GRADUATE TEXTS IN PHYSICS

Florian Scheck

Mechanics

From Newton's Law to Deterministic Chaos

5th

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Fifth Edition

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by Florian Scheck

Mechanics

Graduate Texts In Physics

Graduate Texts in Physics publishes core learning/teaching material for graduate- and advanced-level undergraduate courses on topics of current and emerging fields within physics, both pure and applied. These textbooks serve students at the MS- or PhD-level and their instructors as comprehensive sources of principles, definitions, derivations, experiments and applications (as relevant) for their mastery and teaching, respectively. International in scope and relevance, the textbooks correspond to course syllabi sufficiently to serve as required reading. Their didactic style, comprehensiveness and coverage of fundamental material also make them suitable as introductions or references for scientists entering, or requiring timely knowledge of, a research field.

Preface

Purpose and Emphasis. Mechanics not only is the oldest branch of physics but was and still is the basis for all of theoretical physics. Quantum mechanics can hardly be understood, perhaps cannot even be formulated, without a good knowledge of general mechanics. Field theories such as electrodynamics borrow their formal framework and many of their building principles from mechanics. In short, throughout the many modern developments of physics where one frequently turns back to the principles of classical mechanics its model character is felt. For this reason it is not surprising that the *presentation* of mechanics reflects to some extent the development of modern physics and that today this classical branch of theoretical physics is taught rather differently than at the time of Arnold Sommerfeld, in the 1920s, or even in the 1950s, when more emphasis was put on the theory and the applications of partial-differential equations. Today, *symmetries* and *invariance principles*, the *structure of the space–time continuum*, and the *geometrical structure* of mechanics play an important role. The beginner should realize that mechanics is not primarily the art of describing block-and-tackles, collisions of billiard balls, constrained motions of the cylinder in a washing machine, or bicycle riding. However fascinating such systems may be, mechanics is primarily the field where one learns to develop general principles from which equations of motion may be derived, to understand the importance of symmetries for the dynamics, and, last but not least, to get some practice in using theoretical tools and concepts that are essential for all branches of physics.

Besides its role as a basis for much of theoretical physics and as a training ground for physical concepts, mechanics is a fascinating field in itself. It is not easy to master, for the beginner, because it has many different facets and its structure is less homogeneous than, say, that of electrodynamics. On a first assault one usually does not fully realize both its charm and its difficulty. Indeed, on returning to various aspects of mechanics, in the course of one's studies, one will be surprised to discover again and again that it has new facets and new secrets. And finally, one should be aware of the fact that mechanics is not a closed subject, lost forever in the archives of the nineteenth century. As the reader will realize in Chap. 6, if he or she has not realized it already, mechanics is an exciting field of research with many important questions of qualitative dynamics remaining unanswered.

Structure of the Book and a Reading Guide. Although many people prefer to skip prefaces, I suggest that the reader, if he or she is one of them, make an exception for once and read at least this section and the next. The short introductions at the beginning of each chapter are also recommended because they give a summary of the chapter's content.

Chapter 1 starts from Newton's equations and develops the elementary dynamics of one-, two-, and many-body systems for unconstrained systems. This is the basic material that could be the subject of an introductory course on theoretical physics or could serve as a text for an integrated (experimental and theoretical) course.

Chapter 2 is the "classical" part of general mechanics describing the principles of canonical mechanics following Euler, Lagrange, Hamilton, and Jacobi. Most of the material is a MUST. Nevertheless, the sections on the symplectic structure of mechanics (Sect. 2.28) and on perturbation theory (Sects. 2.38–2.40) may be skipped on a first reading.

Chapter 3 describes a particularly beautiful application of classical mechanics: the theory of spinning tops. The rigid body provides an important and highly nontrivial example of a motion manifold that is not a simple Euclidean space $\mathbb{R}^{2f}$, where f is the number of degrees of freedom. Its rotational part is the manifold of SO(3), the rotation group in three real dimensions. Thus, the rigid body illustrates a Lie group of great importance in physics within a framework that is simple and transparent.

Chapter 4 deals with relativistic kinematics and dynamics of pointlike objects and develops the elements of special relativity. This may be the most difficult part of the book, as far as the physics is concerned, and one may wish to return to it when studying electrodynamics.

Chapter 5 is the most challenging in terms of the mathematics. It develops the basic tools of differential geometry that are needed to formulate mechanics in this setting. Mechanics is then described in geometrical terms and its underlying structure is worked out. This chapter is conceived such that it may help to bridge the gap between the more "physical" texts on mechanics and the modern mathematical literature on this subject. Although it may be skipped on a first reading, the tools and the language developed here are essential if one wishes to follow the modern literature on qualitative dynamics.

Chapter 6 provides an introduction to one of the most fascinating recent developments of classical dynamics: stability and deterministic chaos. It defines and illustrates all important concepts that are needed to understand the onset of chaotic motion and the quantitative analysis of unordered motions. It culminates in a few examples of chaotic motion in celestial mechanics.

Chapter 7, finally, gives a short introduction to continuous systems, i.e. systems with an infinite number of degrees of freedom.

Exercises and Practical Examples. In addition to the exercises that follow Chaps. 1–6, the book contains a number of practical examples in the form of exercises followed by complete solutions. Most of these are meant to be worked out on a personal computer, thereby widening the range of problems that can be solved with elementary means, beyond the analytically integrable ones. I have tried to choose examples simple enough that they can be made to work even on a programmable pocket computer and in a spirit, I hope, that will keep the reader from getting lost in the labyrinth of computional games.

Length of this Book. Clearly there is much more material here than can be covered in one semester. The book is designed for a two-semester course (i.e., typically, an introductory course followed by a course on general mechanics). Even then, a certain choice of topics will have to be made. However, the text is sufficiently self-contained that it may be useful for complementary reading and individual study.

Mathematical Prerequisites. A physicist must acquire a certain flexibility in the use of mathematics. On the one hand, it is impossible to carry out all steps in a deduction or a proof, since otherwise one will not get very far with the physics one wishes to study. On the other hand, it is indispensable to know analysis and linear algebra in some depth, so as to be able to fill in the missing links in a logical deduction. Like many other branches of physics, mechanics makes use of many and various disciplines of mathematics, and one cannot expect to have all the tools ready before beginning its study. In this book I adopt the following, somewhat generous attitude towards mathematics. In many places, the details are worked out to a large extent; in others I refer to well-known material of linear algebra and analysis. In some cases the reader might have to return to a good text in mathematics or else, ideally, derive certain results for him- or herself. In this connection it might also be helpful to consult the appendix at the end of the book.

General Comments and Acknowledgements. This fifth English edition follows closely the eigth German edition (volume 1 of a series of five textbooks). As compared to the third English edition published in 1999, there are a number revisions and additions. Some of these are the following. In Chap. 1 more motivation for the introduction of phase space at this early stage is given. A paragraph on the notion of hodograph is added which emphasizes the special nature of Keplerian bound orbits. Chap. 2 is supplemented by some extensions and further explanations, specifically in relation with Legendre transformation. Also, a new section on a generalized version of Noether's theorem was added, together with some enlightening examples. In Chap. 3 more examples are given for inertia tensors and the use of Steiner's theorem. Here and in Chap. 4 the symbolic "bra" and "ket" notation is introduced in characterizing vectors and their duals. The present, fifth edition differs from the previous, fourth edition of 2005 by a few corrections and some additions in response to specific questions asked by students and other readers.

The book contains the solutions to all exercises, as well as some historical notes on scientists who made important contributions to mechanics and to the mathematics on which it rests. The index of names, in addition to the subject index, may also be helpful in locating quickly specific items in mechanics.

This book was inspired by a two-semester course on general mechanics that I have taught on and off over the last decades at the Johannes Gutenberg University at Mainz and by seminars on geometrical aspects of mechanics. I thank my collaborators, colleagues, and students for stimulating questions, helpful remarks, and profitable discussions. I was happy to realize that the German original, since its

first appearance in October 1988, has become a standard text at German speaking universities and I can only hope that it will continue to be equally successful in its English version. I am grateful for the many encouraging reactions and suggestions I have received over the years. Among those to whom I owe special gratitude are P. Hagedorn, K. Hepp, D. Kastler, H. Leutwyler, L. Okun, N. Papadopoulos, J.M. Richard, G. Schuster, J. Smith, M. Stingl, N. Straumann, W. Thirring, E. Vogt, and V. Vento. Special thanks are due to my former student R. Schöpf who collaborated on the earlier version of the solutions to the exercises. I thank J. Wisdom for his kind permission to use four of his figures illustrating chaotic motions in the solar system, and P. Beckmann who provided the impressive illustrations for the logistic equation and who advised me on what to say about them.

The excellent cooperation with the team of Springer-Verlag is gratefully acknowledged. Last but not least, I owe special thanks to Dörte for her patience and encouragement.

As with the German edition, I dedicate this book to all those students who wish to study mechanics at some depth. If it helps to make them aware of the fascination of this beautiful field and of physics in general then one of my goals in writing this book is reached.

Mainz, March 2010 *Florian Scheck*

As in the past, I will keep track of possible errata on a page attached to my home page. The latter can be accessed via http://wwwthep.physik.uni-mainz.de/site/.

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Contents

1. Elementary Newtonian Mechanics

This chapter deals with the kinematics and the dynamics of a finite number of mass points that are subject to internal, and possibly external, forces, but whose motions are not further constrained by additional conditions on the coordinates. (The mathematical pendulum will be an exception). Constraints such as requiring some mass points to follow given curves in space, to keep their relative distance fixed, or the like, are introduced in Chap. 2. Unconstrained mechanical systems can be studied directly by means of Newton's equations and do not require the introduction of new, generalized coordinates that incorporate the constraints and are dynamically independent. This is what is meant by "elementary" in the heading of this chapter – though some of its content is not elementary at all. In particular, at an early stage, we shall discover an intimate relationship between invariance properties under coordinate transformations and conservation laws of the theory, which will turn out to be a basic, constructive element for all of mechanics and which, for that matter, will be felt like a *cantus firmus*[1] throughout the whole of theoretical physics. The first, somewhat deeper analysis of these relations already leads one to consider the nature of the spatial and temporal manifolds that carry mechanical motions, thereby entering a discussion that is of central importance in present-day physics at both the smallest and the largest dimensions.

We also introduce the notion of *phase space*, i.e. the description of physical motions in an abstract space spanned by coordinates and corresponding momenta, and thus prepare the ground for canonical mechanics in the formulation of Hamilton and Jacobi.

We begin with Newton's fundamental laws, which we interpret and translate into precise analytical statements. They are then illustrated by a number of examples and some important applications.

1.1 Newton's Laws (1687) and Their Interpretation

We begin by stating Newton's fundamental laws in a formulation that is close to the original one. They are as follows:

[1] *cantus firmus*: a preexisting melody, such as a plainchant excerpt, which underlies a polyphonic musical composition.

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