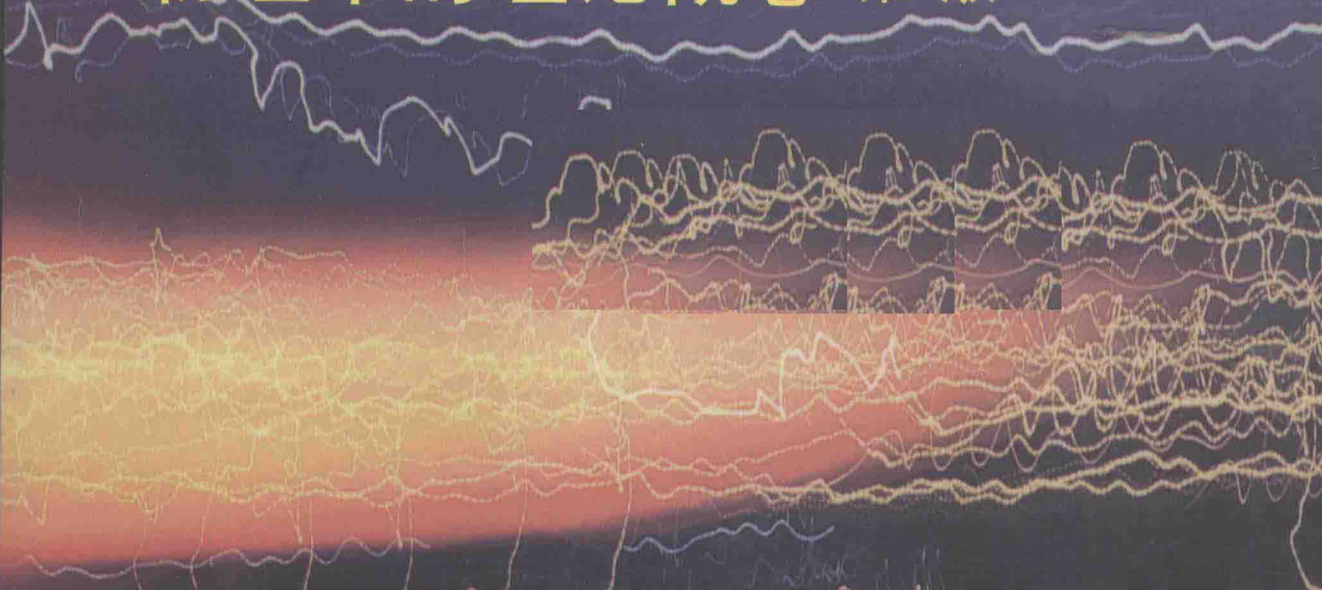
Malcolm Longair

Theoretical Concepts in Physics

An Alternative View of Theoretical Reasoning in Physics

Second Edition

物理中的理论概念 第2版



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Theoretical Concepts in Physics

An Alternative View of Theoretical Reasoning in Physics

A highly original, novel and integrated approach to theoretical reasoning in physics. This book illuminates the subject from the perspective of real physics as practised by research scientists. It is intended to be a supplement to the final years of an undergraduate course in physics and assumes that the reader has some grasp of university physics. By means of a series of seven case studies, the author conveys the excitement of research and discovery, highlighting the intellectual struggles to attain understanding of some of the most difficult concepts in physics. The case studies comprise the origins of Newton's law of gravitation, Maxwell's equations, linear and non-linear mechanics and dynamics, thermodynamics and statistical physics, the origins of the concept of quanta, special relativity, and general relativity and cosmology. The approach is the same as that in the highly acclaimed first edition, but the text has been completely revised and many new topics introduced.

MALCOLM LONGAIR graduated in electronic physics from the University of St Andrews in 1963. He completed his Ph.D. in the Radio Astronomy Group of the Cavendish Laboratory, University of Cambridge, in 1967. From 1968 to 1969 he was a Royal Society Exchange Visitor to the Lebedev Institute, Moscow. He has been an exchange visitor to the USSR Space Research Institute on six subsequent occasions and has held visiting professorships at institutes and observatories throughout the USA. From 1980 to 1990, he held the joint posts of Astronomer Royal for Scotland, Regius Professor of Astronomy of the University of Edinburgh and Director of the Royal Observatory, Edinburgh. He was Deputy Head of the Cavendish Laboratory with special responsibility for the teaching of physics from 1991 to 1997 and has been Head of the Cavendish Laboratory since 1997. He is also a Professorial Fellow of Clare Hall, Cambridge. Professor Longair has received many awards, including the first Britannica Award for the Dissemination of Learning and the Enrichment of Life in February 1986. In December 1990, he delivered the series of Royal Institution Christmas Lectures for Young People on television on the topic 'The origins of our universe'. He was made a CBE in the 2000 Millennium honours list. Professor Longair's primary research interests are in the fields of high energy astrophysics and astrophysical cosmology. He has written numerous books and over 250 journal articles on his research work.

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For
Deborah

Preface and acknowledgements

The inspiration for this book was a course of lectures which I delivered between 1977 and 1980 to undergraduates about to enter their final year in Physics and Theoretical Physics at Cambridge. The aim of the course was to provide a survey of the nature of theoretical reasoning in physics, which would put them in a receptive frame of mind for the very intensive courses of lectures on all aspects of physics in the final year. The objectives of the course are described in the first chapter and concern issues about which I feel very strongly: students can go through an undergraduate course in physics without gaining an understanding of the insights, approaches and techniques which are the tools of the professional physicist, let alone an impression of the intellectual excitement and beauty of the subject. The course was intended as an alternative to the normal mode of presentation and was entitled *Theoretical Concepts in Physics*.

An important feature of the course was that it was entirely optional and strictly non-examinable. The lectures were delivered at 9 am every Monday, Wednesday and Friday during a four-week period in July and August, the old Cambridge Summer Term, prior to the final year of the physics course. Despite the timing of the lectures, the fact that the course was not examinable, and the alternative attractions of Cambridge during the summer months, the course was very well attended. I was very gratified by the positive response of the students and this encouraged me to produce a published version of the course with the same title, but with a health warning in the subtitle, *An alternative view of theoretical reasoning in physics for final-year undergraduates*. I was not aware of any other book which covered the material in quite the same way.

The first edition of the book was published in 1984, and by then it had expanded to include other aspects of my experience of teaching physics and theoretical physics. By that time, I was in Edinburgh and responsible for running the Royal Observatory, Edinburgh and the Department of Astronomy. I returned to Cambridge in 1991 and became deeply involved in the revision of the physics syllabus, which led to the present three- or four-year course structure. For the last four years, I have delivered an updated version of the old course, now renamed *Concepts in Physics*. I have continued to expand the range of the material discussed – many of these recent additions are included in this new edition.

Many of the warnings which I issued in the first edition are still relevant. This book is a highly individual approach to physics and theoretical physics. In no way is it a substitute for the systematic exposition of physics and theoretical physics as taught in the standard undergraduate physics course. The contents of this book should be regarded as a complementary approach, which illuminates and reinforces the material from the viewpoint of how the physics actually came about, and how real physicists and theoretical physicists operate. If I succeed in even marginally improving students' appreciation of physics as professional physicists know and love it, the book will have achieved its aims.

In the first edition, I purposely maintained the first person singular to a much greater extent than would be appropriate in a conventional textbook. My intention was to emphasise the individuality of every physicist's approach to the subject and to feel free to express my own opinions and experiences of how physics is actually carried out. Twenty years later, I find that my style of writing has changed. My earlier writings now seem much 'bouncier' and 'uninhibited' than my present style of writing. Undoubtedly, part of this more cautious approach is the result of the experience of sometimes not having got the arguments quite right and needing to change the emphasis as a result of deeper understanding. Have no fear, however – there is just as much passion in the writing as there was in the first edition, but it is written necessarily from a more experienced perspective. As a result, I have rewritten the whole book from scratch, attempting to make the use of language as precise as possible, whilst maintaining the vitality of the earlier writing.

The views expressed in the text are obviously all my own, but many of my Cambridge and Edinburgh colleagues have played a major role in formulating and clarifying my ideas. The idea of the original course came from discussions with Alan Cook, Volker Heine and John Waldram. I inherited the Examples Class in Mathematical Physics from Volker Heine and the late J.M.C. Scott. Developing that class helped enormously in clarifying many of my own ideas. In later years, Brian Josephson helped with the course and provided many startling insights. The course in thermodynamics was given in parallel with one by Archie Howie and I learned a great deal from discussions with him. As part of the reforms which were introduced in the 1990s, Archie delivered the course *Concepts in Physics* and I have enjoyed exploring and extending many of his innovations.

In Edinburgh, Peter Brand, John Peacock and Alan Heavens contributed in important ways to my understanding. In Cambridge, many members of the Department have been very supportive of my endeavours to bring physics alive for undergraduates. I am particularly grateful to John Waldram and David Green for innumerable discussions concerning the courses we have shared. I also acknowledge invaluable discussions with Steve Gull and Anthony Lasenby. Sanjoy Mahajan kindly took a special interest in the section on dimensional methods and critically reviewed what I have written – I am most grateful for his help and insights. A special debt of gratitude is due to Peter Harman, who kindly read some of my writings on Maxwell and made helpful suggestions.

Two committees have continued to provide valuable insight into physics. First, there is the Department of Physics Teaching Committee. I have often thought that a video recording of some of the heated discussions about how to teach physics and theoretical physics would have taught students more about physics than a whole course of lectures. Second, the Staff–Student Consultative Committee for Physics is the forum where the organisers of the physics courses face a highly intelligent and articulate set of consumers at all stages in their physics education. The participation of the students in these discussions has greatly helped the exposition of much of this material.

I must also acknowledge the stimulation provided over the years by the many generations of undergraduates who attended this and the other courses I have given. Their comments and

enthusiasm were largely responsible for the fact that the first edition of the book appeared at all. The same remark applies to this new edition – Cambridge students are a phenomenal resource, which makes lecturing and teaching an enormous privilege and real pleasure.

Perhaps the biggest debts I owe in my education as a physicist are to the late Martin Ryle and the late Peter Scheuer, who supervised my research work in the Radio Astronomy Group during the 1960s. I learned more from them about real physics than from anyone else. Almost as great has been the influence of the late Yakov Borisevich Zeldovich and my colleague Rashid Sunyaev. The year I spent in Moscow in 1968–9 was a revelation in opening up new ways of thinking about physics and astrophysics. Another powerful influence was Brian Pippard, whose penetrating understanding of physics was a profound inspiration. Although he and I have very different views of physics, there is virtually no aspect of physics which we have discussed in which his insight has not added immensely to my understanding.

Grateful thanks are due to innumerable people who have helped in the preparation of this book. In preparing the first edition in Edinburgh, the bulk of the text was expertly typed by Janice Murray and Susan Hooper. The line drawings were drawn by Marjorie Fretwell and many of these have been redrawn for the second edition. The reduction of the diagrams to a size suitable for publication and the production of all the photographs in the first edition was the work of Brian Hadley and his colleagues in the Photolabs at the Royal Observatory, Edinburgh. The staff of the Royal Observatory Library were very helpful in locating references and also in releasing for photographing the many treasures in the Crawford Collection of old scientific books.

In preparing the new edition, Judith Andrews performed wonders in converting much of the text of the first edition into LaTeX. Equally important, in acting as my secretary and personal assistant she ensured that, despite the task of running the Laboratory, time was made available to enable the book to be rewritten.

As in all my endeavours, the debts I owe to my wife, Deborah, and our children, Mark and Sarah, cannot be adequately expressed in words.

Contents

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1 Introduction

1.1 An explanation for the reader

This book is for students who love physics and theoretical physics. It arises from the dichotomy which, in my view, pervades most attempts to teach the ideal course in physics. On the one hand, there is the way in which university teachers present the subject in lecture courses and examples classes. On the other hand, there is the way in which we actually practise the discipline as professional physicists. In my experience, there is often little relation between these activities. This is a great misfortune because students are then rarely exposed to their lecturers when they are practising their profession as physicists.

There are good reasons, of course, why the standard lecture course has evolved into its present form. First of all, physics and theoretical physics are not particularly easy subjects and it is important to set out the fundamentals in as clear and systematic a manner as possible. It is absolutely essential that students acquire a firm grounding in the basic techniques and concepts of physics. But we should not confuse this process with that of doing real physics. Standard lecture courses in physics and its associated mathematics are basically 'five-finger' exercises, designed to develop technique and understanding. But such exercises are very different from a performance of the *Hammerklavier* sonata at the Royal Festival Hall. You are only doing physics or theoretical physics when the answers *really* matter – when your reputation as a scientist hangs upon being able to reason correctly in a research context or, in more practical terms, when your ability in undertaking original research determines whether you are employable, or whether your research grant is renewed. This is a quite different process from working through drill exercises, for which answers are available at the back of the book.

Second, there is so much material which lecturers feel they have to include in their courses that all physics syllabuses are seriously overloaded. There is generally little time left for sitting back and asking 'What is this all about?' Indeed, the technical aspects of the subject, which are themselves fascinating, can become so totally absorbing that it is generally left to the students to find out for themselves many essential truths about physics.

Let me list some aspects of the practice of physics which can be missed in our teaching but which, I believe, are essential aspects of the way in which we carry it out as professionals.

(i) A series of lecture courses is by its nature a modular exercise. It is only too easy to lose a *global view* of the whole subject. Professionals use the whole of physics in tackling problems and there is no artificial distinction between thermal physics, optics, mechanics, electromagnetism, quantum mechanics and so on.

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