MECHANICS

BERKELEY PHYSICS COURSE

Volume 1

SECOND EDITION

Mechanics

Berkeley Physics Course Volume 1, Second Edition

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Front cover: NGC 4594 spiral galaxy in Virgo, seen on edge; 200-in. photograph. The dark band is due to absorption by a ring of matter surrounding the bright central core. (*Photograph courtesy of the Hale Observatories.*)

Back cover: Hydrogen bubble chamber picture of the production of an anti-Ξ in the reaction $K^+ + p$. (*Photograph courtesy of the Lawrence Berkeley Laboratory.*)

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Table of Values

Value and Units	Item	Symbol or Abbreviation	Derivation of Value
Gases			
22.4×10^3 cm^3/mol	Molar volume at STP	V_0	
2.69×10^{19} cm^{-3}	Loschmidt's number	n_0	N_0/V_0
6.0222×10^{23} mol^{-1}	Avogadro's number	N_0	
8.314×10^7 ergs mol^{-1} deg^{-1}	Gas constant	R	
1.381×10^{-16} erg/K	Boltzmann's constant	k	R/N
1.01×10^6 dyn/cm^2	Atmospheric pressure		
$\approx 10^{-5}$ cm	Mean free path at STP		
3.32×10^4 cm/s	Speed of sound in air at STP		
Atomic			
6.6262×10^{-27} erg-s	Planck's constant	h	
1.0546×10^{-27} erg-s	Planck's constant/2π	$\hbar$	$h/2\pi$
13.6 electron volts	Energy associated with 1 Rydberg	Ry	
1.6022×10^{-12} erg	Energy associated with 1 electron volt	eV	
1.2398×10^{-4} cm	Wavelength associated with 1 electron volt		hc^2/e
2.4180×10^{14} s^{-1}	Frequency associated with 1 electron volt		
0.5292×10^{-8} cm	Bohr radius of the ground state of hydrogen	a_0	$\hbar^2/me^2$
$\approx 10^{-8}$ cm	Radius of an atom		
0.9274×10^{-20} erg/G	Bohr magneton	μ_B	$e\hbar/2mc$
137.036	Reciprocal of fine-structure constant	α^{-1}	$\hbar c/e^2$
Particles			
1.67265×10^{-24} g	Proton rest mass	M_p	
1.67496×10^{-24} g	Neutron rest mass	M_n	
1.66057×10^{-24} g	1 unified atomic mass unit ($\equiv \frac{1}{12}$ mass of C^{12})	u	
0.910954×10^{-27} g	Electron rest mass	m	
0.93828×10^9 eV	Energy equivalent to proton rest mass	E_p	M_pc^2
0.511004×10^6 eV	Energy equivalent to electron rest mass		mc^2
0.93150×10^9 eV	Energy equivalent to 1 atomic mass unit		
1836	Proton mass/electron mass		M_p/m
2.818×10^{-13} cm	Classical radius of the electron	r_0	e^2/mc^2
4.80325×10^{-10} esu	Charge on proton	e	
1.60219×10^{-19} C	Charge on proton	e	
2.423×10^{-10} cm	Electron Compton wavelength	λ_C	h/mc

Table of Values

Value and Units	Item	Symbol or Abbreviation	Derivation of Value
General			
57.3°(57°18′)	= 1 radian	rad	180°/π
3.44×10^3 minutes (of arc)	= 1 radian	rad	
2.06×10^5 seconds (of arc)	= 1 radian	rad	
1.75×10^{-2} rad	= 1 degree	°	π/180°
2.91×10^{-4} rad	= 1 minute (of arc)	′	
4.85×10^{-6} rad	= 1 second (of arc)	″	
1.609×10^5 cm	= 1 statute mile		
10^{-8} cm	≡ 1 angstrom	Å	
10^{-4} cm	≡ 1 micrometer (micron)	μm	
2.998×10^2 V	= 1 statvolt		$10^{-8}\ c$
2.99725×10^{10} cm/s	Speed of light in vacuum	c	
≈ 980 cm/s^2	Acceleration of gravity at earth's surface	g	GM_e/R_e^2
6.671×10^{-8} dyn-cm^2/g^2	Gravitational constant	G	
6.671×10^{-11} N-m^2/kg^2	Gravitational constant	G	
1 dyne	≡ 1 g-cm/s^2	dyn	
1 newton	≡ 1 kg-m/s^2	N	
Astronomical			
3.084×10^{18} cm	= 1 parsec		
9.464×10^{17} cm	= 1 light year		$c \times$ s/yr
1.49×10^{13} cm	= 1 astronomical unit (≡ radius of earth's orbit)	AU	
≈ 10^{80}	Number of nucleons	Known universe	
≈ 10^{28} cm	Radius	Known universe	
≈ 10^{11}	Number of galaxies	Known universe	
≈ 1.6×10^{-18} (cm/s)/cm	Speed of recession of nebulae	Known universe	
≈ 1.6×10^{11}	Number of stars	Galaxy	
≈ 10^{23} cm	Diameter	Galaxy	
≈ 8×10^{44} g	Mass	Galaxy	
6.96×10^{10} cm	Radius	Sun	
2.14×10^6 s	Period of rotation	Sun	
1.99×10^{33} g	Mass	Sun	
1.49×10^{13} cm	Radius of orbit	Earth	
6.37×10^8 cm	Mean radius	Earth	
5.98×10^{27} g	Mass	Earth	
5.52 g/cm^3	Mean density	Earth	
3.156×10^7 s	= 1 year (period of revolution)	Earth	
8.64×10^4 s	= 24 hours (period of rotation)	Earth	
3.84×10^{10} cm	Radius of orbit	Moon	
1.74×10^8 cm	Radius	Moon	
7.34×10^{25} g	Mass	Moon	
2.36×10^6 s	Period of revolution	Moon	

Mechanics

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One of the urgent problems confronting universities today is that of undergraduate teaching. As research has become more and more absorbing to the faculty, a "subtle discounting of the teaching process" (to quote philosopher Sidney Hook) has too often come into operation. Additionally, in many fields the changing content and structure of knowledge growing out of research have created great need for curriculum revision. This is particularly true, of course, in the physical sciences.

It is a pleasure, therefore, to contribute a foreword to the Berkeley Physics Course and Laboratory, which is a major curriculum improvement program at the undergraduate level designed to reflect the tremendous revolutions in physics of the last hundred years. The course has enlisted the efforts of many physicists working in forefront areas of research and has been fortunate to have the support of the National Science Foundation, through a grant to Educational Services Incorporated. It has been tested successfully in lower division physics classes at the University of California, Berkeley, over a period of several semesters. The course represents a marked educational advance, and I hope it will be very widely used.

The University of California is happy to act as host to the inter-university group responsible for developing this new course and laboratory and pleased that a number of Berkeley students volunteered to help in testing the course. The financial support of the National Science Foundation and the cooperation of Educational Services Incorporated are much appreciated. Most gratifying of all, perhaps, is the lively interest in undergraduate teaching evinced by the substantial number of University of California faculty members participating in the curriculum improvement program. The scholar-teacher tradition is an old and honorable one; the work devoted to this new physics course and laboratory shows that the tradition is still honored at the University of California.

Clark Kerr

Foreword

Volume 1 of the Berkeley Physics Course has been in use in its bound form for about seven years. Several years ago it seemed appropriate to consider a revision. At this point each of us had taught the course in Berkeley several times, and on the basis of our experience and talks with colleagues, both in Berkeley and at other institutions, we had developed and considered changes to make a more "teachable" text for an introductory course for engineering and physical science students. Thus we proceeded to such a revision.

We have tried to keep the fresh approach that was characteristic of the whole Berkeley Physics Course, the use of examples drawn from research laboratories, and the presentation of interesting topics often previously judged to be too advanced for an introductory course. We have removed some of the Advanced Topics from Vol. 1 and have removed Chap. 15, Particles of Modern Physics, in the belief that they are not often used in a course at this level. The most substantial change has been the complete rewriting of Chap. 8 on Rigid Body Motion. Although this chapter is certainly more mundane now, it is more suited to the level of the students. The order of presentation of topics remains the same except that Chaps. 3 and 4 have been interchanged in the hope that some familiarity with the ordinary applications of Newton's Laws of Motion will provide the student with background for a better understanding of the somewhat more advanced concept of galilean transformations. Finally, because students have encountered substantial difficulties with mathematics, particularly differential equations, we have added a number of Mathematical Notes.

The Teaching Notes that follow give some detail of the philosophy of using this book as a text. There is still a good deal more material than can be comfortably used in a one-quarter or a one-semester course. An instructor should make conscious choices of the material that he wishes to use. In recent years the change to the quarter system at Berkeley has unfortunately made it necessary to separate laboratory work from the first quarter covering the subject of mechanics. An introductory course should

Preface to the Second Edition of Volume 1

be tied to the laboratory, and the revision of the Berkeley Physics Laboratory by Alan Portis and Hugh Young provides accompanying laboratory work valuable for any introduction to mechanics.

We have benefited from the help and criticisms of many colleagues. The help of Miss Miriam Machlis in preparing this revision has been particularly extensive.

A. Carl Helmholz
Burton J. Moyer

This is a two-year elementary college physics course for students majoring in science and engineering. The intention of the writers has been to present elementary physics as far as possible in the way in which it is used by physicists working on the forefront of their field. We have sought to make a course that would vigorously emphasize the foundations of physics. Our specific objectives were to introduce coherently into an elementary curriculum the ideas of special relativity, of quantum physics, and of statistical physics.

This course is intended for any student who has had a physics course in high school. A mathematics course including the calculus should be taken at the same time as this course.

There are several new college physics courses under development in the United States at this time. The idea of making a new course has come to many physicists, affected by the needs both of the advancement of science and engineering and of the increasing emphasis on science in elementary schools and in high schools. Our own course was conceived in a conversation between Philip Morrison of Cornell University and Charles Kittel late in 1961. We were encouraged by John Mays and his colleagues of the National Science Foundation and by Walter C. Michels, then the Chairman of the Commission on College Physics. An informal committee was formed to guide the course through the initial stages. The committee consisted originally of Luis Alvarez, William B. Fretter, Charles Kittel, Walter D. Knight, Philip Morrison, Edward M. Purcell, Malvin A. Ruderman, and Jerrold R. Zacharias. The committee met first in May 1962, in Berkeley; at that time it drew up a provisional outline of an entirely new physics course. Because of heavy obligations of several of the original members, the committee was partially reconstituted in January 1964 and now consists of the undersigned. Contributions of others are acknowledged in the prefaces to the individual volumes.

The provisional outline and its associated spirit were a powerful influence on the course material finally produced. The outline covered in detail the topics and attitudes that we believed should and could be taught

Original Preface to the Berkeley Physics Course

to beginning college students of science and engineering. It was never our intention to develop a course limited to honors students or to students with advanced standing. We have sought to present the principles of physics from fresh and unified viewpoints, and parts of the course may therefore seem almost as new to the instructor as to the students.

The five volumes of the course as planned will include:

I. Mechanics (Kittel, Knight, Ruderman)
II. Electricity and Magnetism (Purcell)
III. Waves and Oscillations (Crawford)
IV. Quantum Physics (Wichmann)
V. Statistical Physics (Reif)

The authors of each volume have been free to choose that style and method of presentation which seemed to them appropriate to their subject.

The initial course activity led Alan M. Portis to devise a new elementary physics laboratory, now known as the Berkeley Physics Laboratory. Because the course emphasizes the principles of physics, some teachers may feel that it does not deal sufficiently with experimental physics. The laboratory is rich in important experiments and is designed to balance the course.

The financial support of the course development was provided by the National Science Foundation, with considerable indirect support by the University of California. The funds were administered by Educational Services Incorporated, a nonprofit organization established to administer curriculum improvement programs. We are particularly indebted to Gilbert Oakley, James Aldrich, and William Jones, all of ESI, for their sympathetic and vigorous support. ESI established in Berkeley an office under the very competent direction of Mrs. Mary R. Maloney to assist in the development of the course and the laboratory. The University of California has no official connection with our program, but it has aided us in important ways. For this help we thank in particular two successive Chairmen of the Department of Physics, August C. Helmholz and Burton J. Moyer; the faculty and nonacademic staff of the Department; Donald Coney, and many others in the University. Abraham Olshen gave much help with the early organizational problems.

Your corrections and suggestions will always be welcome.

	Eugene D. Commins	Edward M. Purcell
	Frank S. Crawford, Jr.	Frederick Reif
	Walter D. Knight	Malvin A. Ruderman
Berkeley, California	Philip Morrison	Eyvind H. Wichmann
January 1965	Alan M. Portis	Charles Kittel, *Chairman*

This volume is obviously intended for use as a text. The level is that of students who have had some calculus and are taking more and who have had a high school physics course. At the University of California in Berkeley, students in the physical sciences and engineering start calculus in the first quarter of their freshman year and take a course such as this along with calculus in their second quarter. They have had differential calculus by the start of the physics course and reach integration at least by the middle of the quarter. Such a tight scheduling does require fairly close cooperation with those giving the mathematics course. Of course they have not studied differential equations by this time, and so some material about the solution of simple kinds of differential equations is included in the Mathematical Notes at the ends of Chaps. 3 and 7. There are few enough types to be solved in this kind of a mechanics course so that we believe a student can learn each one of the types.

The teacher will find that the Film Lists have been put all together at the end of the book rather than at the end of each chapter. The Commission on College Physics Resource Letter is a very complete list of films. Special ones have been singled out that seemed especially suitable for the subject of mechanics. In recent years a great many film loops have been made. Some of these are very helpful as short illustrations of special topics; each instructor will find through his own use those that are well suited to his teaching.

Although the problems that have been added in this revision are mostly easier than the ones they have replaced, we have not included very simple problems and plug-in problems. Some of these are valuable in giving the student a little confidence. But we believe that each instructor can make these up for himself or at least find them in other books. No two teachers will want to give a mechanics course in exactly the same way, and the use of special problems gives them a good opportunity for diversity. There are also now several problem books that are useful. Some of them as well as other books on mechanics at this level are listed in the Appendix.

Teaching Notes

There are of course several ways to use this book as a text. One of the ways in which the first edition has apparently rarely been used, but for which we believe there might be a very good use for the entire book, is for a course in mechanics following a one-year noncalculus course, such as one might find in smaller institutions that do not have the facilities for both a calculus and a noncalculus introductory course. For such a course, which might be given to second- or third-year college students, the whole book could well be covered since many of the topics would have been included in less advanced form in the first year.

For the regular introductory section of a general physics course, this book contains too much material, and we urge the instructor to abstain from trying to cover everything. Many introductory courses do not include special relativity, so that the first nine chapters make up a coherent introduction to classical mechanics. But even this much material, if one tries to cover it all, is too great for a nine- or ten-week quarter course or the fraction of a semester that is usually devoted to mechanics. Therefore we give some suggestions below for minimum coverage of chapters. Sometimes it is not desirable to include any electrical or magnetic problems in the beginning course. We believe that the text can be used in this fashion, but it is true that many students find the electrical problems very interesting. Many instructors find it difficult to be ruthless in cutting material. Our own experience is that it is better to cover some material well than to cover more material less well. The advanced sections and the Advanced Topics should give the talented students something with which to stretch their abilities and the students who go on in physics a reference work that can be used in connection with later studies.

With these comments we proceed to the details of the several chapters.

Chapter 1. As in the first edition, this chapter is not an essential part of the study of mechanics, but it may provide interesting reading for those with broader interests. For instructors who wish to assign the reading, it may provide a good place to illustrate the concept of *order of magnitude.*

Chapter 2. Vectors introduce the student to the language that is very useful in physics. As pointed out in the text, the vector product can be omitted here along with the examples of magnetic forces in which **v** and **B** are not perpendicular. One can proceed to Chap. 6 without needing the vector product and return to it at that time. The scalar product is used often in finding magnitudes and in Chap. 5 on work and energy, so it is highly desirable to introduce it here. In addition it provides a tool for solving numbers of interesting problems. The section on vector derivatives is also useful, but the parts treating the unit vectors $\hat{\mathbf{r}}$ and $\hat{\boldsymbol{\theta}}$ can be omitted and introduced much later. Hopefully, circular motion is a good introduction of the dynamics to come.

Chapter 3. This is a long chapter with a good many applications. Newton's laws are introduced in conventional form and we proceed to applications of the Second Law. For a shortened course or one that does not include electrical and magnetic applications, the section on them can be omitted entirely or the magnetic field can be treated only for the case of velocity and magnetic field perpendicular. Conservation of momentum is then introduced through Newton's Third Law. Kinetic energy is referred to in collision problems even though it is not introduced until Chap. 5. Most students have heard of it in high school and do not find difficulty with it; but it can be omitted if desired.

Chapter 4. As pointed out in the text, this chapter is not of the conventional type. Many physicists find appeal in the introduction of galilean transformations, and for those planning to go on to special relativity, it does provide a nice introduction to transformations of coordinates. However, to nonphysics students and to those with limited time, it may be too much "frosting on the cake" and should be omitted. Some reference to accelerated frames of reference and fictitious forces should probably be included, but these can be taken from the first few pages.

Chapter 5. Work and kinetic energy are introduced, first in one dimension and then in three dimensions. The scalar product is really necessary here, but certainly the use of the line integral can be skirted. Potential energy is treated in detail. In a shorter course, the discussion of conservative fields could well be omitted as could the discussion of electrical potential. However, this is an important chapter and should not be hurried through.

Chapter 6. This chapter treats collisions again and introduces the center-of-mass system of reference. Center of mass is an important concept for rigid bodies, and although the center-of-mass system is widely used, a shortened version of a mechanics course could well omit this. The introduction of angular momentum and torque requires the use of the vector product. By this time, students have achieved a level where they can grasp and use the vector product, and if it has been omitted earlier, it can be taken up here. The conservation of angular momentum is an appealing topic to many students.

Chapter 7. Here the Mathematical Notes should be studied first if the students have had difficulty with differential equations. The mass on the spring and the pendulum provide straightforward examples of this important subject of oscillatory motion. In a shortened version, the sections on average values of kinetic and potential energy, damped motion, and forced oscillations can be omitted completely. The laboratory can provide excellent examples of this type of motion. The Advanced Topics on the Anharmonic Oscillator and the Driven Oscillator will be interesting to the more advanced student.

Chapter 8. The present authors believe that an introductory treatment of rigid bodies is valuable to all students. The ideas of torque and angular acceleration about a fixed axis are not difficult, and they provide the student connections with the real, visible world. The simple treatment of the gyro is also valuable; but the introduction of principal axes, products of inertia, and rotating coordinate systems should probably be omitted in most courses.

Chapter 9. Central-force problems are very important. Some instructors may not wish to spend so much time on evaluating the potential inside and outside spherical masses, and this of course can be omitted. They may also find the labor of integrating the r equation of motion too much, in which case they can omit it. They should enjoy the Advanced Topic. There is a good deal that can be cut from this chapter if necessary, but the work of mastering it is very rewarding. The two-body problem and the concept of reduced mass are also useful but again can be omitted in a shortened course.

Chapter 10. This chapter reviews a number of methods of determining the speed of light. For a course in mechanics, this material is not essential. We believe that students will be interested in it, but it could be assigned as outside reading. Then comes the Michelson-Morley experiment, which in a course like this is the most convincing evidence of the need for a change from the galilean transformation. The doppler effect is introduced because of the evidence that the recessional doppler effect provides for high speeds of distant stars, and the chapter closes with a section on the speed of light as the ultimate speed for material objects and the failure of the newtonian formula for kinetic energy. For those with limited time for the study of special relativity, a cursory reading of the chapter might be sufficient.

Chapter 11. In this chapter the Lorentz transformation equations are derived and applied to the most common characteristics of special relativity, length contraction, and time dilation. The velocity transformations are introduced and some examples given. This chapter is the basis for the following chapters, and consequently ample time should be allowed for the study of it.

Chapter 12. The results of Chap. 11 are used to show the need for a change in the definition of momentum, and of relativistic energy, and finally to show the origin of $E = mc^2$. The relation to experiments with high-energy particles and to high-energy nuclear physics needs to be emphasized. At this stage students may be only vaguely aware of, for example, nuclear physics; but the examples are so pertinent to the public today that it should be easy to teach. Finally the subject of particles with zero rest mass will answer the questions of many alert students.

Chapter 13. A number of examples of the subjects developed in the previous chapter are treated here. The center-of-mass system is brought in and its advantages pointed out. In a shortened course all this can be omitted. Good students will be interested in it, and it can be referred to as outside reading in other physics courses treating special relativity.

Chapter 14. In recent years the study of general relativity has become quite popular, and this chapter could provide a bridge to reading in general relativity. It is, of course, not central to the subject of special relativity in the usual sense, but many students may be interested in the difference between gravitational and inertial mass, and almost all will have heard about the tests of general relativity.