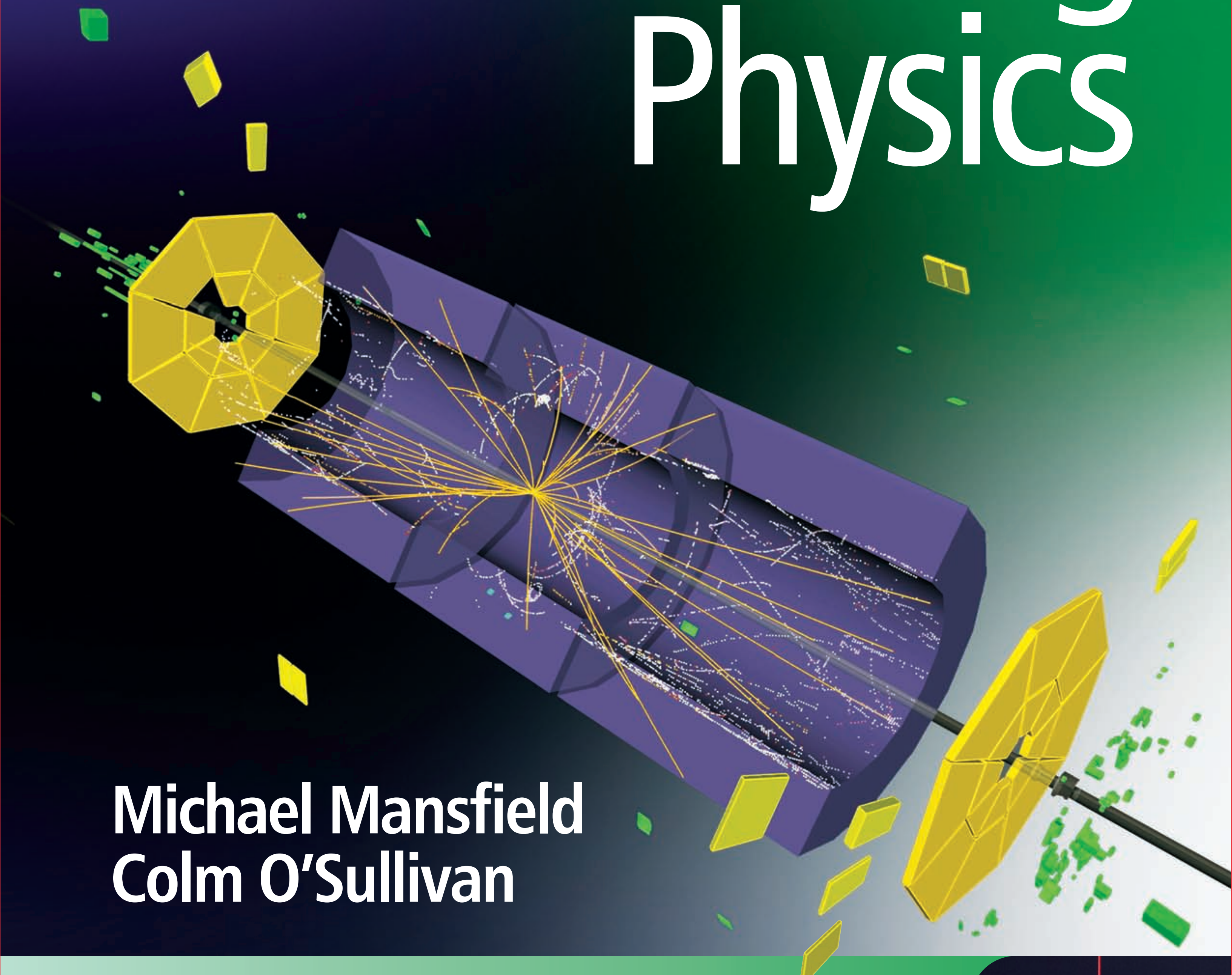
Second Edition

Understanding Physics



Michael Mansfield
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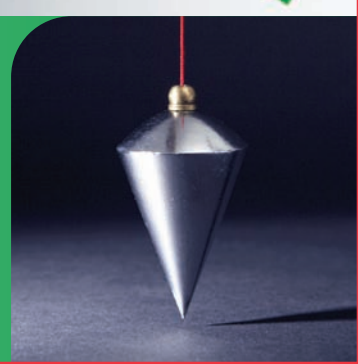

Understanding Physics

Second Edition

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MICHAEL MANSFIELD AND COLM O'SULLIVAN

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WILEY

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

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

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 been have 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 Feiner-Valkier, 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

1

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, discuses 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 Ampére (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.

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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 (ν_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	$\sim10^{-15}$
Nuclei	$\sim10^{-14}$
Atoms	$\sim10^{-10}$
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.

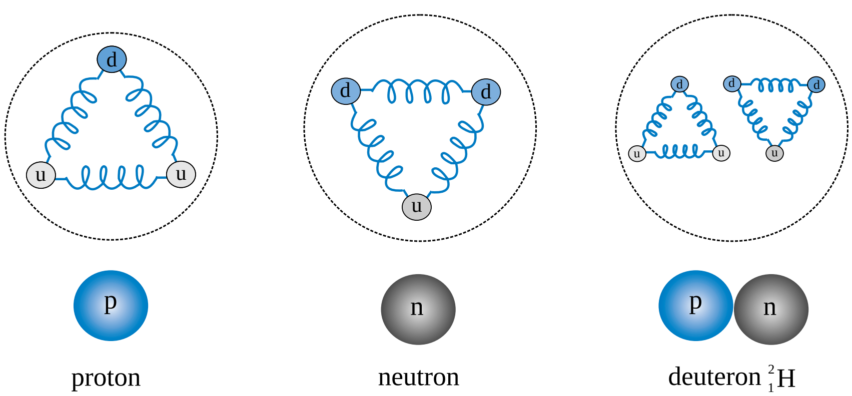

Figure 1.1. The quark and nucleon compositions of the proton ($^1_1$p), neutron ($^1_0$n) and deuteron ($^2_1$H).

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.

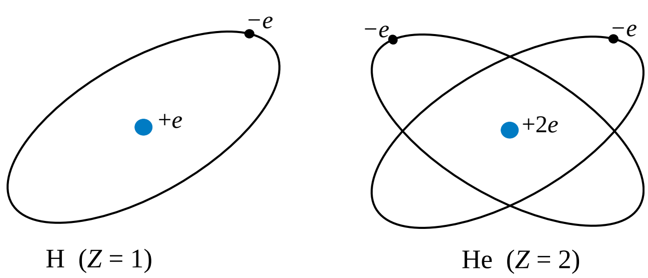

Figure 1.2. The electronic structure of the hydrogen and helium atoms.

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, $^3_2$He (two p and one n) and $^4_2$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 ^A_ZX 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. $^A_ZX^+$ (one electron lost), $^A_ZX^{2+}$ (two electrons lost) or $^A_ZX^-$ (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.

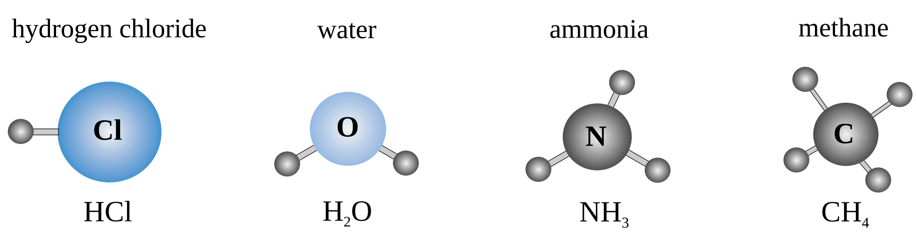

Figure 1.3. The atomic compositions of some common molecules – the smaller gray spheres represent hydrogen atoms.

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 H_2O (or ${}^1_1H_2\,{}^{16}_8O$, 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.

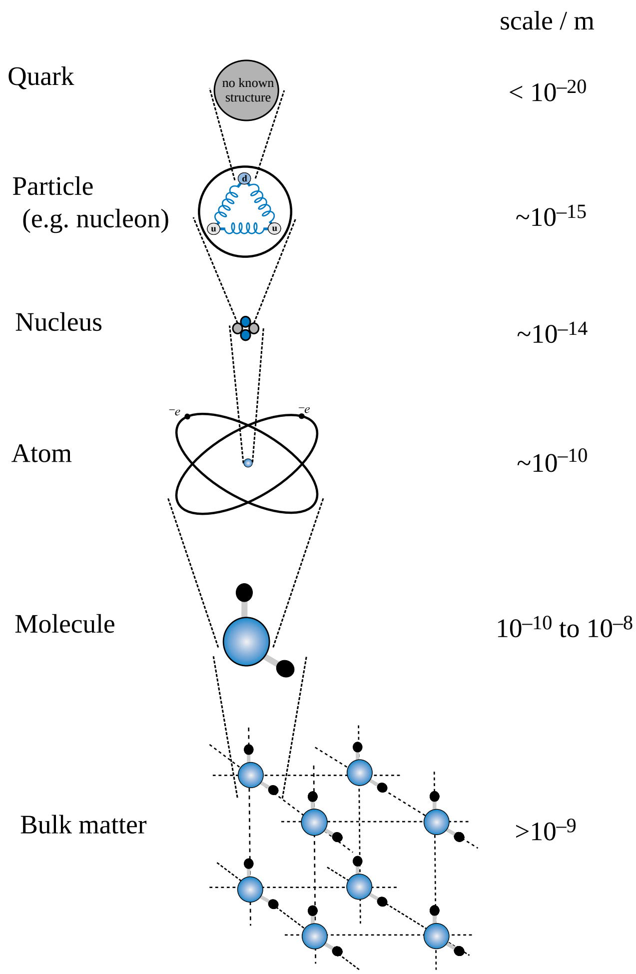

Figure 1.4. Models of the structure of matter – from the quark scale to the bulk matter scale.

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.

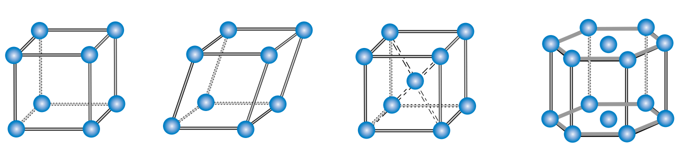

Figure 1.5. Some crystal lattice structures.

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 been have 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.

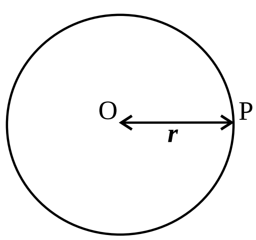

Figure 2.1. The displacement r of the point P from the origin.

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,

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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′.

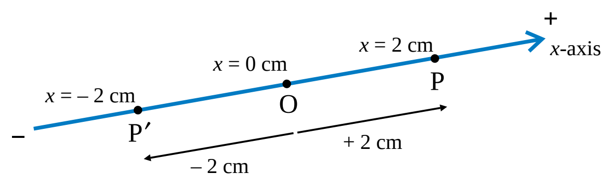

Figure 2.2. The x-coordinate axis, showing the displacements of P and P′ relative to O.

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.

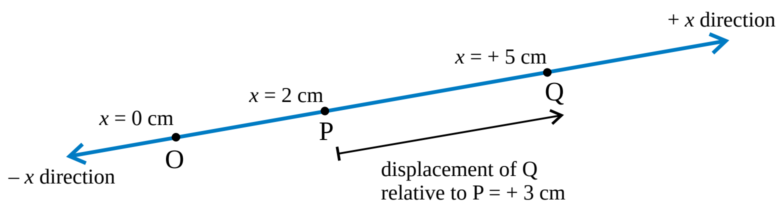

Figure 2.3. The displacements of P and Q relative to O, and of Q relative to P.

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.

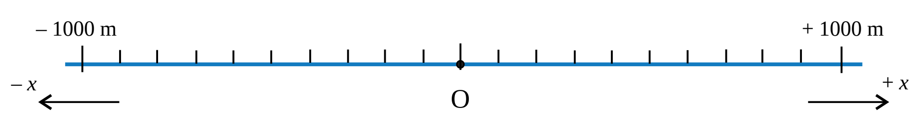

Figure 2.4. The x-axis for a moving train.