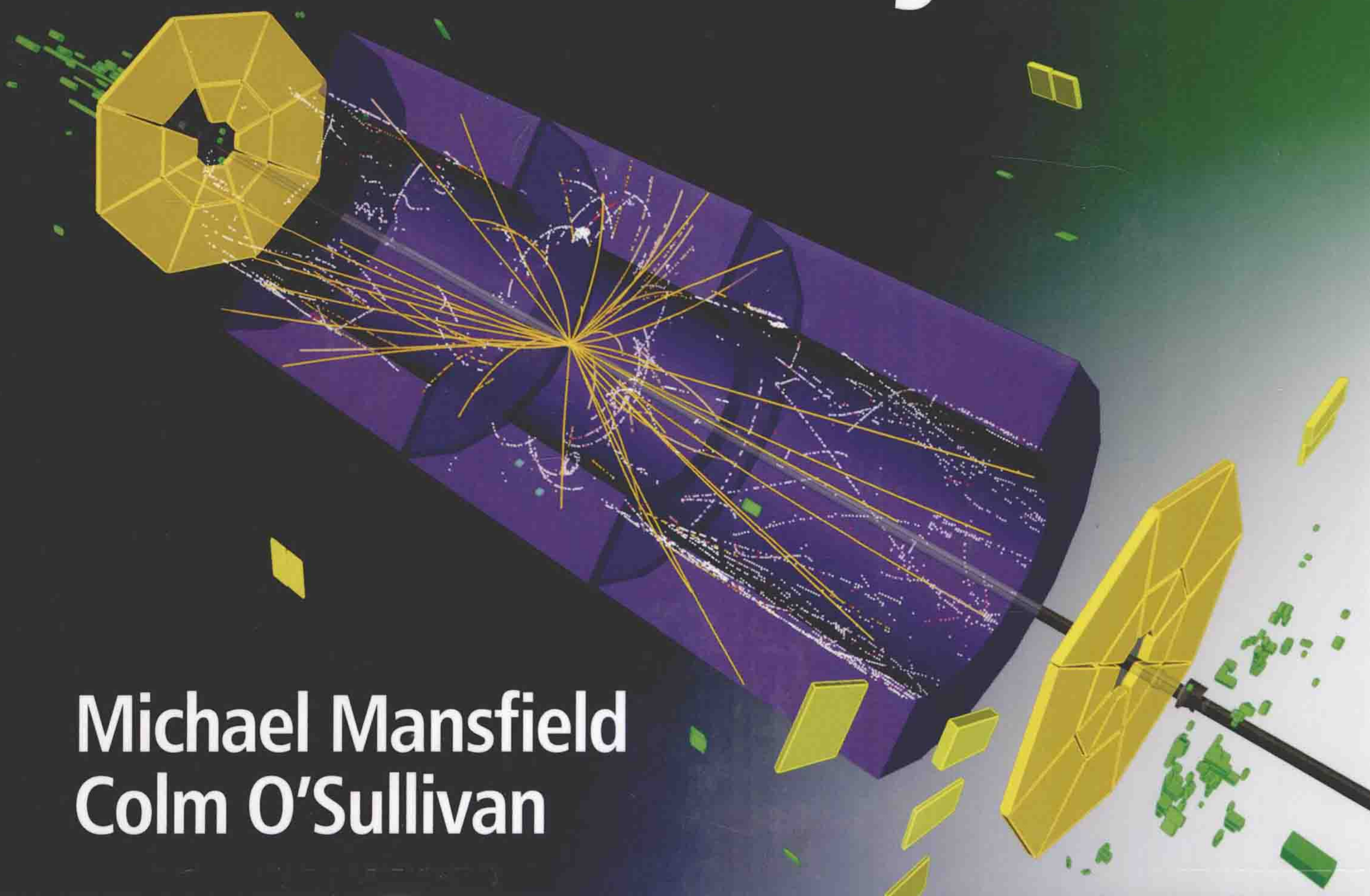
Second Edition

Understanding Physics



Michael Mansfield
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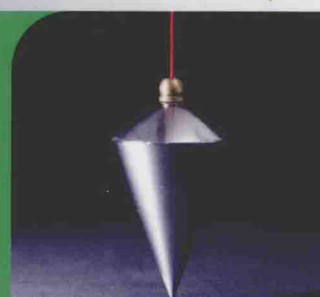

Understanding Physics

Second Edition

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

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

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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

Contents

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

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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.

Understanding Physics – Second Edition Michael Mansfield and Colm O'Sullivan
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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.

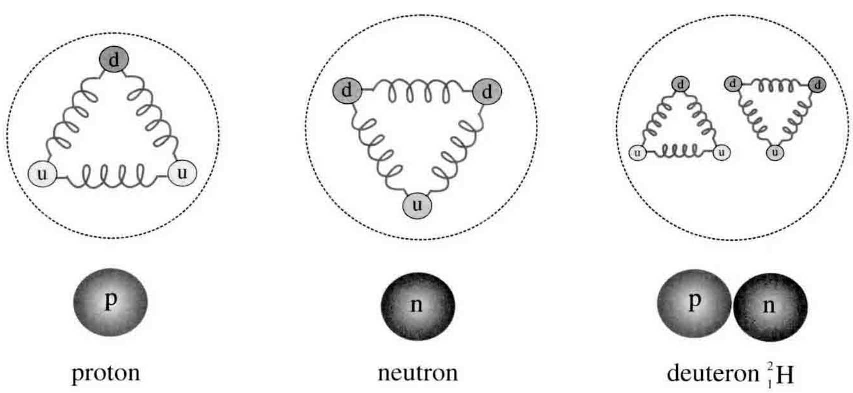

Figure 1.1. The quark and nucleon compositions of the proton ($^1_1$p), neutron ($^1_0$n) and deuteron ($^2_1$H).

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,

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