

**Second Edition**

# Understanding Physics

**Michael Mansfield  
Colm O'Sullivan**

 **WILEY**





---

# **Understanding Physics**

**Second Edition**



---

# Understanding Physics

**Second Edition**

MICHAEL MANSFIELD AND COLM O'SULLIVAN

*Physics Department  
University College Cork  
Ireland*



A John Wiley and Sons, Ltd, Publication

This edition first published 2011  
©2011 John Wiley & Sons

*Registered office*

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at [www.wiley.com](http://www.wiley.com).

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

The publisher and the author make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for every situation. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. The fact that an organisation or Website is referred to in this work as a citation and/or a potential source of further information does not mean that the author or the publisher endorses the information the organisation or Website may provide or recommendations it may make. Further, readers should be aware that Internet Websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the publisher nor the author shall be liable for any damages arising herefrom.

*Library of Congress Cataloging-in-Publication Data*

Mansfield, Michael, 1943-

Understanding physics / Michael Mansfield and Colm O'Sullivan. – 2nd ed.

p. cm.

Includes index.

Summary: Understanding Physics - Second edition is a comprehensive, yet compact, introductory physics textbook aimed at physics undergraduates and also at engineers and other scientists taking a general physics course. Written with today's students in mind, this text covers the core material required by an introductory course in a clear and refreshing way. A second colour is used throughout to enhance learning and understanding. Each topic is introduced from first principles so that the text is suitable for students without a prior background in physics. At the same time the book is designed to enable students to proceed easily to subsequent courses in physics and may be used to support such courses. Mathematical methods (in particular, calculus and vector analysis) are introduced within the text as the need arises and are presented in the context of the physical problems which they are used to analyse. Particular aims of the book are to demonstrate to students that the easiest, most concise and least ambiguous way to express and describe phenomena in physics is by using the language of mathematics and that, at this level, the total amount of mathematics required is neither large nor particularly demanding. 'Modern physics' topics (relativity and quantum mechanics) are introduced at an earlier stage than is usually found in introductory textbooks and are integrated with the more 'classical' material from which they have evolved. This book encourages students to develop an intuition for relativistic and quantum concepts at as early a stage as is practicable. The text takes a reflective approach towards the scientific method at all stages and, in keeping with the title of the text, emphasis is placed on understanding of, and insight into, the material presented" – Provided by publisher.

Summary: "Understanding Physics – Second edition is a comprehensive, yet compact, introductory physics textbook aimed at physics undergraduates and also at engineers and other scientists taking a general physics course" – Provided by publisher.

ISBN 978-0-470-74638-7 (hardback) – ISBN 978-0-470-74637-0 (pbk.)

1. Physics. I. O'Sullivan, Colm. II. Title.

QC23.M287 2011

530–dc22

2010025111

A catalogue record for this book is available from the British Library.

ISBN 9780470746387 (Hbk) 9780470746370 (Pbk)

Set in 10/12pt Times by Thomson Digital, Noida, India.

Printed and bound in the United Kingdom by Antony Rowe Ltd, Chippenham, Wiltshire.

Cover image courtesy of CERN. This image represents a proton-antiproton collision event at the Large Hadron Collider (LHC) ATLAS 7 TeV Collision Events recorded, March 30th, 2010. The tracks show the paths of some of the fundamental particles produced in the collision. The curved paths arise from the motion of charged particles in a magnetic field.

Back cover image: *The Aurora Borealis shines above Bear Lake, Eielson Air Force Base, Alaska.*

Copyright United States Air Force. Photo by Senior Airman Joshua Strang.

# Contents

Sections marked like this indicate somewhat less essential or more advanced material

*Preface to Second Edition*

xv

<b>1</b>	<b>Understanding the physical universe</b>	<b>1</b>
1.1	The programme of physics	1
1.2	The building blocks of matter	2
1.3	Matter in bulk	4
1.4	The fundamental interactions	5
1.5	Exploring the physical universe: the scientific method	5
1.6	The role of physics: its scope and applications	7
<b>2</b>	<b>Using mathematical tools in physics</b>	<b>9</b>
2.1	Applying the scientific method	9
2.2	The use of variables to represent displacement and time	9
2.3	Representation of data	10
2.4	The use of differentiation in analysis: velocity and acceleration in linear motion	12
2.5	The use of integration in analysis	16
2.6	Maximum and minimum values of physical variables: general linear motion	21
2.7	Angular motion: the radian	23
2.8	The role of mathematics in physics	25
	Worked examples	26
	Problems	28
<b>3</b>	<b>The causes of motion: dynamics</b>	<b>31</b>
3.1	The concept of force	31
3.2	The first law of dynamics (Newton's first law)	32
3.3	The fundamental dynamical principle (Newton's second law)	33
3.4	Systems of units: SI	36
3.5	Time dependent forces: oscillatory motion	38
3.6	Simple harmonic motion	40
3.7	Mechanical work and energy: power	44
3.8	Energy in simple harmonic motion	48
3.9	Dissipative forces: damped harmonic motion	50
3.10	Forced oscillations	54
3.11	Nonlinear dynamics: chaos	56
	Worked examples	57
	Problems	61

<b>4</b>	<b>Motion in two and three dimensions</b>	<b>63</b>
4.1	Vector physical quantities	63
4.2	Vector algebra	64
4.3	Velocity and acceleration vectors	67
4.4	Force as a vector quantity: vector form of the laws of dynamics	69
4.5	Constraint forces	70
4.6	Friction	72
4.7	Motion in a circle: centripetal force	74
4.8	Motion in a circle at constant speed	75
4.9	Tangential and radial components of acceleration	77
4.10	Hybrid motion: the simple pendulum	78
4.11	Angular quantities as vectors: the cross product	79
	Worked examples	81
	Problems	84
<b>5</b>	<b>Force fields</b>	<b>87</b>
5.1	Newton's law of universal gravitation	87
5.2	Force fields	88
5.3	The concept of flux	89
5.4	Gauss' law for gravitation	90
5.5	Motion in a constant uniform field: projectiles	94
5.6	Mechanical work and energy	96
5.7	Energy in a constant uniform field	102
5.8	Energy in an inverse square law field	103
5.9	Moment of a force: angular momentum	105
5.10	Planetary motion: circular orbits	107
5.11	Planetary motion: elliptical orbits and Kepler's laws	108
	Worked examples	110
	Problems	114
<b>6</b>	<b>Many-body interactions</b>	<b>117</b>
6.1	Newton's third law	117
6.2	The principle of conservation of momentum	120
6.3	Mechanical energy of systems of particles	121
6.4	Particle decay	122
6.5	Particle collisions	123
6.6	The centre of mass of a system of particles	127
6.7	The two-body problem: reduced mass	128
6.8	Angular momentum of a system of particles	131
6.9	Conservation principles in physics	132
	Worked examples	133
	Problems	137
<b>7</b>	<b>Rigid body dynamics</b>	<b>141</b>
7.1	Rigid bodies	141
7.2	Rigid bodies in equilibrium: statics	142
7.3	Torque	143



7.4	Dynamics of rigid bodies	144
7.5	Measurement of torque: the torsion balance	145
7.6	Rotation of a rigid body about a fixed axis: moment of inertia	146
7.7	Calculation of moments of inertia: the parallel axis theorem	147
7.8	Conservation of angular momentum of rigid bodies	149
7.9	Conservation of mechanical energy in rigid body systems	149
7.10	Work done by a torque: torsional oscillations: rotational power	152
7.11	Gyroscopic motion	154
7.12	Summary: connection between rotational and translational motions	155
	<a href="#">Worked examples</a>	156
	<a href="#">Problems</a>	158
<b>8</b>	<b>Relative motion</b>	<b>161</b>
8.1	Applicability of Newton's laws of motion: inertial reference frames	161
8.2	The Galilean transformation	162
8.3	The CM (centre-of-mass) reference frame	165
8.4	Example of a noninertial frame: centrifugal force	170
8.5	Motion in a rotating frame: the Coriolis force	171
8.6	The Foucault pendulum	175
8.7	Practical criteria for inertial frames: the local view	176
	<a href="#">Worked examples</a>	177
	<a href="#">Problems</a>	181
<b>9</b>	<b>Special relativity</b>	<b>183</b>
9.1	The velocity of light	183
9.2	The principle of relativity	184
9.3	Consequences of the principle of relativity	184
9.4	The Lorentz transformation	187
9.5	The Fitzgerald-Lorentz contraction	190
9.6	Time dilation	191
9.7	Paradoxes in special relativity	192
9.8	Relativistic transformation of velocity	193
9.9	Momentum in relativistic mechanics	194
9.10	Four vectors: the energy-momentum 4-vector	196
9.11	Energy-momentum transformations: relativistic energy conservation	198
9.12	Relativistic energy: mass-energy equivalence	199
9.13	Units in relativistic mechanics	202
9.14	Mass-energy equivalence in practice	202
9.15	General relativity	203
9.16	Simultaneity: quantitative analysis of the twin paradox	204
	<a href="#">Worked examples</a>	206
	<a href="#">Problems</a>	209
<b>10</b>	<b>Continuum mechanics: mechanical properties of materials</b>	<b>211</b>
10.1	Dynamics of continuous media	211
10.2	Elastic properties of solids	212
10.3	Fluids at rest	215

10.4	Elastic properties of fluids	217
10.5	Pressure in gases	217
10.6	Archimedes' principle	218
10.7	Fluid dynamics	220
10.8	Viscosity	223
10.9	Surface properties of liquids	224
10.10	Boyle's law (Mariotte's law)	226
10.11	A microscopic theory of gases	227
10.12	The mole	230
10.13	Interatomic forces: modifications to the kinetic theory of gases	230
10.14	Microscopic models of condensed matter systems	232
	Worked examples	234
	Problems	236
<b>11</b>	<b>Thermal physics</b>	<b>239</b>
11.1	Friction and heating	239
11.2	Temperature scales	240
11.3	Heat capacities of thermal systems	242
11.4	Comparison of specific heat capacities: calorimetry	243
11.5	Thermal conductivity	244
11.6	Convection	245
11.7	Thermal radiation	246
11.8	Thermal expansion	248
11.9	The first law of thermodynamics	249
11.10	Change of phase: latent heat	251
11.11	The equation of state of an ideal gas	252
11.12	Isothermal, isobaric and adiabatic processes: free expansion	252
11.13	The Carnot cycle	256
11.14	Entropy and the second law of thermodynamics	258
11.15	The Helmholtz and Gibbs functions	260
11.16	Microscopic interpretation of temperature	261
11.17	Polyatomic molecules: principle of equipartition of energy	263
11.18	Ideal gas in a gravitational field: the 'law of atmospheres'	265
11.19	Ensemble averages and distribution functions	266
11.20	The distribution of molecular velocities in an ideal gas	267
11.21	Distribution of molecular speeds, momenta and energies	269
11.22	Microscopic interpretation of temperature and heat capacity in solids	271
	Worked examples	272
	Problems	274
<b>12</b>	<b>Wave motion</b>	<b>277</b>
12.1	Characteristics of wave motion	277
12.2	Representation of a wave which is travelling in one dimension	279
12.3	Energy and power in a wave motion	281
12.4	Plane and spherical waves	282
12.5	Huygens' principle: the laws of reflection and refraction	282
12.6	Interference between waves	284
12.7	Interference of waves passing through openings: diffraction	288

12.8	Standing waves	290
12.9	The Doppler effect	293
12.10	The wave equation	294
12.11	Waves along a string	295
12.12	Waves in elastic media: longitudinal waves in a solid rod	296
12.13	Waves in elastic media: sound waves in gases	297
12.14	Superposition of two waves of slightly different frequencies: wave and group velocities	298
12.15	Other wave forms: Fourier analysis	300
	Worked examples	302
	Problems	304
<b>13</b>	<b>Introduction to quantum mechanics</b>	<b>307</b>
13.1	Physics at the beginning of the twentieth century	307
13.2	The blackbody radiation problem	308
13.3	The photoelectric effect	311
13.4	The X-ray continuum	313
13.5	The Compton effect: the photon model	314
13.6	The de Broglie hypothesis: electron waves	316
13.7	Interpretation of wave-particle duality	318
13.8	The Heisenberg uncertainty principle	319
13.9	The wavefunction: expectation values	322
13.10	The Schrödinger (wave mechanical) method	323
13.11	The free particle	324
13.12	The time-independent Schrödinger equation: eigenfunctions and eigenvalues	327
13.13	The infinite square potential well	328
13.14	The potential step	331
13.15	Other potential wells and barriers	336
13.16	The simple harmonic oscillator	339
13.17	Further implications of quantum mechanics	341
	Worked examples	341
	Problems	344
<b>14</b>	<b>Electric currents</b>	<b>347</b>
14.1	Electric currents	347
14.2	Force between currents	349
14.3	The unit of electric current	350
14.4	Heating effect revisited: electrical resistance	351
14.5	Strength of a power supply: emf	353
14.6	Resistance of a circuit	354
14.7	Potential difference	354
14.8	Effect of internal resistance	356
14.9	Comparison of emfs: the potentiometer	358
14.10	Multiloop circuits	359
14.11	Kirchhoff's rules	360
14.12	Comparison of resistances: the Wheatstone bridge	361
14.13	Power supplies connected in parallel	362
14.14	Resistivity	363
14.15	Variation of resistance with temperature	365

	Worked examples	365
	Problems	368
<b>15</b>	<b>Electric fields</b>	<b>371</b>
15.1	The electric charge model	371
15.2	Interpretation of electric current in terms of charge	373
15.3	Electric fields: electric field strength	374
15.4	Forces between point charges: Coulomb's law	376
15.5	Electric flux and electric flux density	376
15.6	Electric fields due to systems of point charges	378
15.7	Gauss' law for electrostatics	381
15.8	Potential difference in electric fields: electric potential	383
15.9	Acceleration of charged particles	388
15.10	Dielectric materials	389
15.11	Capacitors	391
15.12	Capacitors in series and in parallel	395
15.13	Charge and discharge of a capacitor through a resistor	396
	Worked examples	398
	Problems	401
<b>16</b>	<b>Magnetic fields</b>	<b>403</b>
16.1	Magnetism	403
16.2	The work of Ampère, Biot and Savart	405
16.3	Magnetic pole strength	406
16.4	Magnetic field strength	407
16.5	Ampère's law	408
16.6	The Biot-Savart law	410
16.7	Applications of the Biot-Savart law	411
16.8	Magnetic flux and magnetic flux density	413
16.9	Magnetic fields due to systems of poles	413
16.10	Forces between magnets	414
16.11	Forces between currents and magnets	415
16.12	The permeability of vacuum	416
16.13	Current loop in a magnetic field	417
16.14	Magnetic dipoles and magnetic materials	419
16.15	Moving coil meters and electric motors	423
16.16	Magnetic fields due to moving charges	425
16.17	Force on an electric charge in a magnetic field	425
16.18	Magnetic dipole moments of charged particles in closed orbits	427
16.19	Electric and magnetic fields in moving reference frames	428
	Worked examples	431
	Problems	433
<b>17</b>	<b>Electromagnetic induction: time-varying emfs</b>	<b>437</b>
17.1	The principle of electromagnetic induction	437
17.2	Simple applications of electromagnetic induction	440
17.3	Self-inductance	441

17.4	The series L-R circuit	444
17.5	Discharge of a capacitor through an inductor and a resistor	446
17.6	Time-varying emfs: mutual inductance: transformers	447
17.7	Alternating current (a.c.)	449
17.8	Alternating current transformers	453
17.9	Resistance, capacitance and inductance in a.c. circuits	454
17.10	The series L-C-R circuit: phasor diagrams	456
17.11	Power in an a.c. circuit	459
	Worked examples	460
	Problems	462
<b>18</b>	<b>Maxwell's equations: electromagnetic radiation</b>	<b>465</b>
18.1	Reconsideration of the laws of electromagnetism: Maxwell's equations	465
18.2	Plane electromagnetic waves	468
18.3	Experimental observation of electromagnetic radiation	470
18.4	The electromagnetic spectrum	471
18.5	Polarisation of electromagnetic waves	473
18.6	Energy, momentum and angular momentum in electromagnetic waves	476
18.7	Reflection of electromagnetic waves at an interface between nonconducting media	479
18.8	Electromagnetic waves in a conducting medium	480
18.9	The photon model revisited	483
18.10	Invariance of electromagnetism under the Lorentz transformation	484
	Worked examples	485
	Problems	487
<b>19</b>	<b>Optics</b>	<b>489</b>
19.1	Electromagnetic nature of light	489
19.2	Coherence: the laser	492
19.3	Diffraction at a single slit	493
19.4	Two slit interference and diffraction: Young's double slit experiment	496
19.5	Multiple slit interference: the diffraction grating	498
19.6	Diffraction of X-rays: Bragg scattering	501
19.7	The ray model: geometrical optics	504
19.8	Reflection of light	505
19.9	Image formation by spherical mirrors	506
19.10	Refraction of light	508
19.11	Refraction at successive plane interfaces	512
19.12	Image formation by spherical lenses	513
19.13	Image formation of extended objects: magnification	517
19.14	Dispersion of light	520
	Worked examples	521
	Problems	524
<b>20</b>	<b>Atomic physics</b>	<b>527</b>
20.1	Atomic models	527
20.2	The spectrum of hydrogen: the Rydberg formula	529
20.3	The Bohr postulates	530

20.4	The Bohr theory of the hydrogen atom	531
20.5	The quantum mechanical (Schrödinger) solution of the one-electron atom	534
20.6	The radial solutions of the lowest energy state of hydrogen	538
20.7	Interpretation of the one-electron atom eigenfunctions	539
20.8	Intensities of spectral lines: selection rules	543
20.9	Quantisation of angular momentum	544
20.10	Magnetic effects in one-electron atoms: the Zeeman effect	545
20.11	The Stern–Gerlach experiment: electron spin	547
20.12	The spin–orbit interaction	549
20.13	Identical particles in quantum mechanics: the Pauli exclusion principle	550
20.14	The periodic table: multielectron atoms	552
20.15	The theory of multielectron atoms	554
20.16	Further uses of the solutions of the one-electron atom	555
	Worked examples	556
	Problems	557
<b>21</b>	<b>Electrons in solids: quantum statistics</b>	<b>559</b>
21.1	Bonding in molecules and solids	559
21.2	The classical free electron model of solids	563
21.3	The quantum mechanical free electron model: the Fermi energy	565
21.4	The electron energy distribution at 0 K	568
21.5	Electron energy distributions at $T > 0$ K	570
21.6	Specific heat capacity and conductivity in the quantum free electron model	571
21.7	The band theory of solids	573
21.8	Semiconductors	574
21.9	Junctions in conductors and semiconductors: p-n junctions	576
21.10	Transistors	581
21.11	The Hall effect	583
21.12	Quantum statistics: systems of bosons	584
21.13	Superconductivity	585
	Worked examples	586
	Problems	588
<b>22</b>	<b>Nuclear physics, particle physics and astrophysics</b>	<b>589</b>
22.1	Properties of atomic nuclei	589
22.2	Nuclear binding energies	591
22.3	Nuclear models	592
22.4	Radioactivity	595
22.5	$\alpha$ -, $\beta$ - and $\gamma$ -decay	597
22.6	Detection of radiation: units of radioactivity	600
22.7	Nuclear reactions	602
22.8	Nuclear fission and nuclear fusion	603
22.9	Fission reactors	604
22.10	Thermonuclear fusion	606
22.11	Subnuclear particles	609
22.12	The quark model	613
22.13	The physics of stars	617
22.14	The origin of the universe	622

Worked examples	625
Problems	627
<i>Answers to problems</i>	629
Appendix A: <i>Mathematical rules and formulas</i>	639
Appendix B: <i>Some fundamental physical constants</i>	659
Appendix C: <i>Some astrophysical and geophysical data</i>	661
<i>Bibliography</i>	663
<i>Index</i>	665
<i>Inside front cover: Summary of notations used in text</i>	
<i>Inside back cover: The periodic table (Appendix D)</i>	





# Preface to Second Edition

## Goals and objectives

*Understanding Physics* is written primarily for students who are taking their first course in physics at university level. While it is anticipated that many readers will have some previous knowledge of physics or of general science, each topic is introduced from first principles so that the text is suitable for students without any prior background in physics. The book has been written to support most standard first-year undergraduate university physics courses (and often beyond the first year) and can serve as an introductory text for both prospective physics majors and other students who will need to apply the principles and techniques of basic physics in subsequent courses. A principal aim of this book is to give the reader the foundation required to proceed smoothly to intermediate level courses in physics and engineering and to courses in the chemical, computer, materials and earth sciences, all of which require a sound knowledge of basic physics.

Students with some previous knowledge of physics will find that they are already familiar with many of the topics covered in the early sections. These readers should note, however, that the treatment of these topics in *Understanding Physics* often differs from that given in school textbooks and is designed to lay the foundations for the treatment of new and more advanced topics. As authors, one of our aims is to integrate school physics more closely to that studied at university, encouraging students to appreciate the relevance of physics previously studied and to integrate it with the material encountered at university. For these reasons we hope that students with previous knowledge of physics will take the opportunity to refresh and deepen their understanding of topics which they may regard as familiar.

Some knowledge of simple algebra, geometry and trigonometry is assumed but differential and integral calculus, vector analysis and other more advanced mathematical methods are introduced within the text as the need arises and are presented in the context of the physical problems which they are used to analyse. Historically, many mathematical techniques were developed specifically to address problems in physics and these can often be grasped more easily when applied to a relevant physical situation than when presented as an otherwise abstract mathematical concept. These mathematical asides are indicated throughout the text by a grey background and it is hoped that by studying these short sections, the reader will gain some insight into both the mathematical techniques involved and the physics to which the techniques are applied.

The mathematical asides, together with Appendix A (Mathematical Rules and Formulas), however, cannot substitute for a formal course in mathematical methods, rather they could be considered a mathematical ‘survival kit’ for the study of introductory physics. It is hoped that most readers will either have already taken or be studying an introductory mathematics course. In reality the total amount of mathematics required is neither large nor particularly demanding.

## Approach

It is no longer credible to describe the discoveries and developments made during the early years of the twentieth century as ‘modern physics’. This is not to deny the radical and revolutionary nature of these developments but rather is a recognition that they have long since become a part of mainstream physics. Quantum mechanics, relativity and our picture of matter at the subatomic level will surely form part of the ‘classical’ tradition of twenty-first century physicists. On the other hand, the discoveries of the seventeenth, eighteen and nineteenth centuries have lost none of their importance. The majority of everyday experiences of the material world can be understood in a fully satisfactory manner in terms of classical physics. Indeed attempts to explain such phenomena in the language of twentieth century physics, while possible in principle, tend to be unnecessarily complicated and often confusing.

In *Understanding Physics*, ‘modern’ (twentieth century) topics are introduced at an earlier stage than is usually found in introductory textbooks and are integrated with the more ‘classical’ material from which they have evolved. Although many of the concepts which are basic to twentieth century physics are relatively easy to represent mathematically, they are not as intuitive as those of classical physics, particularly for students with an extensive previous acquaintance with ‘classical’ concepts. This book aims to encourage students to develop an intuition for relativistic and quantum concepts at as early a stage as is practicable.

*Understanding Physics* has been kept to a compact format in order to emphasise, in a fully rigorous manner, the essential unity of physics. At each stage new topics are carefully integrated with previous material. Throughout the text references are given to other sources where more detailed discussions of particular topics or applications may be found. In order to avoid breaking the flow and unity of the material within chapters, worked examples and problems are placed at the end of each chapter. Indications are given throughout the text as to when a particular worked example might be studied or a particular problem attempted. The number of problems has been limited so that a student might reasonably expect to attempt all problems in a given chapter; other sources of suitable problems are widely available, for example in other textbooks and on the internet.

The internationally agreed system of units (SI) is now adopted almost universally in science and engineering and is used uncompromisingly in this text. In addition, we have adhered rigorously to the recommendations of the International Union of Pure and Applied Physics (IUPAP) on symbols and nomenclature (Cohen and Giacomo, 1987).

The text takes a reflective approach towards the scientific method at all stages – that is, while learning the fundamentals of physics the student should also become familiar with the scientific method. In keeping with the title of the text, emphasis is placed on understanding of and insight into the material presented. The book therefore seeks not merely to describe the discoveries and the models of physics but also, in the process, to familiarise readers with the skills and techniques which have been developed to analyse natural phenomena, skills and techniques which they can look forward to applying themselves. This book does not seek to reveal and explain all the mysteries of the physical universe but, instead, lays the foundations on which readers can build and (perhaps more importantly) encourages and equips readers to explore further.

### Structure

Chapter 1 starts with a short overview of the way in which physics today describes the material universe, from the very smallest building blocks of matter up to large scale bulk materials. It is a remarkable fact that the same basic principles seem to apply over the full range of distance scales – from subnuclear to intergalactic. The physical principles encountered in subsequent chapters are applied to systems on all of these scales, as the need arises. The basic ideas of calculus are introduced in Chapter 2 in the context of the description of motion in one dimension; readers with a good prior knowledge of this material may wish to skip this chapter, although such readers might find it profitable to use the chapter to refresh their memories.

Chapters 3 to 7 introduce the main themes of classical dynamics. This is followed by an introduction to relative motion (Chapter 8) which is an essential prerequisite to the study of the special theory of relativity (Chapter 9). Chapters 10 and 11, respectively, deal with the mechanical and thermal behaviour of matter. A sound knowledge of wave motion (Chapter 12), a very important part of physics in its own right, is essential for a proper understanding of quantum mechanics (Chapter 13). The five subsequent chapters (14 to 18) cover the main aspects of classical electromagnetism and its application to wave and geometrical optics is covered in Chapter 19.

The final three chapters (20, 21 and 22) – on atomic physics, on electrons in solids and on nuclear and particle physics and astrophysics – are a little more specialised and detailed than the others. Depending on the subjects which the reader plans to pursue subsequently, significant amounts of all or some of these chapters might well be omitted.

Some chapters have a few sections which contain slightly more demanding analyses or less essential material than found in the rest of the book. These sections, (for example Section 5.11 on planetary motion, elliptical orbits and Kepler's laws) indicated by a blue background, could be considered optional and may be omitted if appropriate.

### Note on the second edition

Users of the first edition will notice a number of significant changes in the second edition. These have mostly arisen as a result of suggestions for improvement made by instructors, students and of our own experience with the book. New sections have been included on dissipative forces, forced oscillations, nonlinear dynamics and on electromagnetic waves at interfaces between media. A completely new chapter (Chapter 19) on optics has been added, some of the material of which was covered less fully in Chapter 12 of the first edition. The emphasis on integration of the various topics into a view of physics as a unified whole has been increased; for example, the concept of flux (and Gauss' law) has been introduced at an earlier stage to enable it to be applied to gravitation.

### Supplementary resources

#### The understanding physics website

An *Understanding Physics* website can be accessed on the internet at the following URL <http://www.wiley.com/go/mansfield>.

The website includes additional material, further problems and other teaching and learning resources provided on a section by section basis. In particular, it provides links to suitable interactive exercises in the form of animations, simulations, tutorials, etc. and other multimedia materials. All such resources have been selected for their suitability by the authors and have been evaluated for quality by reputable international organisations such as the European Physical Society (EPS), MPTL (Multimedia in Physics Teaching and Learning) or MERLOT (Multimedia Educational Resource for Learning and Online Teaching).

Students are encouraged to enhance their understanding and insight by using the website in parallel with studying the text.

### A message for students

You should not expect to achieve an instant understanding of all topics studied. The learning process starts through an *understanding of concepts* and then progresses.

New material may not be fully absorbed at first reading but only after more careful study. From our own personal experience, however, we can assure you that persistence will be rewarded and that initially challenging material will be revealed as being both simple and elegant.

We have deliberately not provided end-of-chapter summaries. We feel that it is an important part of the learning exercise that students create such summaries for themselves. To assist this process, however, we have adopted a range of specific highlighting styles throughout

the book (indicating fundamental principles/laws, equations of state, definitions, important relationships, etc.). A key to the more important examples of the notations used is located inside the front cover.

Readers who are studying physics for the first time are starting on a great adventure; we hope that this book will help you to find the early stages of the journey both exciting and rewarding. We also hope that it will prove to be a source of continuing support for your subsequent studies.

## Acknowledgements

*Understanding Physics* has benefited greatly from the many contributions, comments and criticism generously provided over many years by numerous individuals. The second edition, in particular, has also benefited greatly from many suggestions made by users of the first edition, both students and lecturers.

Firstly, we wish to express our gratitude to our present and former colleagues in the Department of Physics at University College Cork. The many detailed discussions on physics and physics education which we have enjoyed with them over decades have taught us much and have contributed substantially to the refinement of our understanding. We are sure that they will find in these pages many of their original ideas which we have exploited and developed, sometimes consciously, frequently unconsciously. In particular, we wish to acknowledge our debt to Frank Fahy, Joe Lennon, Rita O'Sullivan, Tony Deeney, John Delaney, Niall Ó Murchadha, Michel Vandyck, John McInerney, Stephen Fahy, Paul Callanan, Andy Ruth, Frank Peters, Thomas Busch, Paddy McCarthy and David Nikogosyan, all of the Physics Department. The approach we have taken to the presentation of electromagnetism arose from original ideas developed by Frank Fahy in the early 1960s. We acknowledge the support provided by the Department, under the leadership of John McInerney; in particular we are extremely grateful to Stephen Fahy for generously providing the space and resources which enabled the second edition to be completed. Pat Twomey, John O'Riordan and Robin Gillen provided essential technical support and Irene Horne, Susanna Kent, Karmen O'Shea and Niamh O'Sullivan provided keyboard assistance at critical stages in the project.

We also acknowledge the advice and support received from other UCC colleagues, in particular, Garret Barden, Paul Brint, Peter Flynn, Donal Hurley, Paul Lambkin, Des McHale, Tom O'Donovan, Willie Reville, Brian Twomey and from David Rea of St. Colman's College, Fermoy.

Without our students in University College Cork, it would not have been possible to have class tested the approaches, ideas and problems that are central to this book. They have acted as guinea-pigs for many years and we would like to thank them for their invaluable comments and criticisms and for feedback that led to many improvements in the second edition.

Our original external reviewers and a wide variety of users of the text have made major contributions to the development and refinement of *Understanding Physics*, particularly towards improvement in the second edition, for which the authors are particularly grateful. We appreciate the considerable time and effort that this required and we acknowledge their common commitment to physics education.

Particular thanks goes to the following for their helpful contributions: Claes Algström, Lars-Erik Berg, Eric Both, Paddy Bourke, Peter Bourke, Anne Breslin, Iris Choi, Malcolm Cooper, Peter Ditlevsen, Nick van Eijndhoven, Tore Ericsson, Stephen Fahy, Sonja Feinervalkier, Matt Griffin, Lennart Häggström, Jan Petter Hansen, Jan Hedman, Donald Holcomb, Reyer Jochemsen, Christor Johannesson, Leif Karlsson, Martijn Kemerink, John Mason, Leopold Mathelitsch, Vince McCarthy, Niklas Meinander, Alex Montwill, Jim O'Brien, Austin Phelps, Giancarlo Reali, Janez Strnad, Tom Sundius, Agneta Svensson, Edward Thomas, Jozefina Turlo, Ton van Leeuwen, Constantijn van de Pas, David Van Baak, Anders Wallin, Tom Witt and many other instructors and student users around the world.

Our friend and colleague, Joe Lennon, read every page of the manuscript and made many helpful, often vital, suggestions. His exceptional physical insight and his understanding of difficulties in the material from a student's point of view have been available to us throughout the development of both the first and second editions and inform almost every page of the text. We have adopted almost all of his suggestions and we readily acknowledge that the book has been greatly enriched by his generous help.

The authors wish to express our thanks for the support and encouragement received from our publishers. For the first edition we thank Clive Horwood, Stuart MacFarlane and Jim Wilkie at Praxis Publishing and Andrew Slade, Mary Seddon and Celia Carden at John Wiley and Sons. The second edition has been brought to fruition thanks to the professionalism of a number of people at John Wiley and Sons, including Tanushree Mathur in Singapore and Jenny Cosham, Jon Peacock, Amie Marshall, Richard Davies, Emma Strickland, Alexandra Carrick and Steve Williams in Chichester. We are particularly grateful to Aparajita Srivastava at Thomson Digital for her cooperation and flexibility throughout the typesetting/proofreading stage.

Finally, and most importantly, we want to record our deep appreciation of the support we received from our wives, Madeleine and Denise, and our children Niamh, Eoin, Katie, Chris and Claire.

Colm O'Sullivan, Michael Mansfield  
Cork, 1 June 2010



# Understanding the physical universe

## AIMS

- to show how matter can be described in terms of a series of *models* (mental pictures of the structures and workings of systems) of increasing scale, starting with only a few basic building blocks
- to describe how, despite the great complexity of the material world, interactions between its building blocks can be reduced to no more than four distinct interactions
- to describe how natural phenomena can be studied methodically through observation, measurement, analysis, hypothesis and testing (the *scientific method*)

## 1.1 The programme of physics

Humans have always been curious about the environment in which they found themselves and, in particular, have sought explanations for the way in which the world around them behaves. All civilisations have probably engaged in science in this sense but sadly not all have left records of their endeavours. It would seem, however, that sophisticated scientific activity was carried out in ancient Babylonian and Egyptian civilisations and, certainly, many oriental civilisations had expert astronomers – every appearance of Halley’s comet over a time span of 1000 years was recorded by Chinese astronomers. Science as we know it today developed from the Renaissance in Europe which in turn owed much to the rediscovery of the work of the great Greek philosopher/scientists such as Aristotle, Pythagoras and Archimedes, work that had been further developed in the Islamic world between the seventh and sixteenth centuries.

Common to all scientific activity is the general observation that, in most respects, the physical world behaves in a regular and predictable manner. All other things being equal, an archer knows that if he fires successive arrows with the same strength and in the same direction they follow the same path to their target. Similar rules seem to govern the trajectories of stones, spears, discs and other projectiles. Regularities are also evident in phenomena involving light, heat, sound, electricity and magnetism (a magnetic compass would not be much use if its orientation changed randomly!). The primary objective of physics is to discover whether or not basic ‘rules’ exist and, if they do, to identify as exactly as possible what these ‘rules’ are. As we shall see, it turns out that most of the everyday behaviour of the physical universe can be explained satisfactorily in terms of rather few simple ‘rules’. These basic ‘rules’ have come to be called *laws of nature*, examples of which include the Galilean/Newtonian laws of motion (Sections 3.2, 3.3, 6.1), Newton’s law of gravitation (Section 5.1) and the laws of electromagnetism associated with the names of Ampère (Section 16.5), Faraday (Section 17.1), Coulomb (Section 15.5) and Maxwell (Section 18.1). In addition to these basic laws there are also ‘laws’ of a somewhat less fundamental nature which are used to describe the general behaviour of specific systems. Examples of the latter include Hooke’s law for helical springs (Section 3.5), Boyle’s (or Mariotte’s) law for the mechanical behaviour of gases (Section 10.10) and Ohm’s law for the conductivity of metals (Section 14.4).

The objective in studying physics, therefore, is to investigate all aspects of the material world in an attempt to discover the fundamental laws of nature and hence to understand and explain the full range of phenomena observed in the physical universe. This programme must include a satisfactory explanation of the structure of matter in all its forms (e.g. solids, liquids, gases), which in turn requires an understanding of the interactions between the basic building blocks from which all matter is constituted. How these interactions are responsible for the mechanical, thermal, magnetic and electrical properties of matter must also be explained. Such explanations, once discovered, can be applied to develop descriptions of phenomena ranging from the subatomic to the cosmic and to develop practical applications for the benefit of, and use by, society.

In the next three sections we review the language and images currently used by physicists to describe the structure of matter and the fundamental interactions of nature.

1.2   The building blocks of matter

Fundamental particles

Our present view of the nature of matter is very different from that which prevailed even fifty years ago. All matter is currently viewed as comprising various combinations of two classes of elementary particles – the basic building blocks – called, respectively, **quarks** and **leptons**. We give below an introductory account of the terminology and models used in the quark/lepton description of matter. The quark/lepton model will be discussed in more detail in Section 22.12.

Quarks and leptons occur in three distinct **generations** but only those in the first generation are involved in ordinary stable everyday matter. The first generation comprises two quarks, the up quark (symbol *u*) and the down quark (*d*), and two leptons, the electron (*e*) and the electron neutrino ( $\nu_e$ ). Matter comprising particles of the second and third generations is invariably unstable and is normally only formed when particles collide at very high speeds, such as those prevailing at the beginning of the Universe or in experiments with particle accelerators.

Leptons can exist as free isolated particles. Quarks, on the other hand, do not exist in isolation and are only observed grouped together, usually in threes, to form the wide range of different **particles** which form ordinary matter or which are produced in high-speed collisions.

In this section we describe how quarks and leptons, the basic building blocks of matter, combine to form larger building blocks which, in turn, combine to form even larger building blocks etc., as summarised in Table 1.1. Let us consider each stage in more detail, starting with combinations of quarks.

Table 1.1.   Building blocks of matter

Building block	Scale/m
Quarks	$<10^{-20}$
Particles	$\sim 10^{-15}$
Nuclei	$\sim 10^{-14}$
Atoms	$\sim 10^{-10}$
Molecules	$10^{-10}$ to $10^{-8}$
Bulk matter	$> 10^{-9}$

Nuclei

The simplest combinations of first generation quarks which are observed are three-quark combinations called **nucleons**. As illustrated in Figure 1.1 two different types of nucleon are observed, namely the **proton** (*p*), which comprises two *u* quarks and one *d* quark, and the **neutron** (*n*), which comprises one *u* quark and two *d* quarks. The electric charge of the proton is  $+e$  (*e* is called the fundamental electric charge), while that of the neutron is zero. While a proton is stable, a free neutron is not and decays radioactively to form a proton and two leptons. Further three quark combinations, involving quarks from other generations, will be considered when we come to discuss subnuclear particles in Section 22.11.

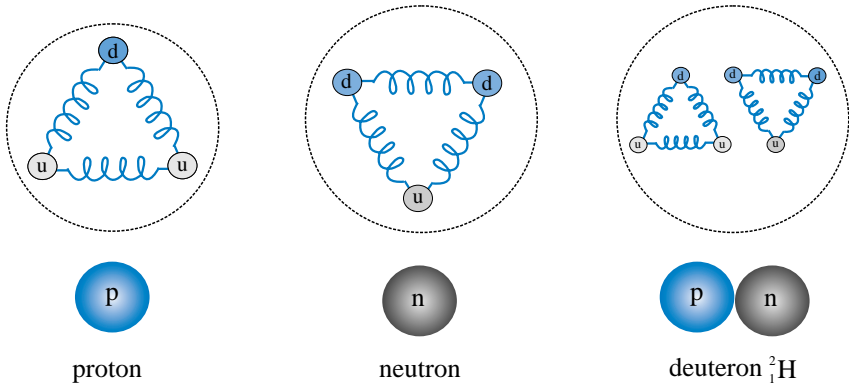


Figure 1.1.   The quark and nucleon compositions of the proton ( ${}^1_1\text{p}$ ), neutron ( ${}^1_0\text{n}$ ) and deuteron ( ${}^2_1\text{H}$ ).

The next simplest combination, also illustrated in Figure 1.1, comprises six quarks (*uuuddd*), equivalent to one *p* and one *n*. This combination occurs in the **nucleus** of the deuterium atom (discussed below) and is called the deuteron. The electric charge of the deuteron,



like that of the proton, is  $+e$ . Two combinations of nine quarks, equivalent to pnn and ppn, are known; the first combination (pnn) is radioactive and the second (ppn) stable. When we consider atoms below we will identify these combinations as nuclei of tritium and helium atoms, respectively. Hundreds of stable particles (nuclei), comprising various combinations of u and d quarks (or, equivalently, protons and neutrons), are the basis of ordinary matter and will be discussed in Chapter 22. A great many other combinations can be created artificially, for example in nuclear reactors, and, while these are unstable, their lifetimes are often sufficiently long for them to be studied in detail and put to practical use (Chapter 22).

### Atoms and molecules

All nuclei have an electric charge of  $+Ze$ , where  $Z$  is an integer;  $Z$  can be thought of as the number of protons in the nucleus. We will discover later (Chapter 15) that positive and negative charges are attracted to one another. Under normal conditions (by which is meant an environment which is not too hot and in which the matter density is not too low) the positively charged nuclei attract electrons to form electrically neutral systems called **atoms**. In atoms the electrons do not coalesce with the nuclei but, instead, behave as though they are moving around them in orbits with radii of the order of  $10^{-10}$  m. This picture of an atom is something like that illustrated in Figure 1.2 – a very small nucleus of charge  $+Ze$  surrounded by  $Z$  orbiting electrons, each of charge  $-e$ . The overall charge on the atom is thus zero – it is electrically neutral. The radius of an atom is 10 000 times greater than the radius of the nucleus (which is about  $10^{-14}$  m). The electron is a very light particle, nearly 2000 times lighter than the proton, so nearly all the matter in an atom is concentrated in the nucleus. The nucleus and electrons are bound together in an atom by electrostatic attraction, a process which we will examine in detail when we study the structure of the atom in Chapter 20.

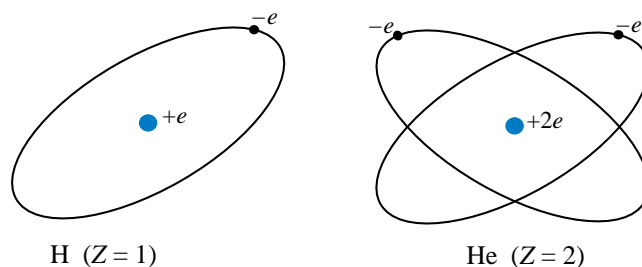


Figure 1.2. The electronic structure of the hydrogen and helium atoms.

As argued above, the electric neutrality of the atom requires that the nuclear charge  $+Ze$  is balanced by the negative charge of  $Z$  electrons;  $Z$  therefore also gives the number of electrons in a neutral atom and is called the **atomic number**. The chemical properties of an atom are determined by the number of electrons it contains. An atom with  $Z = 1$ , that is with a single proton in its nucleus and hence containing a single electron, is known as a hydrogen atom (Figure 1.2). The hydrogen nucleus can also contain one or two neutrons. Such atoms are called deuterium or tritium atoms, respectively, and are known as **isotopes** of hydrogen because they are chemically identical. Helium atoms have  $Z = 2$  (Figure 1.2); two different stable isotopes exist,  ${}^3_2\text{He}$  (two p and one n) and  ${}^4_2\text{He}$  (two p and two n). The chemical **elements**, listed in Appendix D (inside back cover), correspond to different values of  $Z$  ( $Z = 3$  for lithium,  $Z = 4$  for boron and so on). Note that the conventional notation used to specify an atomic nucleus (or **nuclide**) is  ${}_Z^AX$  where  $X$  is the chemical symbol for the particular element,  $Z$  is the atomic number (the number of protons in the nucleus) and  $A$  (the number of nucleons – that is protons plus neutrons – in the nucleus) is called the **mass number**. Isotopes of an element therefore have the same  $Z$  but different values of  $A$ .

If an atom loses or gains an electron it will end up with a net positive or negative electric charge and is called an **ion**. The number of electrons lost or gained is conventionally denoted by a suffix to the notation for the atomic nucleus e.g.  ${}_Z^AX^+$  (one electron lost),  ${}_Z^AX^{2+}$  (two electrons lost) or  ${}_Z^AX^-$  (one electron gained).

When atoms come sufficiently close together that their electron systems begin to overlap, they may form stable groupings of two or more atoms which are called **molecules**. Representations of some common molecules are illustrated in Figure 1.3. Molecular sizes vary from atomic dimensions ( $\sim 10^{-10}$  m) to dimensions which are many hundreds of times larger in the case of biological molecules such as proteins and nucleic acids.

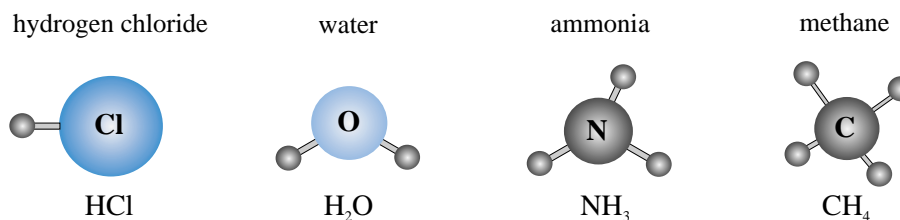
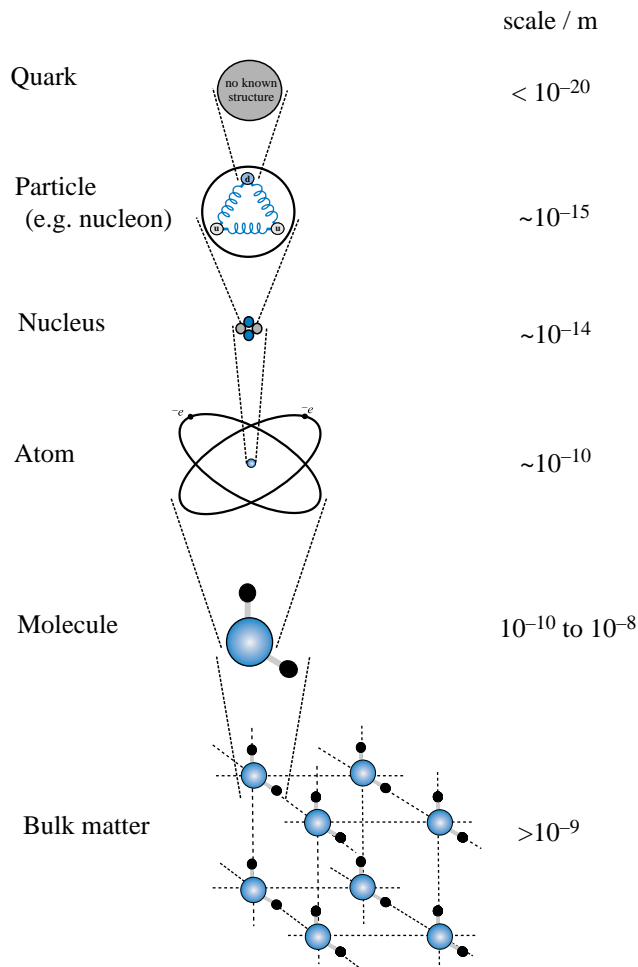


Figure 1.3. The atomic compositions of some common molecules – the smaller gray spheres represent hydrogen atoms.

The conventional notation for a molecule places the number of each type of atom in the molecule at the bottom right of the symbol for that atom. For example, a water molecule (a grouping of two atoms of hydrogen and one atom of oxygen) is denoted by the symbol  $\text{H}_2\text{O}$  (or  ${}^1_1\text{H}_2 {}^{16}_8\text{O}$ , if the isotopic species of each atom is also to be shown). We will consider the various processes by which atoms can bind together to form molecules in Section 21.1.

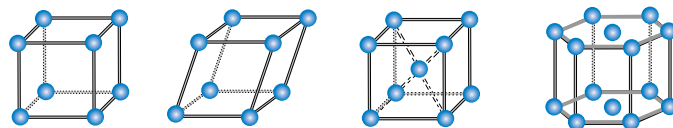
The description of matter which we have outlined in this section is summarised in Figure 1.4.



**Figure 1.4.** Models of the structure of matter – from the quark scale to the bulk matter scale.

### 1.3 Matter in bulk

When large numbers of atoms or molecules are bound closely together the atoms tend to arrange themselves in regular patterns, some examples of which are illustrated in Figure 1.5.



**Figure 1.5.** Some crystal lattice structures.

These patterns can extend over a very large number of atoms to form crystal lattices. Most **solids** are aggregates of crystals formed in this way and, if care is taken in their preparation, a solid may even be grown as one large single crystal.

**Gases**, on the other hand, comprise large numbers of molecules which are spaced so that the average distance between them is much greater than the molecular diameters. Molecules in gases move around rapidly and only interact with one another when they collide; otherwise they move in straight lines between collisions. The molecules in **liquids** are very close together but remain mobile and do not



form crystal lattices. Thus liquids fall somewhere between gases and solids. Many materials, glass for example, do not fall into these simple categories and have properties which are somewhere between those of solids and liquids.

Our everyday experience of solids, liquids and gases does not give any hint of their microscopic nature, that is, of their molecular, atomic or subatomic composition. Indeed, matter in bulk appears continuous – most materials seem to be uniform in their composition and properties at this level. Thus, if we are interested in answering questions such as ‘where is a stone going to land if I throw it from the top of a cliff?’ or ‘how much will the air in a balloon compress if I squeeze it?’, it hardly seems sensible to consider what happens to the atoms in the stone or to the quarks in the air! Questions like this are best addressed by employing **macroscopic models** (large-scale pictures) of the systems being investigated rather than the **microscopic models** which we have outlined in Section 1.2. Clearly a range of different models is available to us and the choice as to which one is best to use depends on the question being asked. The criterion which we must use here is that of *simplicity* – in attempting to explain any phenomenon only those concepts necessary for the explanation should be included in the theory. This principle, which is central to all scientific endeavour, is known as *Occam’s razor* after the medieval philosopher William of Occam (1285–1349), although the formulation in which it is normally stated (*entia non sunt multiplicanda praeter necessitatem* – entities are not to be multiplied unnecessarily) is attributed to John Ponce (1603–1661).

In this book we adhere to this principle as far as possible. We generally begin a discussion of a phenomenon from a macroscopic viewpoint. There will be many cases in which we are also able to discuss a phenomenon starting from a microscopic viewpoint (e.g. kinetic theory in Section 10.11). An important test of the microscopic approach will be whether its predictions agree with those of the macroscopic approach. We will find that when the two approaches agree we can be more confident that the microscopic approach is correct and, perhaps more importantly, we will gain some rewarding insights into the meaning of macroscopic concepts at a more basic level.

## 1.4 The fundamental interactions

We have seen that, despite the extraordinary complexity of the material world, all matter is made up from a relatively small number of basic building blocks. Equally remarkably we find that the way in which these building blocks interact with one another can be reduced to no more than four distinct interactions, namely

1. **The strong interaction:** This is the force between quarks which keeps them bound together within a particle or an atomic nucleus. It is responsible for the force between nucleons in a nucleus, as described in Chapter 22. The range over which the strong interaction operates is very small – it has negligible effect if the distance between particles is much greater than  $10^{-15}$  m.
2. **The electromagnetic interaction:** This is the force which exists between all particles which have an electric charge, such as the force which keeps the electrons bound to the nucleus in an atom. The electromagnetic interaction is long range, extending in principle over infinite distances, but it is over 100 times weaker than the strong interaction within the range over which the strong interaction operates.
3. **The weak interaction:** Leptons are not affected by the strong interaction but interact with one another and with other particles via a much weaker force called the weak interaction, whose strength is only  $10^{-14}$  times that of the strong interaction. While all particles interact weakly, the effect is noticeable only in the absence of the strong and electromagnetic interactions. The weak interaction is very short range ( $\sim 10^{-18}$  m) and only plays a role at the nuclear and subnuclear level.
4. **The gravitational interaction:** By far the weakest of the fundamental interactions is the gravitational interaction, the interaction which, for example, gives a body weight at the surface of the Earth. Its strength is  $10^{-38}$  times that of the strong interaction. All particles interact gravitationally and, like the electromagnetic interaction, the gravitational interaction operates over an infinite range.

There is a long tradition in physics of attempting to unify theories which were originally distinct. For example, for a long time magnetism and electricity were considered to be quite different phenomena but during the nineteenth century the two areas were united in a single theory of electromagnetism (Chapter 16). During the past fifty years the theories covering the fundamental interactions have been undergoing a similar unification process. In the 1960s, due principally to the work of Weinberg, Salam, Ward and Glashow, the electromagnetic and weak interactions came to be seen as different aspects of the same phenomenon (known as the **electroweak interaction**). Since then considerable progress has been made towards the unification of the electroweak interaction with the strong interaction (so-called **Grand Unification**) and this objective is still being pursued. Today, the goal of unifying gravity with the strong-electroweak interaction has become a ‘Holy Grail’ of physics but, to date, even the possibility of such a single theory of all four fundamental interactions, a *Theory of Everything*, remains in the realm of speculation.

## 1.5 Exploring the physical universe: the scientific method

Our aim in physics is to explore the physical universe, to observe, analyse and (hopefully) eventually understand the natural phenomena and processes which underlie the workings of the universe. In the process of achieving an understanding of natural phenomena we will often acquire an ability to predict their future course and hence an ability to apply our knowledge – to use it for practical purposes.

How then can we investigate natural phenomena? We outline below an approach known as the **scientific method**. It is a method which has proved its value over many centuries but it is important to note that there is nothing particularly remarkable about it – it has not been handed to us on ‘tablets of stone’. As we shall see, it is merely a series of practical steps that anyone who wishes to study a natural phenomenon methodically might well devise on his or her own initiative. We outline the steps below.

### Observation

The first step is simply to observe the phenomenon – to watch it unfold. Careful systematic observation leads us inevitably to take notes on what we see – to **record** our observations. With records we can later remind ourselves, or others, of what we have observed. The process of recording what we see in a thorough and rigorous manner leads us quickly to make measurements. For example, if we are observing the motion of a moving object we could describe its motion in words by stating that ‘the object is first a long way from us, then not so far, then nearer and finally very near’. It is clear however that words alone soon become inadequate; they are not sufficiently precise and can be ambiguous. One person’s idea of ‘very near’ may not be the same as that of the next person. Measurement is therefore the next step in the scientific method.

### Measurement

In making measurements we must decide which (physical) quantities associated with the phenomenon that we are observing can be measured most conveniently and accurately. Note that the process is already becoming a little arbitrary. One person’s idea of what can be measured conveniently may not be the same as that of the next person. As experience is built up, a consensus usually emerges on the best way to make a certain measurement. Sometimes, as we will see, technical developments can force a change in the consensus and hence even in the way in which physics is formulated. The development of physics has always been rooted strongly in empirical observation and hence in the process of measurement.

In making a measurement we inevitably have to choose a **unit** in which to make the measurement. In the case of the moving object we would naturally tend to measure its distance from us in metres because a unit of distance, the metre, has already been defined for us. Had it not been defined we would have had to invent some such unit. In choosing units for measurement it is also sensible to coordinate our choice with that of others, i.e. to choose agreed **measurement standards** and **systems of units**. This enables us to communicate our observations to colleagues on the other side of the world in such a way that they will know precisely what we mean.

### Analysis and hypothesis

Having observed a phenomenon and having collected a set of measurements – our **experimental data** – the next step in the scientific method, in our attempt to understand the phenomenon, is to look for relationships between the quantities we have measured. For example in the case of a moving object we may have a set of measurements which gives the object’s position at certain times. In comparing the measurements of position with those of time can we see any pattern? Can we put forward any **hypothesis** (inspired guess) which describes and accounts for the relationship between the quantities? Can we go further and put forward a **model** of the situation, an idealised picture of what is happening, usually based on situations we already understand – i.e. on our experience?

At this stage the scientific method becomes arbitrary and personal. Different people from different backgrounds and with different experiences may see different patterns and may put forward different models. There is not necessarily any one correct interpretation. In time it may turn out that one approach is simpler and easier to follow than the others but it does not follow that this is the only correct approach. It is always wise to keep an open mind in studying natural phenomena – we are less likely to spot new patterns if we have already decided what we expect to see. We must always be on our guard against introducing prejudices when drawing on our experience.

A number of procedures may help us to identify patterns in our observations. As will be illustrated in Section 2.3 for the case of a moving object, we can assemble tables of data and can draw graphs of one measured quantity against another. We will see in Section 2.3 how analyses of tables and graphs often enable us to deduce relationships between observed quantities. Very general relationships are described as **laws** of physics. One of the things which makes physics such a rewarding subject to study is that not only are the fundamental laws few in number but they are also usually of relatively simple form. Because of the essential simplicity of the laws, the simplest and most natural way to express them is through the language of mathematics.

When we are successful in identifying relationships between observed quantities we are usually able to express them as mathematical equations, which, as we will see in Section 2.3, are usually the most concise and unambiguous way of expressing relationships.

The description of relationships between quantities as ‘laws’ of physics is perhaps unfortunate because these laws should not be regarded as incontrovertible edicts. They are merely well-established principles. Sometimes laws are found not to be as well established as was first believed. It is important therefore to **test** hypotheses and models regularly. This brings us to the final step in the scientific method.

### Testing and prediction

It is now necessary to establish the range of applicability of any hypotheses and models which may have been proposed. We use these hypotheses and models, therefore, to *predict* results in situations in which measurements have not yet been made. We then make measurements in the new situations and see how well these measurements match predictions. Sometimes they do not match, although this

does not necessarily mean that our prior hypotheses and models were wrong. It means that they are limited in their applicability and that we have to extend the hypotheses and models to cover the new situations.

As we shall see, developments in physics in the twentieth century have shown that many apparently universal laws of classical physics do not apply at velocities which approach the speed of light or to particles on the microscopic (atomic and nuclear) scale. It has been necessary to develop new more comprehensive theories, namely the special theory of relativity (Chapter 9) and quantum mechanics (Chapter 13), to interpret and understand these situations.

As is apparent from the account of the scientific method given above, there is nothing particularly remarkable about the method. It has been described quite simply as ‘organised common sense’, a method which a person without a scientific background might well adopt when faced with the task of trying to understand a physical process. In physics we have the advantage of a wealth of techniques for observation and analysis that have been developed by the scientific community over a long period of time. This gives us a head start in seeking to understand new phenomena although we should always be aware of the possible limitations of established thinking.

In this book, therefore, we will not only describe the discoveries and the models which have been put forward by physicists, we will also, in the process, learn the skills and techniques which have been developed to analyse natural phenomena. We will then be able to apply these skills and techniques ourselves as we study the physical universe. The end product will be the ability to describe a whole range of apparently disconnected and complex phenomena in terms of an underlying simplicity of mathematically expressed structures. On many occasions we will see how advances in knowledge have led to new theories or models which replace a whole range of different models which were needed previously. This unifying process is one of the most satisfying aspects of physics. New understanding can actually simplify a situation, or a number of situations; we then feel instinctively that we are closer to the truth. The methods which we will uncover are powerful, intellectually satisfying and useful. We will not be able to reveal all the mysteries of the physical universe in this book but we will take some steps along the way and, perhaps more importantly, we will emerge equipped to explore further ourselves.

## 1.6 The role of physics: its scope and applications

In Sections 1.2 to 1.4 we saw how physics describes the basic components of matter and their mutual interactions. We also saw how physics endeavours to describe the physical world on all its scales – from that of the quark to that of the universe. In this sense, physics provides the basic conceptual and theoretical framework on which other natural sciences are founded and may therefore be regarded as the most fundamental and comprehensive of the natural sciences.

The techniques which have been developed to analyse the physical world can be used in almost any area of pure and applied research. Physics provides an excellent testing ground for the scientific method. Moreover, in seeking to unify understanding of the natural world, physics can play an important simplifying role in science, reducing complex situations to more understandable forms. In doing so, physics can also counteract the fragmentation into separate disciplines which tends to accompany the ever-expanding growth in scientific and technical knowledge.

Physics is at the basis of most present technology and is sure to be at the basis of much future technology, tackling problems as pressing and diverse as the development of new energy sources, of more powerful and less intrusive medical diagnostics and treatments and of more effective electronic devices. The growth of physics has spawned a multitude of technological advances which impact on almost all areas of science. Engineering practice must be revised regularly to take advantage of opportunities presented by the advance of physics.

In the previous section we noted that new, and more comprehensive, theories, namely the special theory of relativity and quantum mechanics, were developed in the last century to account for situations in which the laws of classical physics do not apply. The new theories have stimulated important new technologies, such as quantum engineering (the development of new microelectronic devices), laser technology and nuclear technology, technologies which could hardly have been dreamt of at the beginning of the twentieth century.

A sound knowledge of physics is needed by scientists and technologists if they are to be able to understand and adjust to the rapidly changing world in which they find themselves. Moreover this understanding should stimulate them to devise and initiate further changes themselves.



# 2

## Using mathematical tools in physics

### AIMS

- to demonstrate the scientific method by applying it to the analysis of motion in a straight line
- to introduce the basic calculus methods used in this book and to demonstrate how they may be used in the analysis of physical phenomena
- to derive equations which describe some special cases of one-dimensional motion quantitatively and which can be used to predict their future courses

### 2.1 Applying the scientific method

In this chapter we illustrate the scientific method by using it to study certain types of motion. In doing so we introduce some important mathematical techniques which will enable us to analyse and represent physical processes in a concise and rigorous manner. At the same time we introduce the physical quantities which are used to describe motion in a straight line and angular motion about a fixed axis.

While readers, who are familiar with the analysis of linear and of angular motion and who are also familiar with the use of elementary calculus in physics, may choose proceed to Chapter 3, we recommend that they take the opportunity to refresh their understanding of these topics.

### 2.2 The use of variables to represent displacement and time

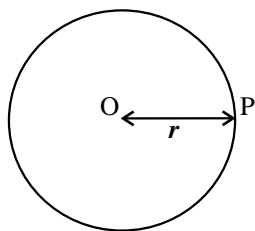
We begin our investigation of motion by studying and characterising different types of motion. At this stage we are not concerned with the cause of motion, although the cause of motion is a topic which is of central interest in physics and will be investigated in detail in the next chapter. First we simply consider the behaviour of a moving object and decide which quantities associated with the motion we can measure. We will then see if there is any discernible pattern in a particular motion — whether we can establish any relationships between the measured quantities and whether we can establish any *model* for the motion.

A moving object is an object whose position changes with time. The obvious physical quantities to measure in recording the behaviour of a moving object are therefore its **position** and the **time** at which it is at that position. Let us first consider measurement of position.

We can specify the position of a point P by measuring its **displacement** with respect to some reference point O which we call the **origin**. We use the symbol  $r$  to represent the value of displacement, a variable quantity. Note, however, that in specifying the

position of P relative to O it is not sufficient simply to state the distance from O to P. If, for example, we say that a point P is in the plane of this page and is at a distance  $r$  from O, P could be anywhere on a circle of radius  $r$  drawn around O (as illustrated in Figure 2.1). To avoid ambiguity in specifying the position of P we must also specify the direction of P relative to O. In this case this could be achieved by stating that P is directly to the right of O.

To specify a displacement  $r$  unambiguously, therefore, we must specify both its magnitude (the distance from O to P) and its *direction* (the direction of the line OP). Later (Section 4.1) we will use the term *vector* to describe a quantity which has both magnitude and direction; we will also show that vectors must be handled using well defined methods. For our present purposes however, we can simplify the treatment of displacement by considering the special case of *linear (or one-dimensional) motion*, that is,



**Figure 2.1.** The displacement  $r$  of the point P from the origin.

motion which is confined to a straight line. As illustrated in Figure 2.2, a linear displacement from the origin  $O$  along a straight line can be in one of only two directions so that a point which is a distance 2 cm from  $O$  can be at either of the two positions  $P$  or  $P'$ .

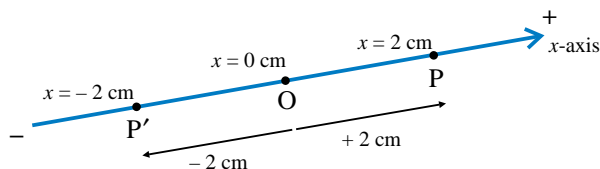


Figure 2.2. The  $x$ -coordinate axis, showing the displacements of  $P$  and  $P'$  relative to  $O$ .

We distinguish between the two possible directions in linear motion by using a sign convention to specify the direction of the displacement. Displacement, therefore, can be represented by an **algebraic quantity**, namely a quantity which can be expressed in terms of its magnitude preceded by a plus or minus sign; thus the displacements of the points  $P$  and  $P'$  with respect to  $O$  are  $+2$  cm and  $-2$  cm, respectively.

The choice between the  $+$  and  $-$  labels for the two directions in Figure 2.2 is of course arbitrary. We could equally well have chosen the opposite sign labels. The important point is that, having adopted a **convention for signs**, we follow this convention consistently throughout our analysis.

In linear motion, displacements from the origin are usually represented by the variable quantity  $x$ . The straight line along which the motion occurs is then described as the  **$x$ -axis** and the algebraic value of the displacement,  $x$ , of a certain position from the origin  $O$  is the **coordinate** of this position. The position of a point on the straight line is specified unambiguously by stating the algebraic value of  $x$ , as indicated in Figure 2.2, provided a convention for positive  $x$  has been adopted.

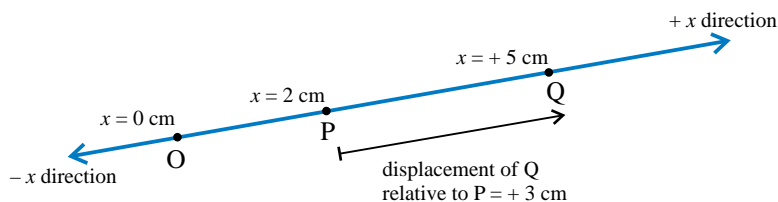


Figure 2.3. The displacements of  $P$  and  $Q$  relative to  $O$ , and of  $Q$  relative to  $P$ .

We can also define the displacement of a second point on the straight line, such as  $Q$  in Figure 2.3, *relative to*  $P$ .

If the displacement of  $P$  relative to  $O$  is  $+2$  cm (i.e. the  $x$ -coordinate of  $P$  is  $+2$  cm) and the displacement of  $Q$  relative to  $O$  is  $+5$  cm, we can easily deduce from an inspection of Figure 2.3 that the displacement of  $Q$  relative to  $P$  is  $5 - 2 = +3$  cm, a positive displacement. Similarly, the displacement of  $P$  relative to  $Q$ , is  $2 - 5 = -3$  cm, a negative displacement. Note how the signs of the algebraic quantities which represent relative displacements give the directions of the displacements.

The second quantity which we have decided to measure in our study of motion is **time**, denoted by the symbol  $t$ , which can also be represented by an algebraic quantity. Unlike displacement,  $t$  can only increase while we are making our observations – it can change in only one direction, which we define to be the positive direction. Like displacement, time is measured with reference to an origin, in this case the starting instant. Note that, although time can change only in the positive direction, it is possible for  $t$  to be negative. For example if we choose 10.00 a.m. as our starting instant the time 9.55 a.m. becomes  $-5$  minutes.

## 2.3 Representation of data

Let us consider the case of an object which is confined to move along a straight line, the  $x$ -axis, as illustrated in Figure 2.4. As an example we consider the motion of a train along a straight section of track. Suppose that we make a series of measurements of the train's position together with the corresponding times. We can display these measurements (our *data*) in a number of ways, the most obvious of which is the **tabular representation**, illustrated in Table 2.1 for a particular motion of the train which we call motion M.

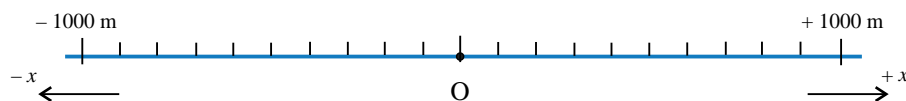


Figure 2.4. The  $x$ -axis for a moving train.