
Undergraduate Lecture Notes in Physics

Series Editors

Neil Ashby
William Brantley
Michael Fowler
Elena Sassi
Helmy S. Sherif

For further volumes:
<http://www.springer.com/series/8917>

Undergraduate Lecture Notes in Physics (ULNP) publishes authoritative texts covering topics throughout pure and applied physics. Each title in the series is suitable as a basis for undergraduate instruction, typically containing practice problems, worked examples, chapter summaries, and suggestions for further reading.

ULNP titles must provide at least one of the following:

- An exceptionally clear and concise treatment of a standard undergraduate subject.
- A solid undergraduate-level introduction to a graduate, advanced, or non-standard subject.
- A novel perspective or an unusual approach to teaching a subject.

ULNP especially encourages new, original, and idiosyncratic approaches to physics teaching at the undergraduate level.

The purpose of ULNP is to provide intriguing, absorbing books that will continue to be the reader's preferred reference throughout their academic career.

Hafez A. Radi
John O. Rasmussen

Principles of Physics

For Scientists and Engineers

Hafez A. Radi
October University for Modern Sciences and Arts (MSA)
6th of October City
Egypt

John O. Rasmussen
University of California at Berkeley and Lawrence Berkeley Lab
Berkeley, CA
USA

Solutions to the exercises are accessible to qualified instructors at springer.com on this book's product page. Instructors may click on the link *additional information* and register to obtain their restricted access.

ISSN 2192-4791 ISSN 2192-4805 (electronic)
ISBN 978-3-642-23025-7 ISBN 978-3-642-23026-4 (eBook)
DOI 10.1007/978-3-642-23026-4
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012947066

© Springer-Verlag Berlin Heidelberg 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

This book on Principles of Physics is intended to serve fundamental college courses in scientific curricula.

Physics is one of the most important tools to aid undergraduates, graduates, and researchers in their technical fields of study. Without it many phenomena cannot be described, studied, or understood. The topics covered here will help students interpret such phenomena, ultimately allowing them to advance in the applied aspects of their fields.

The goal of this text is to present many key concepts in a clear and concise, yet interesting way, making use of practical examples and attractively colored illustrations whenever appropriate to satisfy the needs of today's science and engineering students.

Some of the examples, proofs, and subsections in this textbook have been identified as optional and are preceded with an asterisk *. For less intensive courses these optional portions may be omitted without significantly impacting the objectives of the chapter. Additional material may also be omitted depending on the course's requirements.

The first author taught the material of this book in many universities in the Middle East for almost four decades. Depending on the university, he leveraged different international textbooks, resources, and references. These used different approaches, but were mainly written in an expansive manner delivering a plethora of topics while targeting students who wanted to dive deeply into the subject matter. In this textbook, however, the authors introduce a large subset of these topics but in a more simplified manner, with the intent of delivering these topics and their key facts to students all over the world and in particular to students in the Middle East and neighboring regions where English may not be the native language. The second author went over the entire text with the background of study and/or teaching at Caltech, UC Berkeley, and Yale.

Instructors teaching from this textbook will be able to gain online access from the publisher to the solutions manual, which provides step-by-step solutions to all exercises contained in the book. The solutions manual also contains many tips, colored illustrations, and explanations on how the solutions were derived.

Acknowledgments from Prof. Hafez A. Radi

I owe special thanks to my wife and two sons Tarek and Rami for their ongoing support and encouragement. I also owe special thanks to my colleague and friend Prof. Rasmussen for his invaluable contributions to this book, and for everything that I learned from him over the years while carrying out scientific research at Lawrence Berkeley Lab. Additionally, I would like to express my gratitude to Prof. Ali Helmy Moussa, Prof. of Physics at Ain Shams University in Egypt, for his assistance, support, and guidance over the years. I also thank all my fellow professors and colleagues who provided me with valuable feedback pertaining to many aspects of this book, especially Dr. Sana'a Ismail, from Dar El Tarbiah School, IGCSE section and Dr. Hesham Othman from the Faculty of Engineering at Cairo University. I would also like to thank Professor Mike Guidry, Professor of Physics and Astronomy at the University of Tennessee Knoxville, for his valuable recommendations. I am also grateful to the CD Odessa LLC for their Concept-Draw software suite which was used to create almost all the figures in this book. I finally extend my thanks and appreciation to Professor Nawal El-Degwi, Professor Khayri Abdel-Hamid, Professor Said Ashour, and the staff members and teaching assistants at the faculty of Engineering at MSA University, Egypt, for all their support and input.

Hafez A. Radi
hafez.radi@gmail.com

Acknowledgments from Prof. John O. Rasmussen

I would like to thank Prof. Radi for the opportunity to join him as coauthor. I am grateful to the many teachers, students, and colleagues from whom I learned various aspects of the fascinating world of the physical sciences, notably the late Drs. Linus Pauling, Isadore Perlman, Stanley Thompson, Glenn Seaborg, Earl Hyde, Hilding Slätis, Aage Bohr, Gaja Alaga, and Hans-Jörg Mang. There are many others, still living, too numerous to list here. I would also like to extend my special thanks to my wife for her support and encouragement.

John O. Rasmussen
oxras@berkeley.edu

Contents

Part I Fundamental Basics

1	Dimensions and Units	3
1.1	The International System of Units	3
1.2	Standards of Length, Time, and Mass	5
1.3	Dimensional Analysis	9
1.4	Exercises	12
2	Vectors	17
2.1	Vectors and Scalars	17
2.2	Properties of Vectors	19
2.3	Vector Components and Unit Vectors	22
2.4	Multiplying Vectors	27
2.5	Exercises	33

Part II Mechanics

3	Motion in One Dimension	41
3.1	Position and Displacement	41
3.2	Average Velocity and Average Speed	42
3.3	Instantaneous Velocity and Speed	44
3.4	Acceleration	48
3.5	Constant Acceleration	52
3.6	Free Fall	57
3.7	Exercises	62
4	Motion in Two Dimensions	71
4.1	Position, Displacement, Velocity, and Acceleration Vectors	71
4.2	Projectile Motion	79

4.3	Uniform Circular Motion	87
4.4	Tangential and Radial Acceleration	90
4.5	Non-uniform Circular Motion	91
4.6	Exercises	93
5	Force and Motion	103
5.1	The Cause of Acceleration and Newton's Laws	103
5.2	Some Particular Forces	106
5.3	Applications to Newton's Laws	113
5.4	Exercises	124
6	Work, Energy, and Power	137
6.1	Work Done by a Constant Force	137
6.2	Work Done by a Variable Force	142
6.3	Work-Energy Theorem	148
6.4	Conservative Forces and Potential Energy	151
6.5	Conservation of Mechanical Energy	157
6.6	Work Done by Non-conservative Forces	159
6.7	Conservation of Energy	162
6.8	Power	166
6.9	Exercises	170
7	Linear Momentum, Collisions, and Center of Mass	181
7.1	Linear Momentum and Impulse	181
7.2	Conservation of Linear Momentum	184
7.3	Conservation of Momentum and Energy in Collisions	187
	7.3.1 Elastic Collisions in One and Two Dimensions	187
	7.3.2 Inelastic Collisions	194
7.4	Center of Mass (CM)	195
7.5	Dynamics of the Center of Mass	199
7.6	Systems of Variable Mass	203
	7.6.1 Systems of Increasing Mass	204
	7.6.2 Systems of Decreasing Mass; Rocket Propulsion	205
7.7	Exercises	209
8	Rotational Motion	227
8.1	Radian Measures	227
8.2	Rotational Kinematics; Angular Quantities	228
8.3	Constant Angular Acceleration	232
8.4	Angular Vectors	233
8.5	Relating Angular and Linear Quantities	233
8.6	Rotational Dynamics; Torque	238
8.7	Newton's Second Law for Rotation	240
8.8	Kinetic Energy, Work, and Power in Rotation	248

8.9	Rolling Motion	252
8.10	Exercises	259
9	Angular Momentum	269
9.1	Angular Momentum of Rotating Systems	269
9.1.1	Angular Momentum of a Particle	269
9.1.2	Angular Momentum of a System of Particles	271
9.1.3	Angular Momentum of a Rotating Rigid Body	271
9.2	Conservation of Angular Momentum	277
9.3	The Spinning Top and Gyroscope	285
9.4	Exercises	289
10	Mechanical Properties of Matter	303
10.1	Density and Relative Density	304
10.2	Elastic Properties of Solids	306
10.2.1	Young's Modulus: Elasticity in Length	307
10.2.2	Shear Modulus: Elasticity of Shape	310
10.2.3	Bulk Modulus: Volume Elasticity	312
10.3	Fluids	314
10.4	Fluid Statics	316
10.5	Fluid Dynamics	328
10.6	Exercises	345

Part III Introductory Thermodynamics

11	Thermal Properties of Matter	357
11.1	Temperature	357
11.2	Thermal Expansion of Solids and Liquids	360
11.2.1	Linear Expansion	361
11.2.2	Volume Expansion	362
11.3	The Ideal Gas	365
11.4	Exercises	371
12	Heat and the First Law of Thermodynamics	379
12.1	Heat and Thermal Energy	379
12.1.1	Units of Heat, The Mechanical Equivalent of Heat	379
12.1.2	Heat Capacity and Specific Heat	380
12.1.3	Latent Heat	384
12.2	Heat and Work	390
12.3	The First Law of Thermodynamics	395
12.4	Applications of the First Law of Thermodynamics	396
12.5	Heat Transfer	406
12.6	Exercises	416

13	Kinetic Theory of Gases	427
13.1	Microscopic Model of an Ideal Gas	427
13.2	Molar Specific Heat Capacity of an Ideal Gas	434
	13.2.1 Molar Specific Heat at Constant Volume	435
	13.2.2 Molar Specific Heat at Constant Pressure	436
13.3	Distribution of Molecular Speeds	441
13.4	Non-ideal Gases and Phases of Matter	442
13.5	Exercises	444
 Part IV Sound and Light Waves		
14	Oscillations and Wave Motion	451
14.1	Simple Harmonic Motion	451
	14.1.1 Velocity and Acceleration of SHM	452
	14.1.2 The Force Law for SHM	455
	14.1.3 Energy of the Simple Harmonic Oscillator	459
14.2	*Damped Simple Harmonic Motion	462
14.3	Sinusoidal Waves	463
	14.3.1 Transverse and Longitudinal Waves	463
	14.3.2 Wavelength and Frequency	465
	14.3.3 Harmonic Waves: Simple Harmonic Motion	466
14.4	The Speed of Waves on Strings	470
14.5	Energy Transfer by Sinusoidal Waves on Strings	472
14.6	The Linear Wave Equation	476
14.7	Standing Waves	477
	14.7.1 Reflection at a Boundary	481
	14.7.2 Standing Waves and Resonance	482
14.8	Exercises	486
15	Sound Waves	499
15.1	Speed of Sound Waves	499
15.2	Periodic Sound Waves	502
15.3	Energy, Power, and Intensity of Sound Waves	505
15.4	The Decibel Scale	510
15.5	Hearing Response to Intensity and Frequency	514
15.6	The Doppler Effect	514
15.7	Supersonic Speeds and Shock Waves	521
15.8	Exercises	523
16	Superposition of Sound Waves	531
16.1	Superposition and Interference	531
16.2	Spatial Interference of Sound Waves	533
16.3	Standing Sound Waves	537
16.4	Standing Sound Waves in Air Columns	541

16.5	Temporal Interference of Sound Waves: Beats	549
16.6	Exercises	554
17	Light Waves and Optics	561
17.1	Light Rays	561
17.2	Reflection and Refraction of Light	563
17.3	Total Internal Reflection and Optical Fibers	568
17.4	Chromatic Dispersion and Prisms	571
17.5	Formation of Images by Reflection	575
	17.5.1 Plane Mirrors	575
	17.5.2 Spherical Mirrors	576
17.6	Formation of Images by Refraction	583
	17.6.1 Spherical Refracting Surfaces	583
	17.6.2 Flat Refracting Surfaces	584
	17.6.3 Thin Lenses	586
17.7	Exercises	595
18	Interference, Diffraction and Polarization of Light	603
18.1	Interference of Light Waves	603
18.2	Young's Double Slit Experiment	604
18.3	Thin Films—Change of Phase Due to Reflection	611
18.4	Diffraction of Light Waves	615
18.5	Diffraction Gratings	620
18.6	Polarization of Light Waves	624
18.7	Exercises	627
Part V Electricity		
19	Electric Force	637
19.1	Electric Charge	637
19.2	Charging Conductors and Insulators	639
19.3	Coulomb's Law	642
19.4	Exercises	651
20	Electric Fields	659
20.1	The Electric Field	659
20.2	The Electric Field of a Point Charge	660
20.3	The Electric Field of an Electric Dipole	666
20.4	Electric Field of a Continuous Charge Distribution	670
	20.4.1 The Electric Field Due to a Charged Rod	672
	20.4.2 The Electric Field of a Uniformly Charged Arc	679
	20.4.3 The Electric Field of a Uniformly Charged Ring	681
	20.4.4 The Electric Field of a Uniformly Charged Disk	682
20.5	Electric Field Lines	684

20.6	Motion of Charged Particles in a Uniform Electric Field. . . .	686
20.7	Exercises	691
21	Gauss's Law	701
21.1	Electric Flux	701
21.2	Gauss's Law	705
21.3	Applications of Gauss's Law	707
21.4	Conductors in Electrostatic Equilibrium.	717
21.5	Exercises	720
22	Electric Potential	731
22.1	Electric Potential Energy	731
22.2	Electric Potential	733
22.3	Electric Potential in a Uniform Electric Field.	735
22.4	Electric Potential Due to a Point Charge	741
22.5	Electric Potential Due to a Dipole	745
22.6	Electric Dipole in an External Electric Field	747
22.7	Electric Potential Due to a Charged Rod	749
22.8	Electric Potential Due to a Uniformly Charged Arc	752
22.9	Electric Potential Due to a Uniformly Charged Ring.	753
22.10	Electric Potential Due to a Uniformly Charged Disk.	754
22.11	Electric Potential Due to a Uniformly Charged Sphere	756
22.12	Electric Potential Due to a Charged Conductor	757
22.13	Potential Gradient.	758
22.14	The Electrostatic Precipitator	761
22.15	The Van de Graaff Generator.	762
22.16	Exercises	763
23	Capacitors and Capacitance	773
23.1	Capacitor and Capacitance.	773
23.2	Calculating Capacitance.	775
23.3	Capacitors with Dielectrics	781
23.4	Capacitors in Parallel and Series.	790
23.5	Energy Stored in a Charged Capacitor.	795
23.6	Exercises	797
24	Electric Circuits	809
24.1	Electric Current and Electric Current Density.	809
24.2	Ohm's Law and Electric Resistance	814
24.3	Electric Power	823
24.4	Electromotive Force	825
24.5	Resistors in Series and Parallel.	829
24.6	Kirchhoff's Rules	834

24.7	The RC Circuit	838
24.8	Exercises	844
Part VI Magnetism		
25	Magnetic Fields	859
25.1	Magnetic Force on a Moving Charge	859
25.2	Motion of a Charged Particle in a Uniform Magnetic Field . .	863
25.3	Charged Particles in an Electric and Magnetic Fields	865
	25.3.1 Velocity Selector	866
	25.3.2 The Mass Spectrometer	866
	25.3.3 The Hall Effect	867
25.4	Magnetic Force on a Current-Carrying Conductor.	869
25.5	Torque on a Current Loop	874
	25.5.1 Electric Motors.	876
	25.5.2 Galvanometers	877
25.6	Non-Uniform Magnetic Fields	878
25.7	Exercises	879
26	Sources of Magnetic Field.	889
26.1	The Biot-Savart Law.	889
26.2	The Magnetic Force Between Two Parallel Currents.	895
26.3	Ampere's Law	897
26.4	Displacement Current and the Ampere-Maxwell Law	901
26.5	Gauss's Law for Magnetism.	903
26.6	The Origin of Magnetism	904
26.7	Magnetic Materials	908
26.8	Diamagnetism and Paramagnetism	910
26.9	Ferromagnetism	914
26.10	Some Applications of Magnetism	919
26.11	Exercises	921
27	Faraday's Law, Alternating Current, and Maxwell's Equations . .	933
27.1	Faraday's Law of Induction	933
27.2	Motional emf	936
27.3	Electric Generators	940
27.4	Alternating Current	942
27.5	Transformers	943
27.6	Induced Electric Fields	945
27.7	Maxwell's Equations of Electromagnetism	947
27.8	Exercises	950
28	Inductance, Oscillating Circuits, and AC Circuits	961
28.1	Self-Inductance.	961

28.2	Mutual Inductance	964
28.3	Energy Stored in an Inductor	966
28.4	The L - R Circuit	967
28.5	The Oscillating L - C Circuit	971
28.6	The L - R - C Circuit	974
28.7	Circuits with an ac Source	977
28.8	L - R - C Series in an ac Circuit	984
28.9	Resonance in L - R - C Series Circuit	988
28.10	Exercises	988
Appendix A Conversion Factors		999
Appendix B Basic Rules and Formulas		1003
Appendix C The Periodic Table of Elements		1013
Answers to All Exercises		1015
Index		1057

Fundamental Physical Constants

Quantity	Symbol	Approximate value
Speed of light in vacuum	c	3.00×10^8 m/s
Avogadro's number	N_A	$6.02 \times 10^{23} \text{ mol}^{-1} = 6.02 \times 10^{26} \text{ kmol}^{-1}$
Gas constant	R	$8.314 \text{ J/mol} \cdot \text{K} = 8.314 \text{ J/kmol} \cdot \text{K}$
Boltzmann's constant	k	$1.38 \times 10^{-23} \text{ J/K}$
Gravitational constant	G	$6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$
Planck's constant	h	$6.63 \times 10^{-34} \text{ J} \cdot \text{s}$
Permittivity of free space	ϵ_0	$8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2$
Permeability of free space	$\mu_0 = 1/(c^2\epsilon_0)$	$4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}$
Atomic mass unit	1u	$1.6605 \times 10^{-27} \text{ kg} = 931.49 \text{ MeV}/c^2$
Electron charge	$-e$	$-1.60 \times 10^{-19} \text{ C}$
Electron rest mass	m_e	$9.11 \times 10^{-31} \text{ kg} = 0.000549 \text{ u}$ $= 0.511 \text{ MeV}/c^2$
Proton rest mass	m_p	$1.6726 \times 10^{-27} \text{ kg} = 1.00728 \text{ u}$ $= 938.27 \text{ MeV}/c^2$
Neutron rest mass	m_n	$1.6749 \times 10^{-27} \text{ kg} = 1.008665 \text{ u}$ $= 939.57 \text{ MeV}/c^2$

Other useful constants

Acceleration due to gravity at the Earth's surface (av.)	$g = 9.8 \text{ m/s}^2$
Absolute zero (0 K)	-273.15°C
Joule equivalent (1 kcal)	4,186 J
Speed of sound in air (20°C)	343 m/s
Density of air (dry)	1.29 kg/m^3
Standard atmosphere	$1.01 \times 10^5 \text{ Pa}$
Electric breakdown strength	$3 \times 10^6 \text{ V/m}$
Earth: Mass	$5.98 \times 10^{24} \text{ kg}$
Radius (av.)	$6.38 \times 10^3 \text{ km}$
Moon: Mass	$7.35 \times 10^{22} \text{ kg}$
Radius (av.)	$1.74 \times 10^3 \text{ km}$
Sun: Mass	$1.99 \times 10^{30} \text{ kg}$
Radius (av.)	$6.96 \times 10^5 \text{ km}$
Earth–Moon distance (av.)	$3.84 \times 10^5 \text{ km}$
Earth–Sun distance (av.)	$1.5 \times 10^8 \text{ km}$

The greek alphabet

Alpha	A	α	Nu	N	ν
Beta	B	β	Xi	Ξ	ξ
Gamma	Γ	γ	Omicron	O	o
Delta	Δ	δ	Pi	Π	π
Epsilon	E	ϵ	Rho	P	ρ
Zeta	Z	ζ	Sigma	Σ	σ
Eta	H	η	Tau	T	τ
Theta	Θ	θ	Upsilon	Y	υ
Iota	I	ι	Phi	Φ	ϕ
Kappa	K	κ	Chi	X	χ
Lambda	Λ	λ	Psi	Ψ	ψ
Mu	M	μ	Omega	Ω	ω

Some SI base units and derived units

Quantity	Unit name	Unit symbol	In terms of base units
Mass	kilogram	kg	$\left\{ \begin{array}{l} \text{Base} \\ \text{SI} \\ \text{units} \end{array} \right.$
Length	meter	m	
Time	second	s	
Electric current	ampere	A	
Force	newton	N	$\text{kg}\cdot\text{m}/\text{s}^2$
Energy and work	joule	J	$\text{kg}\cdot\text{m}^2/\text{s}^2$
Power	watt	W	$\text{kg}\cdot\text{m}^2/\text{s}^3$
Pressure	pascal	Pa	$\text{kg}/(\text{m}\cdot\text{s}^2)$
Frequency	hertz	Hz	s^{-1}
Electric charge	coulomb	C	$\text{A}\cdot\text{s}$
Electric potential	volt	V	$\text{kg}\cdot\text{m}^2/(\text{A}\cdot\text{s}^3)$
Electric resistance	ohm	Ω	$\text{kg}\cdot\text{m}^2/(\text{A}^2\cdot\text{s}^3)$
Capacitance	farad	F	$\text{A}^2\cdot\text{s}^4/(\text{kg}\cdot\text{m}^2)$
Magnetic field	tesla	T	$\text{kg}/(\text{A}\cdot\text{s}^2)$
Magnetic flux	weber	Wb	$\text{kg}\cdot\text{m}^2/(\text{A}\cdot\text{s}^2)$
Inductance	henry	H	$\text{kg}\cdot\text{m}^2/(\text{s}^2\cdot\text{A}^2)$

SI multipliers

yotta	Y	10^{24}
zeta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^9
mega	M	10^6
kilo	k	10^3
hecto	h	10^2
deka	da	10^1
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}