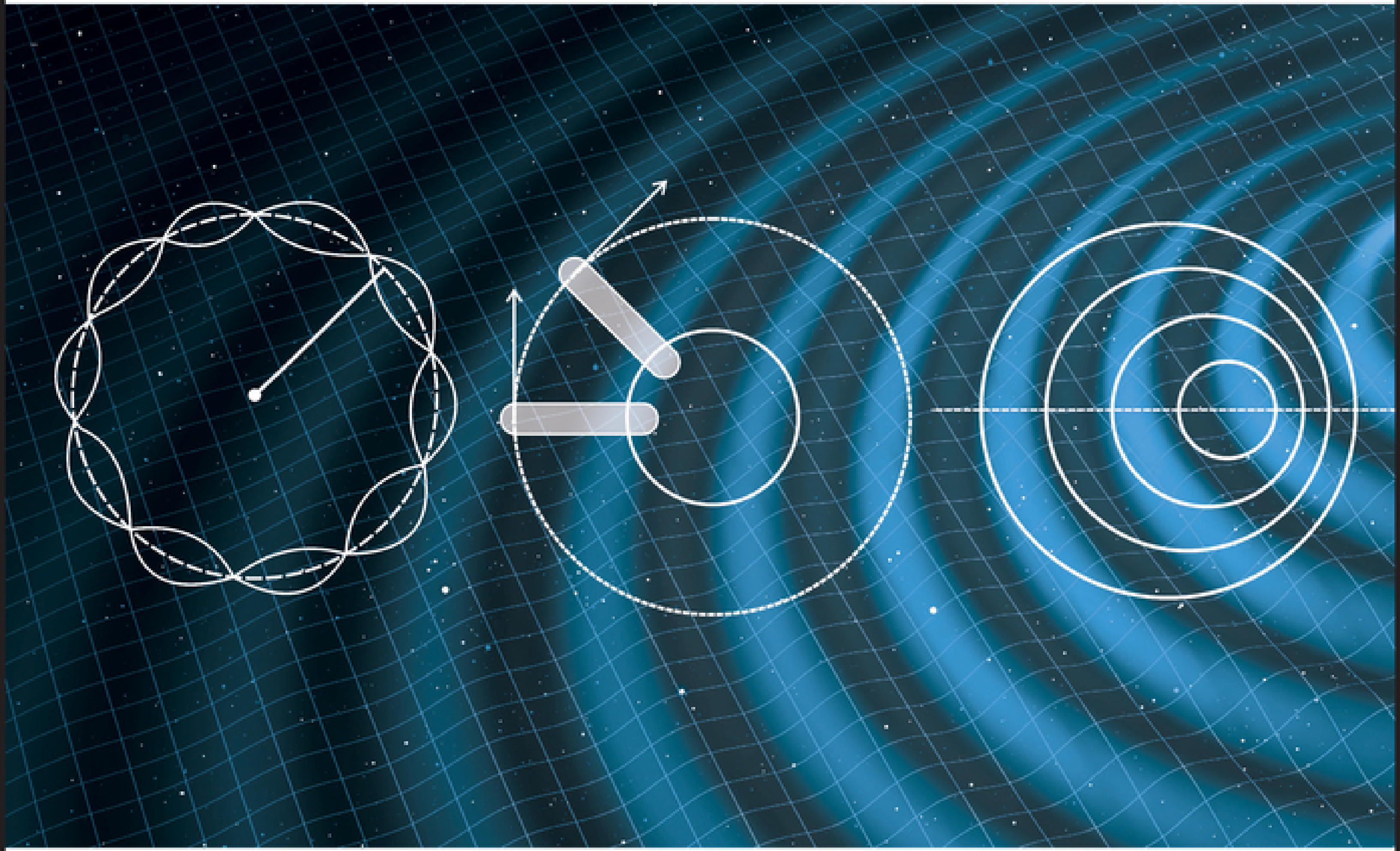
MICHAEL MANSFIELD | COLM O'SULLIVAN

UNDERSTANDING PHYSICS

THIRD EDITION



WILEY

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WILEY

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Preface to Third 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 a 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), cannot, however, substitute for a formal course in mathematical methods, but 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, eighteenth, 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. However, if instructors prefer to introduce relativity (Chapter 9) and quantum physics (Chapter 14) at a later stage, their introduction may be delayed until after Chapter 23.

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 are placed at the end of each chapter. Indications are given throughout the text as to when a particular worked example might be studied.

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). As noted below, this edition of *Understanding Physics* has been rewritten to conform with the revision of the SI which came into force in May 2019.

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 sub-nuclear to inter-galactic. 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 to 12, deal with the mechanical and thermal behaviour of matter. A sound knowledge of wave motion (Chapter 13), a very important part of physics in its own right, is essential for a proper understanding of quantum mechanics (Chapter 14). The seven subsequent chapters (15 to 21) cover the main aspects of classical electromagnetism and its application to wave and geometrical optics is covered in Chapters 22 and 23.

The final four chapters (24 to 27) – on atomic physics, on electrons in solids, on semiconductors and on nuclear and particle physics – 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.

Changes in the third edition

- This edition has been rewritten to conform with the revision of the SI which came into force in May 2019. In the revised system definitions are achieved by adopting fixed numerical values for certain fundamental constants of nature (see Appendix D for details).
- The electromagnetism chapters have been reorganised to emphasise the integration of the various topics into a view of physics as a unified whole. Particular emphasis is placed on the use of the concept of flux (and Gauss's law) as a basis for the analyses of gravitation, electricity and magnetism.
- More advanced sections, which were indicated by a blue background in previous editions may now be accessed through links to the *Understanding Physics* Website (described below). Problems are also accessed through the Website.
- Numerous detailed improvements have been made throughout the book following suggestions from instructors, students and from our own experience.

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 benefitted greatly from the many contributions, comments, and criticism generously provided over many years by numerous individuals.

We wish to express our gratitude again to all those colleagues in University College Cork and elsewhere, to our students and to the staff of Praxis Publishing and of John Wiley and Sons whose help and advice was so important in the preparation of the first and second editions of *Understanding Physics*.

The third edition has benefitted particularly from the assistance of Tony Deeney, Stephen Fahy, Joe Lennon, and David Rea, and again from the support provided by the Physics Department of University College Cork under the leadership of John McInerney. The third edition has been brought to fruition through the professionalism of a number of people at John Wiley and Sons, in particular Jenny Cossham and Emma Strickland in Chichester, Shirly Samuel and Adalfin Jayasingh in India and Mary Malin of Transtype for copyediting.

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, July 2019

The Understanding Physics Website

The Student Companion Website for this textbook may be found at http://up.ucc.ie

The site comprises a wide selection of problems for each Chapter and a number of additional sections and subsections covering somewhat more advanced material. These resources may be accessed either by specifying the relevant URL on a browser or via the QR codes in the book margins using a mobile phone, tablet or laptop with an appropriate QR reader. Documents may be downloaded in the form of .pdf files. The Website also contains a range of interactive software designed to enhance insight and understanding of various topics covered in the text. Any reported errata will be published on the Website.

Students are encouraged to enhance their understanding and insight by using the website in parallel with studying the text. The Website will continue to be developed. The authors wish to thank Lisa Faherty of the Physics Department and Peter Flynn and Noelette Hurley of IT Services UCC for their many important contributions to the Website.

Problems

More than 600 problems are available on the Website. For each problem a link is given to its answer. Each answer is then linked to a detailed solution. Students are encouraged to refrain from studying the detailed solution to a problem until they have made a number of serious attempts to find the solution for themselves.

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 behaved. 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 documented and further developed in the Islamic world between the seventh and sixteenth centuries particularly during the Golden Age of Islamic Science, circa 750 to 1250 CE.

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 Ampère (Section 18.5), Faraday (Section 20.1), Coulomb (Section 16.3) and Maxwell (Section 21.1). 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 15.4).

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 (for example 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 will review the language and images currently used by physicists to describe the structure of matter and the fundamental interactions of nature.

Understanding Physics, Third Edition. Michael Mansfield and Colm O'Sullivan.

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 sixty 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 Sections 27.11 and 27.12

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 will 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 27.11.

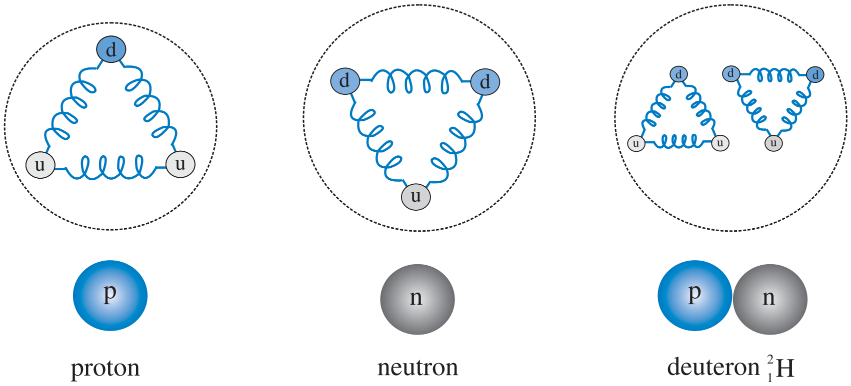

Figure 1.1. The quark and nucleon compositions of the proton ($^1_1$p), neutron ($^1_0$n) and deuteron ($^2_1$H).

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 unstable (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 27. 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 27).

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 16) that positive and negative charges are attracted to one another by electrostatic attraction. 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, may be thought of as 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 $-e$. Alternatively, as we will see in Chapter 24, the electrons may be considered as a cloud of negative charge surrounding the nucleus.

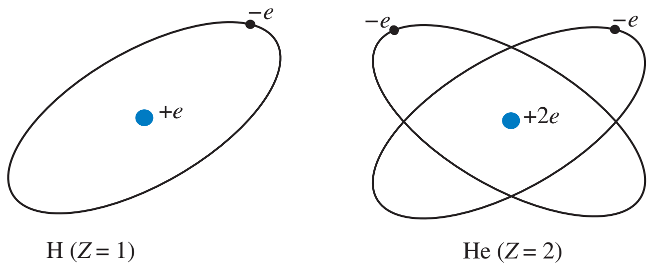

Figure 1.2. The electronic structure of the hydrogen and helium atoms.

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.

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, ${}^{3}_{2}\mathrm{He}$ (two p and one n) and ${}^{4}_{2}\mathrm{He}$ (two p and two n). The chemical **elements,** listed in Appendix E, 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 ${}^{A}_{Z}\mathrm{X}$ 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, for example ${}^{A}_{Z}\mathrm{X}^{+}$(one electron lost), ${}^{A}_{Z}\mathrm{X}^{2+}$ (two electrons lost) or ${}^{A}_{Z}\mathrm{X}^{-}$(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.

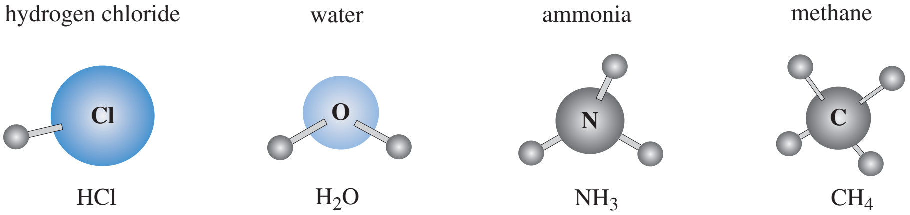

Figure 1.3. The atomic compositions of some common molecules – the smaller grey spheres represent hydrogen atoms.

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 ${}^{1}_{1}\mathrm{H}_2\,{}^{16}_{8}\mathrm{O}$, 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 25.1.

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

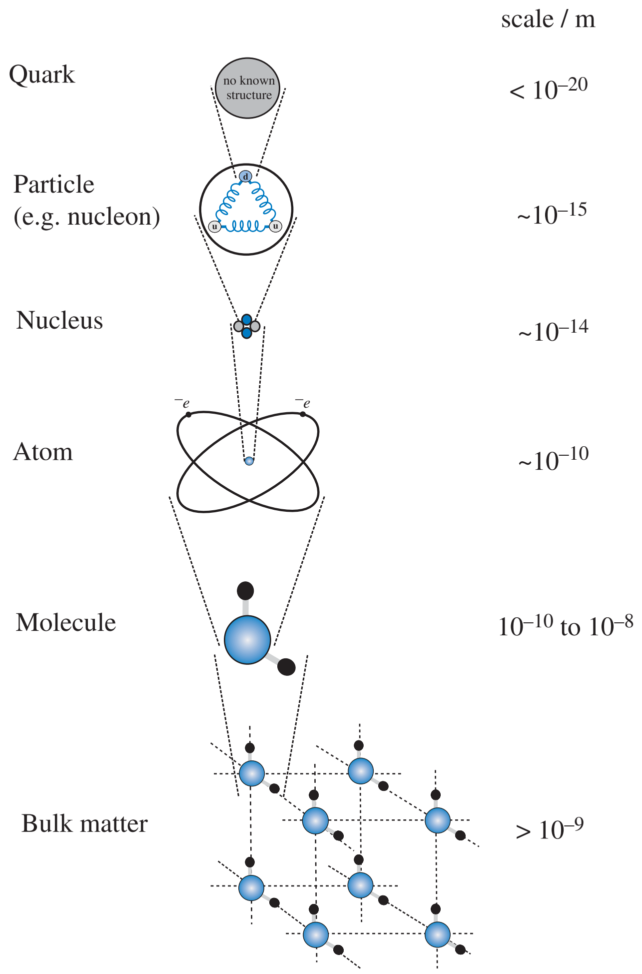

Figure 1.4. Models of the structure of matter — from the quark scale to the bulk matter scale.

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.

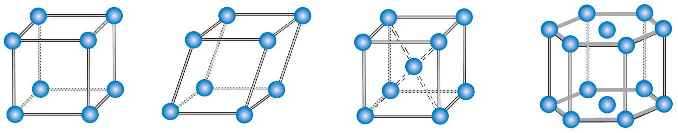

Figure 1.5. Some crystal lattice structures.

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 sub-atomic composition. Indeed, matter in bulk appears continuous – most materials seeming 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 will adhere to this principle as far as possible. We will 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 (for example, kinetic theory in Section 10.11). An important test of the microscopic approach will be whether its predictions agree with those of the macroscopic treatment. 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:

(a) ***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 27. 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.

(b) ***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.

(c) ***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 only noticeable in the absence of the strong and electromagnetic interactions. The weak interaction is very short range ($\sim 10^{-18}$ m) and plays a role only at the nuclear and sub-nuclear level.

(d) ***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.

Unification of the basic interactions

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 Maxwell's theory of electromagnetism (which will be described in Chapter 21). Over the past sixty years the theories covering the fundamental interactions have been undergoing a similar unification process. In the 1960s Weinberg, Salam, and Glashow showed that, when viewed at a more fundamental level, the electromagnetic and weak interactions can be seen to be manifestations of a single interaction (known as the **electroweak interaction**).

Since then considerable progress has been made towards the unification of the electroweak interaction with the strong interaction and this objective (known as **Grand Unified Theory**) is still being pursued. The relative strengths of the four basic interactions can be stated in terms of *coupling constants*. The values of the coupling constants of the electroweak and strong interactions vary with energy and tend to converge on the same value at very high energies, indicating that these interactions are indeed manifestations of a single interaction. A model known as the **standard model** has been developed to provide a theory of the electroweak and strong interactions and of the elementary particles that take part in these interactions. To date the results of high energy nuclear physics experiments are consistent with the standard model. In particular, in 2012, an important particle predicted by the standard model – the *Higgs boson* – which explains the existence of mass, was observed at CERN's Large Hadron Collider.

The final step in the unification of the fundamental interactions is to unify the gravitational interaction with the other fundamental interactions 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. Several possible lines of approach to this goal are being pursued.

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 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 these 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 a 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, that is to choose agreed **measurement standards** and **systems of units**. This will enable 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.

The internationally agreed system of units (SI), summarised in Appendix D, is now adopted almost universally in science and engineering and is used uncompromisingly in this book by following rigorously the recommendations of the General Conference on Weights and Measures. In particular we use the revised definitions of SI base units which came into force in May 2019. As we will see (for example in Section 3.4 where the definition of the metre is discussed) the revisions, which are based on the adoption of fixed numerical values for certain fundamental constants of nature, provide a good illustration of how technical developments can force a change in the way in which units are defined and physics is communicated.

Analysis and hypothesis

Having observed a phenomenon, and then 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 – that is, 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 that predict the behaviour of systems in nature 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 natural and most straightforward 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 based on the experimental evidence available. Sometimes, after further investigation, 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 previous 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 14), 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 advances.

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 shall illustrate the scientific method by using it to study certain types of motion. In doing so we shall introduce some important mathematical techniques which will enable us to analyze and represent physical processes in a concise and rigorous manner. At the same time we will 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 motion and of angular motion, and who are also familiar with the use of elementary calculus in physics, may choose to proceed to Chapter 3, we recommend that they take the opportunity to refresh their understanding of these topics in this chapter.

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, as shown in Figure 2.1.

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 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′.

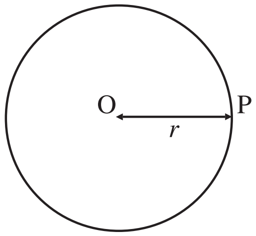

Figure 2.1. The displacement r of the point P from the origin.

Understanding Physics, Third Edition. Michael Mansfield and Colm O'Sullivan.

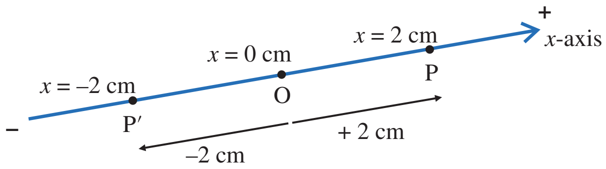

Figure 2.2. The x-coordinate axis, showing the displacements of P and P′ relative to O.

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′ are +2 cm and −2 cm from O, 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 provided a convention for positive x has been adopted. For example, based on the conventions adopted in Figure 2.2, the displacement of P is $x = +2$ cm and that of P′ is $x = -2$ cm.

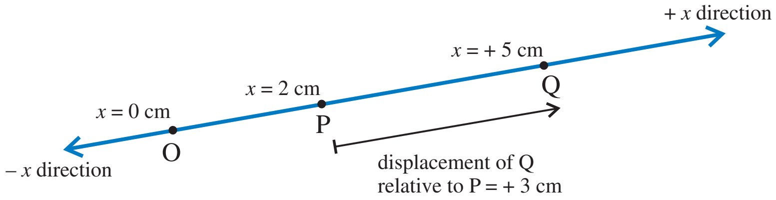

Figure 2.3. The displacements of P and Q relative to O, and of Q relative to P.

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 (that is, 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 only change 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 only free to move along a straight line, the x-axis, as illustrated in Figure 2.4. As an example we will 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.

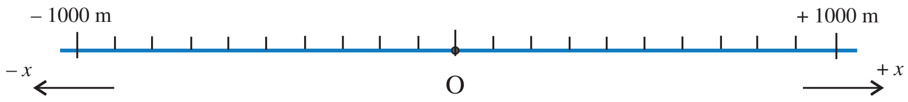

Figure 2.4. The x-axis for a moving train.

In the third column of Table 2.1, in order to make the relationship between displacement and time more obvious, times are also stated with reference to 10.00 a.m., the time at which we start observing the train's motion (our time origin). In this case a simple relationship between x and t can be deduced quite easily from an inspection of the numbers in the first and third columns of Table 2.1.