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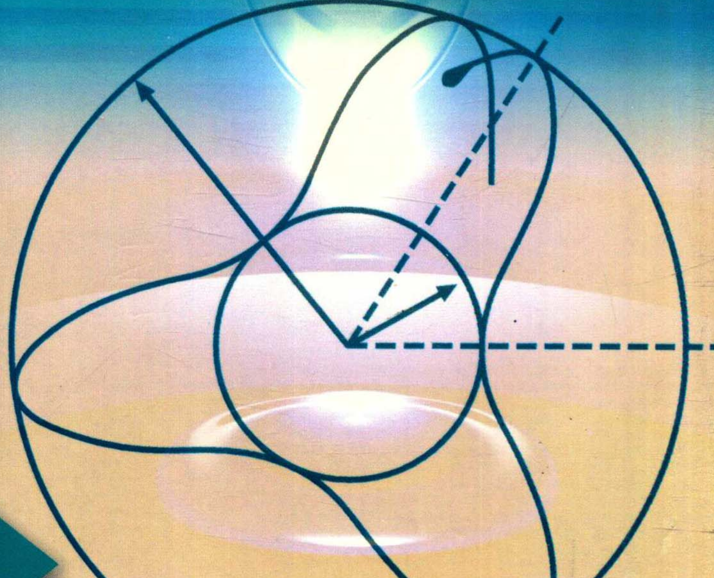
Classical Mechanics (Third Edition)

经典力学（第三版）

□ Herbert Goldstein
□ Charles Poole
□ John Safko



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内 容 简 介

美国哥伦比亚州大学 Herbert Goldstein 编著的《经典力学》（Classical Mechanics）是一本有着很高知名度的经典力学教材，长期以来被世界上多所大学选用。本影印版是2002年出版的第3版。与前两版相比，第3版在保留基本经典力学内容的基础上，做了不少调整。例如，增加了混沌一章；引入了一些对新研究问题的方法的讨论，例如张量、群论等；对于第二版中的一些内容做了适当的压缩和调整。

全书共13章，可作为物理类专业经典力学课程的教材，尤其适合开展双语教学的学校，对于有志出国深造的人员也是一本不可多得的参考书。

Preface to the Third Edition

The first edition of this text appeared in 1950, and it was so well received that it went through a second printing the very next year. Throughout the next three decades it maintained its position as the acknowledged standard text for the introductory Classical Mechanics course in graduate level physics curricula throughout the United States, and in many other countries around the world. Some major institutions also used it for senior level undergraduate Mechanics. Thirty years later, in 1980, a second edition appeared which was "a through-going revision of the first edition." The preface to the second edition contains the following statement: "I have tried to retain, as much as possible, the advantages of the first edition while taking into account the developments of the subject itself, its position in the curriculum, and its applications to other fields." This is the philosophy which has guided the preparation of this third edition twenty more years later.

The second edition introduced one additional chapter on Perturbation Theory, and changed the ordering of the chapter on Small Oscillations. In addition it added a significant amount of new material which increased the number of pages by about 68%. This third edition adds still one more new chapter on Nonlinear Dynamics or Chaos, but counterbalances this by reducing the amount of material in several of the other chapters, by shortening the space allocated to appendices, by considerably reducing the bibliography, and by omitting the long lists of symbols. Thus the third edition is comparable in size to the second.

In the chapter on relativity we have abandoned the complex Minkowski space in favor of the now standard real metric. Two of the authors prefer the complex metric because of its pedagogical advantages (HG) and because it fits in well with Clifford Algebra formulations of Physics (CPP), but the desire to prepare students who can easily move forward into other areas of theory such as field theory and general relativity dominated over personal preferences. Some modern notation such as 1-forms, mapping and the wedge product is introduced in this chapter.

The chapter on Chaos is a necessary addition because of the current interest in nonlinear dynamics which has begun to play a significant role in applications of classical dynamics. The majority of classical mechanics problems and applications in the real world include nonlinearities, and it is important for the student to have a grasp of the complexities involved, and of the new properties that can emerge. It is also important to realize the role of fractal dimensionality in chaos.

New sections have been added and others combined or eliminated here and there throughout the book, with the omissions to a great extent motivated by the desire not to extend the overall length beyond that of the second edition. A section was added on the Euler and Lagrange exact solutions to the three body problem. In several places phase space plots and Lissajous figures were appended to illustrate solutions. The damped-driven pendulum was discussed as an example that explains the workings of Josephson junctions. The symplectic approach was clarified by writing out some of the matrices. The harmonic oscillator was treated with anisotropy, and also in polar coordinates. The last chapter on continua and fields was formulated in the modern notation introduced in the relativity chapter. The significances of the special unitary group in two dimensions SU(2) and the special orthogonal group in three dimensions SO(3) were presented in more up-to-date notation, and an appendix was added on groups and algebras. Special tables were introduced to clarify properties of ellipses, vectors, vector fields and 1-forms, canonical transformations, and the relationships between the spacetime and symplectic approaches.

Several of the new features and approaches in this third edition had been mentioned as possibilities in the preface to the second edition, such as properties of group theory, tensors in non-Euclidean spaces, and "new mathematics" of theoretical physics such as manifolds. The reference to "One area omitted that deserves special attention—nonlinear oscillation and associated stability questions" now constitutes the subject matter of our new Chapter 11 "Classical Chaos." We debated whether to place this new chapter after Perturbation theory where it fits more logically, or before Perturbation theory where it is more likely to be covered in class, and we chose the latter. The referees who reviewed our manuscript were evenly divided on this question.

The mathematical level of the present edition is about the same as that of the first two editions. Some of the mathematical physics, such as the discussions of hermitean and unitary matrices, was omitted because it pertains much more to quantum mechanics than it does to classical mechanics, and little used notations like dyadics were curtailed. Space devoted to power law potentials, Cayley-Klein parameters, Routh's procedure, time independent perturbation theory, and the stress-energy tensor was reduced. In some cases reference was made to the second edition for more details. The problems at the end of the chapters were divided into "derivations" and "exercises," and some new ones were added.

The authors are especially indebted to Michael A. Unseren and Forrest M. Hoffman of the Oak Ridge National laboratory for their 1993 compilation of errata in the second edition that they made available on the Internet. It is hoped that not too many new errors have slipped into this present revision. We wish to thank the students who used this text in courses with us, and made a number of useful suggestions that were incorporated into the manuscript. Professors Thomas Sayetta and the late Mike Schuette made helpful comments on the Chaos chapter, and Professors Joseph Johnson and James Knight helped to clarify our ideas on Lie Algebras. The following professors reviewed the manuscript and made many helpful suggestions for improvements: Yoram Alhassid, Yale University; Dave Ellis, University of Toledo; John Gruber, San Jose State; Thomas Handler, University of Tennessee; Daniel Hong, Lehigh University; Kara Keeter, Idaho State University; Carolyn Lee; Yannick Meurice, University of Iowa; Daniel

Marlow, Princeton University; Julian Noble, University of Virginia; Muhammad Numan, Indiana University of Pennsylvania; Steve Ruden, University of California, Irvine; Jack Semura, Portland State University; Tammy Ann Smecker-Hane, University of California, Irvine; Daniel Stump, Michigan State University; Robert Wald, University of Chicago; Doug Wells, Idaho State University.

Special thanks are due Peter M. Brown, Robert Reynolds, Andy Tenne-Sens, and Jun Suzuki for providing us with corrections to the third printing. This material was considered and mostly included in the fourth and successive printings of this edition.

A list of corrections for all printings through the fourth edition are on the Web at ⟨http://astro.physics.sc.edu/goldstein/goldstein.html⟩. Additions to this listing may be emailed to the address given on that page.

It has indeed been an honor for two of us (CPP and JLS) to collaborate as co-authors of this third edition of such a classic book fifty years after its first appearance. We have admired this text since we first studied Classical Mechanics from the first edition in our graduate student days (CPP in 1953 and JLS in 1960), and each of us used the first and second editions in our teaching throughout the years. Professor Goldstein is to be commended for having written and later enhanced such an outstanding contribution to the classic Physics literature.

Above all we register our appreciation and acknolwedgement in the words of Psalm 19,1:

Οἱ οὐρανοι διηγοῦνται δοξαν Θεοῦ

Flushing, New York HERBERT GOLDSTEIN
Columbia, South Carolina CHARLES P. POOLE, JR.
Columbia, South Carolina JOHN L. SAFKO
July, 2002

Preface to the Second Edition

The prospect of a second edition of *Classical Mechanics*, almost thirty years after initial publication, has given rise to two nearly contradictory sets of reactions. On the one hand it is claimed that the adjective "classical" implies the field is complete, closed, far outside the mainstream of physics research. Further, the first edition has been paid the compliment of continuous use as a text since it first appeared. Why then the need for a second edition? The contrary reaction has been that a second edition is long overdue. More important than changes in the subject matter (which have been considerable) has been the revolution in the attitude towards classical mechanics in relation to other areas of science and technology. When it appeared, the first edition was part of a movement breaking with older ways of teaching physics. But what were bold new ventures in 1950 are the commonplaces of today, exhibiting to the present generation a slightly musty and old-fashioned air. Radical changes need to be made in the presentation of classical mechanics.

In preparing this second edition, I have attempted to steer a course somewhere between these two attitudes. I have tried to retain, as much as possible, the advantages of the first edition (as I perceive them) while taking some account of the developments in the subject itself, its position in the curriculum, and its applications to other fields. What has emerged is a thorough-going revision of the first edition. Hardly a page of the text has been left untouched. The changes have been of various kinds:

Errors (some egregious) that I have caught, or which have been pointed out to me, have of course been corrected. It is hoped that not too many new ones have been introduced in the revised material.

The chapter on small oscillations has been moved from its former position as the penultimate chapter and placed immediately after Chapter 5 on rigid body motion. This location seems more appropriate to the usual way mechanics courses are now being given. Some material relating to the Hamiltonian formulation has therefore had to be removed and inserted later in (the present) Chapter 8.

A new chapter on perturbation theory has been added (Chapter 11). The last chapter, on continuous systems and fields, has been greatly expanded, in keeping with the implicit promise made in the Preface to the first edition.

New sections have been added throughout the book, ranging from one in Chapter 3 on Bertrand's theorem for the central-force potentials giving rise to closed orbits, to the final section of Chapter 12 on Noether's theorem. For the most part these sections contain completely new material.

In various sections arguments and proofs have been replaced by new ones that seem simpler and more understandable, e.g., the proof of Euler's theorem in Chapter 4. Occasionally, a line of reasoning presented in the first edition has been supplemented by a different way of looking at the problem. The most important example is the introduction of the symplectic approach to canonical transformations, in parallel with the older technique of generating functions. Again, while the original convention for the Euler angles has been retained, alternate conventions, including the one common in quantum mechanics, are mentioned and detailed formulas are given in an appendix.

As part of the fruits of long experience in teaching courses based on the book, the body of exercises at the end of each chapter has been expanded by more than a factor of two and a half. The bibliography has undergone similar expansion, reflecting the appearance of many valuable texts and monographs in the years since the first edition. In deference to—but not in agreement with—the present neglect of foreign languages in graduate education in the United States, references to foreign-language books have been kept down to a minimum.

The choices of topics retained and of the new material added reflect to some degree my personal opinions and interests, and the reader might prefer a different selection. While it would require too much space (and be too boring) to discuss the motivating reasons relative to each topic, comment should be made on some general principles governing my decisions. The question of the choice of mathematical techniques to be employed is a vexing one. The first edition attempted to act as a vehicle for introducing mathematical tools of wide usefulness that might be unfamiliar to the student. In the present edition the attitude is more one of caution. It is much more likely now than it was 30 years ago that the student will come to mechanics with a thorough background in matrix manipulation. The section on matrix properties in Chapter 4 has nonetheless been retained, and even expanded, so as to provide a convenient reference of needed formulas and techniques. The cognoscenti can, if they wish, simply skip the section. On the other hand, very little in the way of newer mathematical tools has been introduced. Elementary properties of group theory are given scattered mention throughout the book. Brief attention is paid in Chapters 6 and 7 to the manipulation of tensors in non-Euclidean spaces. Otherwise, the mathematical level in this edition is pretty much the same as in the first. It is more than adequate for the physics content of the book, and alternate means exist in the curriculum for acquiring the mathematics needed in other branches of physics. In particular the "new mathematics" of theoretical physics has been deliberately excluded. No mention is made of manifolds or diffeomorphisms, of tangent fibre bundles or invariant tori. There are certain highly specialized areas of classical mechanics where the powerful tools of global analysis and differential topology are useful, probably essential. However, it is not clear to me that they contribute to the understanding of the physics of classical mechanics at the level sought in this edition. To introduce these mathematical concepts, and their applications, would swell the book beyond bursting, and serve, probably, only to obscure the physics. Theoretical physics, current trends to the contrary, is not merely mathematics.

In line with this attitude, the complex Minkowski space has been retained for most of the discussion of special relativity in order to simplify the mathematics. The bases for this decision (which it is realized goes against the present fashion) are given in detail on pages 292–293.

It is certainly true that classical mechanics today is far from being a closed subject. The last three decades have seen an efflorescence of new developments in classical mechanics, the tackling of new problems, and the application of the techniques of classical mechanics to far-flung reaches of physics and chemistry. It would clearly not be possible to include discussions of all of these developments here. The reasons are varied. Space limitations are obviously important. Also, popular fads of current research often prove ephemeral and have a short lifetime. And some applications require too extensive a background in other fields, such as solid-state physics or physical chemistry. The selection made here represents something of a personal compromise. Applications that allow simple descriptions and provide new insights are included in some detail. Others are only briefly mentioned, with enough references to enable the student to follow up his awakened curiosity. In some instances I have tried to describe the current state of research in a field almost entirely in words, without mathematics, to provide the student with an overall view to guide further exploration. One area omitted deserves special mention—nonlinear oscillation and associated stability questions. The importance of the field is unquestioned, but it was felt that an adequate treatment deserves a book to itself.

With all the restrictions and careful selection, the book has grown to a size probably too large to be covered in a single course. A number of sections have been written so that they may be omitted without affecting later developments and have been so marked. It was felt however that there was little need to mark special "tracks" through the book. Individual instructors, familiar with their own special needs, are better equipped to pick and choose what they feel should be included in the courses they give.

I am grateful to many individuals who have contributed to my education in classical mechanics over the past thirty years. To my colleagues Professors Frank L. DiMaggio, Richard W. Longman, and Dean Peter W. Likins I am indebted for many valuable comments and discussions. My thanks go to Sir Edward Bullard for correcting a serious error in the first edition, especially for the gentle and gracious way he did so. Professor Boris Garfinkel of Yale University very kindly read and commented on several of the chapters and did his best to initiate me into the mysteries of celestial mechanics. Over the years I have been the grateful recipient of valuable corrections and suggestions from many friends and strangers, among whom particular mention should be made of Drs. Eric Ericsen (of Oslo University), K. Kalikstein, J. Neuberger, A. Radkowsky, and Mr. W. S. Pajes. Their contributions have certainly enriched the book, but of course I alone am responsible for errors and misinterpretations. I should like to add a collective acknowledgment and thanks to the authors of papers on classical mechanics that have appeared during the last three decades in the *American Journal of Physics*, whose pages I hope I have perused with profit.

The staff at Addison-Wesley have been uniformly helpful and encouraging. I want especially to thank Mrs. Laura R. Finney for her patience with what must have seemed a never-ending process, and Mrs. Marion Howe for her gentle but persistent cooperation in the fight to achieve an acceptable printed page.

To my father, Harry Goldstein ז״ל, I owe more than words can describe for his lifelong devotion and guidance. But I wish at least now to do what he would not permit in his lifetime—to acknowledge the assistance of his incisive criticism and careful editing in the preparation of the first edition. I can only hope that the present edition still reflects something of his insistence on lucid and concise writing.

I wish to dedicate this edition to those I treasure above all else on this earth, and who have given meaning to my life—to my wife, Channa, and our children, Penina Perl, Aaron Meir, and Shoshanna.

And above all I want to register the thanks and acknowledgment of my heart, in the words of Daniel (2:23):

לך אלה אבהתי מהודא ומשבח אנה
די חכמתא וגבורתא יהבת לי

Kew Gardens Hills, New York
January 1980

HERBERT GOLDSTEIN

Preface to the First Edition

An advanced course in classical mechanics has long been a time-honored part of the graduate physics curriculum. The present-day function of such a course, however, might well be questioned. It introduces no new physical concepts to the graduate student. It does not lead him directly into current physics research. Nor does it aid him, to any appreciable extent, in solving the practical mechanics problems he encounters in the laboratory.

Despite this arraignment, classical mechanics remains an indispensable part of the physicist's education. It has a twofold role in preparing the student for the study of modern physics. First, classical mechanics, in one or another of its advanced formulations, serves as the springboard for the various branches of modern physics. Thus, the technique of action-angle variables is needed for the older quantum mechanics, the Hamilton-Jacobi equation and the principle of least action provide the transition to wave mechanics, while Poisson brackets and canonical transformations are invaluable in formulating the newer quantum mechanics. Secondly, classical mechanics affords the student an opportunity to master many of the mathematical techniques necessary for quantum mechanics while still working in terms of the familiar concepts of classical physics.

Of course, with these objectives in mind, the traditional treatment of the subject, which was in large measure fixed some fifty years ago, is no longer adequate. The present book is an attempt at an exposition of classical mechanics which does fulfill the new requirements. Those formulations which are of importance for modern physics have received emphasis, and mathematical techniques usually associated with quantum mechanics have been introduced wherever they result in increased elegance and compactness. For example, the discussion of central force motion has been broadened to include the kinematics of scattering and the classical solution of scattering problems. Considerable space has been devoted to canonical transformations, Poisson bracket formulations, Hamilton-Jacobi theory, and action-angle variables. An introduction has been provided to the variational principle formulation of continuous systems and fields. As an illustration of the application of new mathematical techniques, rigid body rotations are treated from the standpoint of matrix transformations. The familiar Euler's theorem on the motion of a rigid body can then be presented in terms of the eigenvalue problem for an orthogonal matrix. As a consequence, such diverse topics as the inertia tensor, Lorentz transformations in Minkowski space, and resonant frequencies of small oscillations become capable of a unified mathematical treatment. Also, by this technique it becomes possible to include at an early stage the difficult concepts of reflection operations and pseudotensor quantities, so important in modern quantum mechanics. A further advantage of matrix methods is that "spinors" can be introduced in connection with the properties of Cayley-Klein parameters.

Several additional departures have been unhesitatingly made. All too often, special relativity receives no connected development except as part of a highly specialized course which also covers general relativity. However, its vital importance in modern physics requires that the student be exposed to special relativity at an early stage in his education. Accordingly, Chapter 6 has been devoted to the subject. Another innovation has been the inclusion of velocity-dependent forces. Historically, classical mechanics developed with the emphasis on static forces dependent on position only, such as gravitational forces. On the other hand, the velocity-dependent electromagnetic force is constantly encountered in modern physics. To enable the student to handle such forces as early as possible, velocity-dependent potentials have been included in the structure of mechanics from the outset, and have been consistently developed throughout the text.

Still another new element has been the treatment of the mechanics of continuous systems and fields in Chapter 11, and some comment on the choice of material is in order. Strictly interpreted, the subject could include all of elasticity, hydrodynamics, and acoustics, but these topics lie outside the prescribed scope of the book, and adequate treatises have been written for most of them. In contrast, no connected account is available on the classical foundations of the variational principle formulation of continuous systems, despite its growing importance in the field theory of elementary particles. The theory of fields can be carried to considerable length and complexity before it is necessary to introduce quantization. For example, it is perfectly feasible to discuss the stress-energy tensor, microscopic equations of continuity, momentum space representations, etc., entirely within the domain of classical physics. It was felt, however, that an adequate discussion of these subjects would require a sophistication beyond what could naturally be expected of the student. Hence it was decided, for this edition at least, to limit Chapter 11 to an elementary description of the Lagrangian and Hamiltonian formulation of fields.

The course for which this text is designed normally carries with it a prerequisite of an intermediate course in mechanics. For both the inadequately prepared graduate student (an all too frequent occurrence) and the ambitious senior who desires to omit the intermediate step, an effort was made to keep the book self-contained. Much of Chapters 1 and 3 is therefore devoted to material usually covered in the preliminary courses.

With few exceptions, no more mathematical background is required of the student than the customary undergraduate courses in advanced calculus and vector analysis. Hence considerable space is given to developing the more complicated mathematical tools as they are needed. An elementary acquaintance with Maxwell's equations and their simpler consequences is necessary for understanding the sections on electromagnetic forces. Most entering graduate students have had at least one term's exposure to modern physics, and frequent advantage has been taken of this circumstance to indicate briefly the relation between a classical development and its quantum continuation.

A large store of exercises is available in the literature on mechanics, easily accessible to all, and there consequently seemed little point to reproducing an extensive collection of such problems. The exercises appended to each chapter therefore have been limited, in the main, to those which serve as extensions of the text, illustrating some particular point or proving variant theorems. Pedantic museum pieces have been studiously avoided.

The question of notation is always a vexing one. It is impossible to achieve a completely consistent and unambiguous system of notation that is not at the same time impracticable and cumbersome. The customary convention has been followed by indicating vectors by bold face Roman letters. In addition, matrix quantities of whatever rank, and tensors other than vectors, are designated by bold face sans serif characters, thus: **A**. An index of symbols is appended at the end of the book, listing the initial appearance of each meaning of the important symbols. Minor characters, appearing only once, are not included.

References have been listed at the end of each chapter, for elaboration of the material discussed or for treatment of points not touched on. The evaluations accompanying these references are purely personal, of course, but it was felt necessary to provide the student with some guide to the bewildering maze of literature on mechanics. These references, along with many more, are also listed at the end of the book. The list is not intended to be in any way complete, many of the older books being deliberately omitted. By and large, the list contains the references used in writing this book, and must therefore serve also as an acknowledgement of my debt to these sources.

The present text has evolved from a course of lectures on classical mechanics that I gave at Harvard University, and I am grateful to Professor J. H. Van Vleck, then Chairman of the Physics Department, for many personal and official encouragements. To Professor J. Schwinger, and other colleagues I am indebted for many valuable suggestions. I also wish to record my deep gratitude to the students in my courses, whose favorable reaction and active interest provided the continuing impetus for this work.

תושלב"ע

Cambridge, Mass.
March 1950

HERBERT GOLDSTEIN

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