

'I admire this highly personal and unusual book. Too much of undergraduate education consists of polished gems that might have fallen from the sky, rather than being the work of people, but Longair restores the human dimension. His presentation has a nice balance between pedagogy and history, so that students can learn new elements of physics while also appreciating the real-world fog of confusion and the false turnings from which our present understanding emerged.'

John Peacock, University of Edinburgh

'Malcolm Longair's reworked and updated exploration of the unifying concepts of physics complements traditional, technique-heavy lectures and is better than ever. The writing is so lucid that the reader barely notices the broad scholarship and wise pedagogy that underlie it. *Theoretical Concepts in Physics* should be read not only by the undergraduates for whom it was first conceived, and research physicists seeking an elixir that will lead them to fame and fortune, but – especially – by all who love big ideas and the very human stories that led to their formulation, development and ultimate acceptance.'

Roger Blandford, KIPAC, Stanford University

In this original and integrated approach to theoretical reasoning in physics, Malcolm Longair illuminates the subject from the perspective of real physics as practised by research scientists. Concentrating on the basic insights, attitudes and techniques that are the tools of the modern physicist, this approach conveys the intellectual excitement and beauty of the subject.

Through a series of seven case studies, the contents of an undergraduate course in classical physics and the discovery of quanta are reviewed from the point of view of how the great discoveries and changes of perspective came about. This approach illuminates the intellectual struggles needed to attain understanding of some of the most difficult concepts in physics.

Longair's highly acclaimed text has been fully revised and includes new studies on the physics of fluids, Maxwell's great paper on equations for the electromagnetic field, and problems of contemporary cosmology and the very early Universe.

Cover illustration: Baac3nes/ Moment/ Getty Images

CAMBRIDGE
UNIVERSITY PRESS
www.cambridge.org

ISBN 978-1-108-48453-4



9 781108 484534 >

<i>Preface and Acknowledgements</i>	page	xiii
<i>Origins</i>		xiii
<i>Acknowledgements</i>		xiv
<i>Figure Credits</i>		xv
1 Introduction		1
1.1 Pedagogical and Real Physics		1
1.2 Reflections on What Every Student Should Know		2
1.3 The Nature of Physics and Theoretical Physics		4
1.4 Environmental Influences		6
1.5 Final Disclaimer		7
Notes		8
Case Study I The Origins of Newton's Laws of Motion and of Gravity		9
2 From Ptolemy to Kepler: The Copernican Revolution		11
2.1 Ancient History		11
2.2 The Copernican Revolution		15
2.3 Tycho Brahe: The Lord of Uraniborg		17
2.4 Johannes Kepler and Heavenly Harmonies		21
Notes		28
3 Galileo and the Nature of the Physical Sciences		29
3.1 Introduction		29
3.2 Galileo as an Experimental Physicist		29
3.3 Galileo's Telescopic Discoveries		35
3.4 Aristotelian versus Galilean Physics: The Heart of the Matter		37
3.5 The Trial of Galileo		42
3.6 Galilean Relativity		43
3.7 Reflections		45
Notes		47
4 Newton and the Law of Gravity		48
4.1 Introduction		48
4.2 Lincolnshire 1642–61		48

4.3	Cambridge 1661–65	49
4.4	Lincolnshire 1665–67	49
4.5	Cambridge 1667–96	55
4.6	Newton the Alchemist	57
4.7	The Interpretation of Ancient Texts and the Scriptures	60
4.8	London 1696–1727	61
	Appendix to Chapter 4: Notes on Conic Sections and Central Orbits	62
	Notes	70
	Case Study II Maxwell's Equations	73
5	The Origin of Maxwell's Equations	75
5.1	How It All Began	75
5.2	Michael Faraday: Mathematics without Mathematics	78
5.3	Maxwell's Route to the Equations for the Electromagnetic Field	84
	Appendix to Chapter 5: Notes on Vector Fields	93
	Notes	105
6	Maxwell (1865): <i>A Dynamical Theory of the Electromagnetic Field</i>	107
6.1	PART I – Introductory	108
6.2	PART II – On Electromagnetic Induction	108
6.3	PART III – General Equations of the Electromagnetic Field	112
6.4	PART IV – Mechanical Actions in the Field	115
6.5	PART V – Theory of Condensers	115
6.6	PART VI – Electromagnetic Theory of Light	116
6.7	PART VII – Calculation of the Coefficients of Electromagnetic Induction	117
6.8	The Aftermath	118
	Notes	121
7	How to Rewrite the History of Electromagnetism	123
7.1	Introduction	123
7.2	Maxwell's Equations as a Set of Vector Equations	123
7.3	Gauss's Theorem in Electromagnetism	124
7.4	Time-Independent Fields as Conservative Fields of Force	125
7.5	Boundary Conditions in Electromagnetism	126
7.6	Ampère's Law	129
7.7	Faraday's Law	130
7.8	Coulomb's Law	130
7.9	The Biot–Savart Law	133
7.10	The Interpretation of Maxwell's Equations in Material Media	133
7.11	The Energy Densities of Electromagnetic Fields	137
7.12	Concluding Remarks	141
	Notes	142

8 Approaches to Mechanics and Dynamics	146
8.1 Newton's Laws of Motion	146
8.2 Principles of 'Least Action'	148
8.3 The Euler–Lagrange Equations	150
8.4 Lagrangians, Conservation Laws and Symmetry	154
8.5 Lagrangians, Small Oscillations and Normal Modes	157
8.6 Hamilton's Equations	162
8.7 Hamilton's Equations and Poisson Brackets	164
8.8 The Hamilton–Jacobi Equations and Action–Angle Variables	165
8.9 A Warning	170
Notes	170

9 The Motion of Fluids	172
9.1 The Equation of Continuity	172
9.2 The Equations of Motion for an Incompressible Fluid in the Absence of Viscosity	175
9.3 Some Applications of Bernoulli's Theorem	177
9.4 Gravity Waves in Shallow and Deep Water	184
9.5 The Equation of Motion of an Incompressible Fluid Including Viscous Forces	187
9.6 Stokes' Formula for Highly Viscous Flow	193
9.7 Vorticity, Circulation and Kelvin's Circulation Theorem	196
9.8 Concluding Remarks	202
Notes	202

10 Dimensional Analysis, Chaos and Self-Organised Criticality	204
10.1 Introduction	204
10.2 Dimensional Analysis	205
10.3 Introduction to Chaos	220
10.4 Scaling Laws and Self-Organised Criticality	230
10.5 Beyond Computation	237
Notes	238

Case Study IV Thermodynamics and Statistical Physics 241

11 Basic Thermodynamics	244
11.1 Heat and Temperature	244
11.2 Heat as Motion <i>versus</i> the Caloric Theory of Heat	245
11.3 The First Law of Thermodynamics	250
11.4 The Origin of the Second Law of Thermodynamics	260
11.5 The Second Law of Thermodynamics	266

11.6	Entropy	276
11.7	The Law of Increase of Entropy	278
11.8	The Differential Form of the Combined First and Second Laws of Thermodynamics	282
	Appendix to Chapter 11: Maxwell's Relations and Jacobians	282
	Notes	287
12	Kinetic Theory and the Origin of Statistical Mechanics	288
12.1	The Kinetic Theory of Gases	288
12.2	Kinetic Theory of Gases: First Version	289
12.3	Kinetic Theory of Gases: Second Version	290
12.4	Maxwell's Velocity Distribution	295
12.5	The Viscosity of Gases	301
12.6	Pedagogical Digression (1): A Numerical Approach to the Boltzmann and Maxwell Distributions	304
12.7	The Statistical Nature of the Second Law of Thermodynamics	309
12.8	Entropy and Probability	310
12.9	Entropy and the Density of States	314
12.10	Pedagogical Digression (2): A Numerical Approach to the Law of Increase of Entropy	318
12.11	Gibbs Entropy and Information	320
12.12	Concluding Remarks	323
	Notes	323
	Case Study V The Origins of the Concepts of Quantisation and Quanta	325
13	Black-Body Radiation up to 1895	328
13.1	Physics and Theoretical Physics in 1890	328
13.2	Kirchhoff's Law of Emission and Absorption of Radiation	329
13.3	The Stefan–Boltzmann Law	334
13.4	Wien's Displacement Law and the Spectrum of Black-Body Radiation	342
	Notes	346
14	1895–1900: Planck and the Spectrum of Black-Body Radiation	348
14.1	Planck's Early Career	348
14.2	Oscillators and Their Radiation in Thermal Equilibrium	350
14.3	The Equilibrium Radiation Spectrum of a Harmonic Oscillator	355
14.4	Towards the Spectrum of Black-Body Radiation	359
14.5	The Primitive Form of Planck's Radiation Law	363
14.6	Rayleigh and the Spectrum of Black-Body Radiation	365
14.7	Comparison of the Laws for Black-Body Radiation with Experiment	368
	Appendix to Chapter 14: Rayleigh's Paper of 1900	369
	Notes	371

15 Planck's Theory of Black-Body Radiation	373
15.1 Introduction	373
15.2 Boltzmann's Procedure in Statistical Mechanics	373
15.3 Planck's Analysis	376
15.4 Planck and 'Natural Units'	380
15.5 Planck and the Physical Significance of h	381
15.6 Why Planck Found the Right Answer	384
Notes	387
16 Einstein and the Quantisation of Light	389
16.1 1905: Einstein's <i>Annus Mirabilis</i>	389
16.2 Einstein (1905) <i>On a Heuristic Viewpoint Concerning the Production and Transformation of Light</i>	392
16.3 The Quantum Theory of Solids	398
16.4 Debye's Theory of Specific Heat Capacities	401
16.5 The Specific Heat Capacities of Gases Revisited	404
16.6 Conclusion	407
Notes	408
17 The Triumph of the Light Quantum Hypothesis	409
17.1 The Situation in 1909	409
17.2 Fluctuations of Particles and Waves	409
17.3 Fluctuations of Randomly Superposed Waves	412
17.4 Fluctuations in Black-Body Radiation	414
17.5 The First Solvay Conference	419
17.6 Experimental and Theoretical Advances 1911 to 1925	421
17.7 Einstein (1916) 'On the Quantum Theory of Radiation'	428
17.8 Compton Scattering	433
17.9 The Threshold of Quantum Mechanics	434
17.10 The Story Concluded	436
Notes	437
Case Study VI Special and General Relativity	439
18 Special Relativity: A Study in Invariance	442
18.1 Introduction	442
18.2 Geometry and the Lorentz Transformation	451
18.3 Three-Vectors and Four-Vectors	454
18.4 Relativistic Dynamics: The Momentum and Force Four-Vectors	460
18.5 The Relativistic Equations of Motion	464
18.6 The Frequency Four-Vector	466
18.7 Lorentz Contraction and the Origin of Magnetic Fields	467
18.8 Reflections	470
Notes	470

19 An Introduction to General Relativity	472
19.1 Introduction	472
19.2 Essential Features of the Relativistic Theory of Gravity	475
19.3 Isotropic Curved Spaces	485
19.4 The Route to General Relativity	493
19.5 The Schwarzschild Metric	497
19.6 Particle Orbits about a Point Mass	499
19.7 Advance of the Perihelia of Planetary Orbits	506
19.8 Light Rays in Schwarzschild Space-Time	509
19.9 Particles and Light Rays near Black Holes	511
19.10 Circular Orbits about Schwarzschild Black Holes	513
19.11 Gravitational Waves	516
Notes	522

Case Study VII Cosmology and Physics 525

20 Cosmology	527
20.1 Cosmology and Physics	527
20.2 Basic Cosmological Data	528
20.3 The Robertson–Walker Metric	533
20.4 Observations in Cosmology	537
20.5 The Standard World Models	542
20.6 Historical Interlude: Steady State Theory	555
20.7 The Thermal History of the Universe	557
20.8 Nucleosynthesis in the Early Universe	563
20.9 The Values of the Cosmological Parameters	566
Notes	572

21 Dark Matter, Dark Energy and the Inflationary Paradigm	574
21.1 Introduction	574
21.2 Dark Matter and Dark Energy	574
21.3 The Big Problems	581
21.4 A Pedagogical Interlude: Distances and Times in Cosmology	586
21.5 The Inflationary Universe: Historical Background	591
21.6 The Origin of the Spectrum of Primordial Perturbations	594
21.7 Baryogenesis	602
21.8 The Planck Era	603
Notes	605

<i>Author Index</i>	609
---------------------	-----

<i>Subject Index</i>	613
----------------------	-----