundation in mechanics: the remainder covers material that can be picked up in the future. The first chapter introduces the language of vectors and provides a background in kinematics that is used throughout the text. Students are likely to return to Chapter 1, using it as a resource for later chapters.

On a few occasions we have been able to illustrate concepts by examples based on relatively recent advances in physics, for instance exoplanets, laser-slowing of atoms, the solar powered space kite, and stars orbiting around the cosmic black hole at the center of our galaxy.

The question of student preparation for Physics 8.012 at M.I.T. comes up regularly. We have found that the most reliable predictor of performance is a quiz on elementary calculus. At the other extreme, occasionally a student takes Physics 8.012 having already completed an AP physics course. Taking a third introductory physics course might be viewed as cruel and unusual, but to our knowledge, these students all felt that the experience was worthwhile.

LIST OF EXAMPLES

Chapter 7 ANGULAR MOMENTUM AND FIXED AXIS ROTATION

Chapter 8 RIGID BODY MOTION

Chapter 9 NON-INERTIAL SYSTEMS AND FICTITIOUS FORCES

Chapter 10 CENTRAL FORCE MOTION