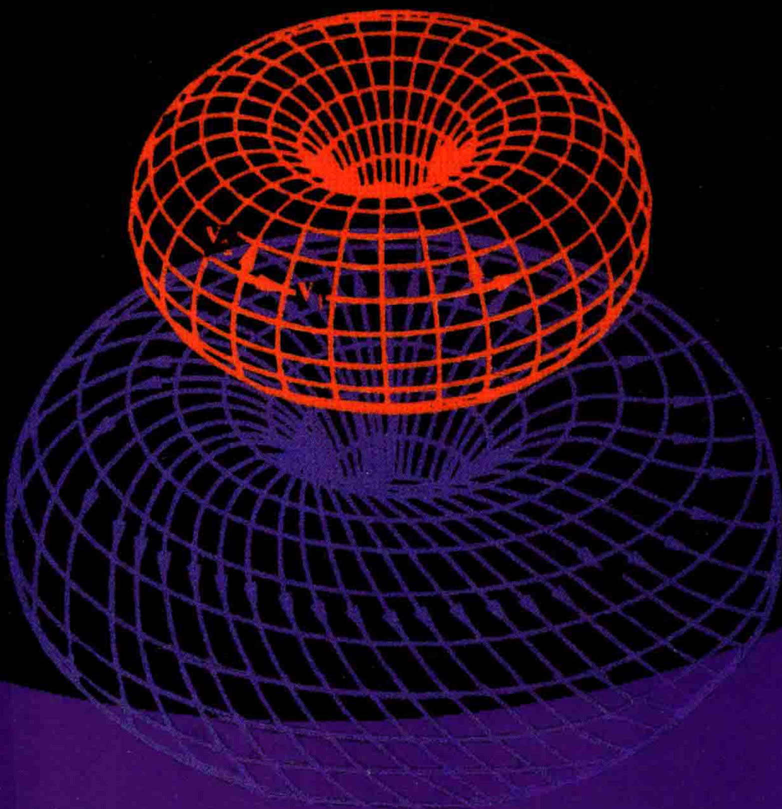
Tom W. B. Kibble, Frank H. Berkshire

CLASSICAL MECHANICS

5th Edition

经典力学 第5版



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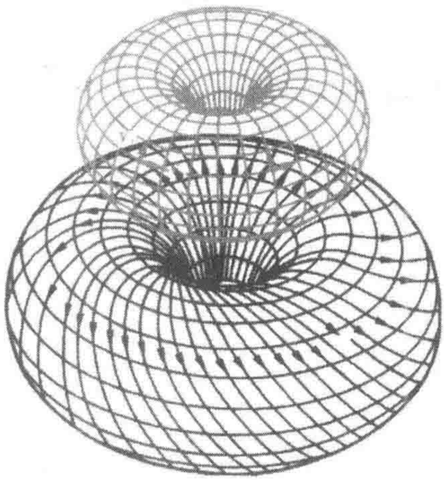

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To Anne and Rosie

Preface

This book, based on courses given to physics and applied mathematics students at Imperial College, deals with the mechanics of particles and rigid bodies. It is designed for students with some previous acquaintance with the elementary concepts of mechanics, but the book starts from first principles, and little detailed knowledge is assumed. An essential prerequisite is a reasonable familiarity with differential and integral calculus, including partial differentiation. However, no prior knowledge of differential equations should be needed. Vectors are used from the start in the text itself; the necessary definitions and mathematical results are collected in an appendix.

Classical mechanics is a very old subject. Its basic principles have been known since the time of Newton, when they were formulated in the *Principia*, and the mathematical structure reached its mature form with the works of Lagrange in the late eighteenth century and Hamilton in the nineteenth. Remarkably enough, within the last few decades the subject has once again become the focus of very active fundamental research. Some of the most modern mathematical tools have been brought to bear on the problem of understanding the qualitative features of dynamics, in particular the transition between regular and turbulent or chaotic behaviour. The fourth edition of the book was extended to include new chapters providing a brief introduction to this exciting work. In this fifth edition, the material is somewhat expanded, in particular to contrast continuous and discrete behaviours. We have also taken the opportunity to revise the earlier chapters, giving more emphasis to specific examples worked out in more detail.

Many of the most fascinating recent discoveries about the nature of the Earth and its surroundings — particularly since the launching of artificial satellites — are direct applications of classical mechanics. Several of these are discussed in the following chapters, or in problems.

For physicists, however, the real importance of classical mechanics lies not so much in the vast range of its applications as in its role as the base on which the whole pyramid of modern physics has been erected. This book, therefore, emphasizes those aspects of the subject which are of importance in quantum mechanics and relativity — particularly the conservation laws, which in one form or another play a central role in all physical theories.

For applied mathematicians, the methods of classical mechanics have evolved into a much broader theory of dynamical systems with many applications well outside of physics, for example to biological systems.

The first five chapters are primarily concerned with the mechanics of a single particle, and Chapter 6, which could be omitted without substantially affecting the remaining chapters, deals with potential theory. Systems of particles are discussed in Chapters 7 and 8, and rigid bodies in Chapter 9. The powerful methods of Lagrange are introduced at an early stage, and in simple contexts, and developed more fully in Chapters 10 and 11. Chapter 12 contains a discussion of Hamiltonian mechanics, emphasizing the relationship between symmetries and conservation laws — a subject directly relevant to the most modern developments in physics. It also provides the basis for the later treatment of order and chaos in Hamiltonian systems in Chapter 14. This follows the introduction to the geometrical description of continuous dynamical systems in Chapter 13, which includes a discussion of various non-mechanics applications. Appendices from the fourth edition on (A) Vectors, (B) Conics, (C) Phase-plane analysis near critical points are supplemented here by a new appendix (D) Discrete dynamical systems — maps.

The writing of the first edition of this book owed much to the advice and encouragement of the late Professor P.T. Matthews. Several readers have also helped by pointing out errors, particularly in the answers to problems.

We are grateful to the following for permission to reproduce copyright material: Springer–Verlag and Professor Oscar E. Lanford III for Fig. 13.20; Cambridge University Press for Fig. 13.22 and, together with Professors G.L. Baker and J.P. Gollub, for Fig. D.5; Institute of Physics Publishing Limited and Professor M.V. Berry for Figs. 14.11, 14.12 and 14.13; the Royal Society and Professors W.P. Reinhardt and I. Dana for the figure in the answer to Appendix D, Problem 13.

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Useful Constants and Units

Physical constants	
speed of light	$c = 2.997\,924\,58 \times 10^8\,\mathrm{m\,s^{-1}}$
gravitational constant	$G = 6.673 \times 10^{-11}\,\mathrm{N\,m^2\,kg^{-2}}$
Planck's constant/2π	$\hbar = 1.054\,57 \times 10^{-34}\,\mathrm{J\,s}$
mass of hydrogen atom	$m_\mathrm{H} = 1.673\,52 \times 10^{-27}\,\mathrm{kg}$
mass of electron	$m_\mathrm{e} = 9.109\,38 \times 10^{-31}\,\mathrm{kg}$
charge of proton	$e = 1.602\,18 \times 10^{-19}\,\mathrm{C}$
permittivity of vacuum	$\epsilon_0 = 8.854\,19 \times 10^{-12}\,\mathrm{F\,m^{-1}}$
permeability of vacuum	$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$
Defined standard values	
standard gravitational acceleration	$g_\mathrm{n} = 9.806\,65\,\mathrm{m\,s^{-2}}$
normal atmospheric pressure	$1\,\mathrm{atm} = 1.013\,25 \times 10^5\,\mathrm{Pa}$
	$= 1.013\,25\,\mathrm{bar}$
Properties of Earth	
mass	$M = 5.974 \times 10^{24}\,\mathrm{kg}$
	$GM = 3.9860 \times 10^{14}\,\mathrm{m^3\,s^{-2}}$
radius (polar)	$R_\mathrm{p} = 6356.8\,\mathrm{km}$
(equatorial)	$R_\mathrm{e} = 6378.1\,\mathrm{km}$
(mean)[$= (R_\mathrm{e}^2 R_\mathrm{p})^{1/3}$]	$R = 6371.0\,\mathrm{km}$
semi-major axis of orbit	$a = 1.495\,98 \times 10^8\,\mathrm{km}$
eccentricity of orbit	$e = 0.016\,722$
orbital period (sidereal year)	$\tau = 3.155\,75 \times 10^7\,\mathrm{s}$
mean orbital velocity	$v = 29.785\,\mathrm{km\,s^{-1}}$
surface escape velocity (mean)	$v_\mathrm{e} = 11.18\,\mathrm{km\,s^{-1}}$
rotational angular velocity	$\omega = 7.2921 \times 10^{-5}\,\mathrm{s^{-1}}$

Properties of Sun and Moon

mass of Sun	$M_S = 1.989 \times 10^{30}\,\text{kg}$
	$= 3.3295 \times 10^5\,M$
	$GM_S = 1.32712 \times 10^{20}\,\text{m}^3\,\text{s}^{-2}$
mass of Moon	$M_M = 7.348 \times 10^{22}\,\text{kg}$
	$= 0.012300\,M$
semi-major axis of lunar orbit	$a_M = 3.8440 \times 10^5\,\text{km}$
lunar orbital period (sidereal month)	$\tau_M = 2.3606 \times 10^6\,\text{s}$

SI units

kilogramme (kg): mass of the international standard kilogramme kept at Sèvres in France.

second (s): 9 192 631 770 oscillation periods of the hyperfine transition between the levels $F = 4, m_F = 0$ and $F = 3, m_F = 0$ in the ground state of ^{133}Cs.

metre (m): distance travelled by light in vacuum in (1/299 792 458) s.

ampere (A): defined so that the force per unit length between two infinitely long parallel wires of negligible cross section 1 m apart in vacuum, each carrying a current of 1 A is $2 \times 10^{-7}\,\text{N}\,\text{m}^{-1}$ (or, equivalently, so that the constant μ_0 has the precise value $4\pi \times 10^{-7}\,\text{N}\,\text{A}^{-2}$).

(The *kelvin*, *candela* and *mole* are not used in this book.)

Subsidiary units

newton	$1\,\text{N} = 1\,\text{kg}\,\text{m}\,\text{s}^{-2}$	*pascal*	$1\,\text{Pa} = 1\,\text{N}\,\text{m}^{-2}$
joule	$1\,\text{J} = 1\,\text{N}\,\text{m}$	*ton(ne)*	$1\,\text{t} = 10^3\,\text{kg}$
watt	$1\,\text{W} = 1\,\text{J}\,\text{s}^{-1}$	*bar*	$1\,\text{bar} = 10^5\,\text{Pa}$
coulomb	$1\,\text{C} = 1\,\text{A}\,\text{s}$	*hertz*	$1\,\text{Hz} = 1\,\text{s}^{-1}$

British and American units

foot	$1\,\text{ft} = 0.3048\,\text{m}$	*pound*	$1\,\text{lb} = 0.45259237\,\text{kg}$

Prefixes denoting multiples and submultiples

10^3	kilo (k)	10^{-3}	milli (m)
10^6	mega (M)	10^{-6}	micro (μ)
10^9	giga (G)	10^{-9}	nano (n)
10^{12}	tera (T)	10^{-12}	pico (p)
10^{15}	peta (P)	10^{-15}	femto (f)
10^{18}	exa (E)	10^{-18}	atto (a)

List of Symbols

The following list is not intended to be exhaustive. It includes symbols of frequent occurrence or special importance. The figures refer to the section in which the symbol is defined.

A, A_α	complex amplitude	2.3, 11.3
$\boldsymbol{A}$	vector potential	A.7
$\boldsymbol{a}, a$	acceleration	1.2
a	amplitude of oscillation	2.2
a	semi-major axis of orbit	4.4, B.1
a	equatorial radius	6.5
$\boldsymbol{B}$	magnetic field	5.2, A.7
b	semi-minor axis of orbit	4.4, B.1
b	impact parameter	4.3, 4.5
c	polar radius	6.5
c	propagation velocity	10.6
$\mathbf{c}$	control parameters	13.1
$\boldsymbol{d}$	dipole moment	6.2, 6.4
E	total energy	2.1, 3.1, 8.5
$\boldsymbol{E}$	electric field	6.1, A.7
e	base of natural logarithms	
e	(minus) electron charge	4.7
e	eccentricity of orbit	4.4, B.2
$\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3$	principal axes	9.4, A.10
$\boldsymbol{F}, \boldsymbol{F}_i, \boldsymbol{F}_{ij}$	force	1.2, 8.1
F_α	generalized force	3.7, 10.2
$\boldsymbol{F}$	phase-space velocity	13.1
F_i	constants of the motion	14.1
f	particle flux	4.5

G	gravitational constant	1.2
$\boldsymbol{G}$	moment of force	3.3
G	generator of transformation	12.7
$g, \boldsymbol{g}$	gravitational acceleration	5.3, 6.1
$\boldsymbol{g}^*$	observed gravitational acceleration	5.3
H	Hamiltonian function	12.1
I	action integral	3.7
I, I_{xx}	moment of inertia	9.2, 9.3
I_{xy}	product of inertia	9.3
I_i, I_i^*	principal moment of inertia	9.4, 9.5
I_i	action variables	14.3
i	$\sqrt{-1}$	
i	particle index	1.2, 8.1
$\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}$	unit vectors	A.1, 1.1
$\boldsymbol{J}, \boldsymbol{J}^*$	angular momentum	3.3, 7.1, 8.3
$k, k_{\alpha\beta}$	oscillator constant	2.2, 11.2
k	inverse square law constant	4.3
L	Lagrangian function	3.7, 10.2
l	semi-latus rectum of orbit	4.3, 4.4, B.2
ln	natural logarithm	
M	total mass	7.1, 8.1
M	Jacobian matrix	14.1
$\boldsymbol{M}$	invariant torus	14.1
m, m_i	mass	1.2, 6.1
N	number of particles	1.2, 8.1
n	number of degrees of freedom	10.1
$\boldsymbol{P}$	total momentum	7.1, 8.1
$\boldsymbol{p}, \boldsymbol{p}_i, \boldsymbol{p}^*$	momentum	1.2, 7.2
p_i, p_α	generalized momentum	3.7, 12.1
p	exponential rate coefficient	2.2
Q	quality factor	2.5
Q	quadrupole moment	6.2, 6.4
q, q_i	electric charge	1.2, 6.1
q_i	curvilinear co-ordinate	3.7, A.8
q_α	generalized co-ordinate	10.1
R	radius of Earth	4.3
$\boldsymbol{R}$	position of centre of mass	7.1, 8.1
r	radial co-ordinate	3.5

$\boldsymbol{r}, \boldsymbol{r}_i$	position vector	1.1, A.1
$\boldsymbol{r}, \boldsymbol{r}_{ij}$	relative position	1.2, 7.1
$\boldsymbol{r}_i^*$	position in CM frame	7.2, 8.3
T, T^*	kinetic energy	2.1, 3.1, 7.2, 8.5
T, T_ϵ	twist map	D.3
t	time	1.1
U	effective potential energy function	4.2, 12.4
V	potential energy	2.1, 3.1, 8.5, 13.3
$\boldsymbol{v}, \boldsymbol{v}_i$	velocity	1.2
$\mathrm{d}W, \delta W$	work done in small displacement	2.4, 10.2
X, Y, Z	co-ordinates of centre of mass $\boldsymbol{R}$	10.1
X, Y	fixed points of maps	D.1
x, y, z	Cartesian co-ordinates	A.1, 1.1
$\boldsymbol{x}, x_i, x, y$	phase-space co-ordinates	13.1, 13.2
x_n, y_n	iterates of maps	D.1
α	rotation number	D.3
γ	damping constant	2.5
δ	small variation	3.6
δ	Feigenbaum number	D.1
ϵ	oblateness	6.5
ϵ_0	permittivity of free space	1.2, A.7
θ	polar angle, Euler angle	3.5, 9.9
Θ, θ, θ^*	scattering angle	4.4, 7.3
λ, λ_i	Lyapunov exponent	13.7, D.1, D.2
λ_i	eigenvalues	C.1
μ	reduced mass	7.1
μ_0	permeability of free space	A.7
$\boldsymbol{\xi}, \xi, \eta$	linearized phase-space co-ordinates	13.2, C.1
π	circumference/diameter ratio of circle	
ρ	cylindrical polar co-ordinate	3.5
ρ	mass or charge density	6.3, A.7
$\sigma, \mathrm{d}\sigma$	cross-section	4.5
τ	period	2.2, 4.4
Φ	gravitational potential	6.1
ϕ	electrostatic potential	6.1, A.7
φ	azimuth angle, Euler angle	3.5, 9.9
ϕ_i	angle variables	14.3
ψ	Euler angle	9.9

$d\Omega$	solid angle	4.5
$\boldsymbol{\omega}, \boldsymbol{\Omega}$	angular velocity	5.1, 9.2, 9.7
ω	angular frequency	2.2, 11.3
ω_i	natural angular frequencies	14.1
$\boldsymbol{\nabla}$	vector differential operator	A.5
$\boldsymbol{a} \cdot \boldsymbol{b}$	scalar product of $\boldsymbol{a}$ and $\boldsymbol{b}$	A.2
$\boldsymbol{a} \wedge \boldsymbol{b}$	vector product of $\boldsymbol{a}$ and $\boldsymbol{b}$	A.3

Contents