FOR THE
IB DIPLOMA

SECOND EDITION

Physics

John Allum and
Christopher Talbot

DYNAMIC
LEARNING

HODDER
EDUCATION

Physics

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Introduction

Welcome to the second edition of *Physics for the IB Diploma*. The content and structure of this second edition has been completely revised to meet the demands of the 2014 *IB Diploma Programme Physics Guide*.

Within the IB Diploma Programme, the physics content is organized into compulsory topics plus a number of options, from which all students select one. The organization of this resource exactly follows the IB *Physics Guide* sequence:

- **Core:** Chapters 1–8 cover the common core topics for Standard *and* Higher Level students.
- **Additional Higher Level (AHL):** Chapters 9–12 cover the additional topics for Higher Level students.
- **Options:** Chapters 13–16 cover Options A, B, C and D respectively. Each of these is available to both Standard and Higher Level students. (Higher Level students study more topics within the same option.)

Each of the core and AHL topics is the subject of a corresponding single chapter in the *Physics for the IB Diploma* printed book.

The Options (Chapters 13–16) are available on the website accompanying this book, as are useful appendices and additional student support (including Starting points and Summary of knowledge): www.hoddereducation.com/IBextras

There are two additional short chapters offering physics-specific advice on the skills necessary for **Graphs and data analysis** and **Preparing for the IB Diploma Physics examination**, including explanations of the **command terms**. These chapters can be found on the accompanying website.

Special features of the chapters of *Physics for the IB Diploma* are described below.

- The text is written in **straightforward language**, without phrases or idioms that might confuse students for whom English is a second language.
- The **depth of treatment** of topics has been carefully planned to accurately reflect the objectives of the IB syllabus and the requirements of the examinations.

Nature of Science

- The **Nature of Science** is an important new aspect of the IB Physics course, which aims to broaden students' interests and knowledge beyond the confines of its specific physics content. Throughout this book we hope that students will develop an appreciation of the processes and applications of physics and technology. Some aspects of the *Nature of Science* may be examined in IB Physics examinations and important discussion points are highlighted in the margins.
- The **Utilizations** and **Additional Perspectives** sections also reflect the *Nature of Science*, but they are designed to take students *beyond* the limits of the IB syllabus in a variety of ways. They might, for example, provide a historical context, extend theory or offer an interesting application. They are sometimes accompanied by more challenging, or research-style, questions. They do *not* contain any knowledge that is essential for the IB examinations.
- Science and technology have developed over the centuries with contributions from scientists from all around the world. In the modern world science knows few boundaries and the flow of information is usually quick and easy. Some international applications of science have been indicated with the **International Mindedness** icon.
- **Worked examples** are provided in each chapter whenever new equations are introduced. A large number of **self-assessment questions** are placed throughout the chapters close to the relevant theory. **Answers** to most questions are provided at the end of the book.
- It is not an aim of this book to provide detailed information about experimental work or the use of computers. However, our **Skills** icon has been placed in the margin to indicate wherever such work may usefully aid understanding. A number of key experiments are included in the *IB Physics Guide* and these are listed in Chapter 18: Preparing for the IB Diploma Physics examination, to be found on the website that accompanies this book.

- A selection of **IB examination-style questions** is provided at the end of each chapter, as well as some past IB Physics examination questions.
- Links to the interdisciplinary **Theory of Knowledge (ToK)** element of the IB Diploma course are made in all chapters.
- Comprehensive **glossaries** of words and terms for Core and AHL topics are included in the printed book. Glossaries for the Options are available on the website.

Using this book

The sequence of chapters in *Physics for the IB Diploma* deliberately follows the sequence of the syllabus content. However, the *IB Diploma Physics Guide* is not designed as a teaching syllabus, so the order in which the syllabus content is presented is not necessarily the order in which it will be taught. Different schools and colleges should design a course based on their individual circumstances.

In addition to the study of the physics principles contained in this book, IB science students carry out experiments and investigations, as well as collaborating in a Group 4 Project. These are assessed within the school (Internal Assessment), based on well-established criteria.

The contents of Chapter 1 (Physics and physical measurement) have applications that recur throughout the rest of the book and also during practical work. For this reason, it is intended more as a source of reference, rather than as material that should be fully understood before progressing to the rest of the course.

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1

Measurements and uncertainties

ESSENTIAL IDEAS

- Since 1948, the Système International d'Unités (SI) has been used as the preferred language of science and technology across the globe and reflects current best measurement practice.
- Scientists aim towards designing experiments that can give a 'true value' from their measurements but, due to the limited precision in measuring devices, they often quote their results with some form of uncertainty.
- Some quantities have direction and magnitude, others have magnitude only, and this understanding is the key to correct manipulation of quantities.

1.1 Measurements in physics

– since 1948, the Système International d'Unités (SI) has been used as the preferred language of science and technology across the globe and reflects current best measurement practice

Fundamental and derived SI units

To communicate with each other we need to share a common language, and to share numerical information we need to use common **units of measurement**. An internationally agreed system of units is now used by scientists around the world. It is called the **SI system** (from the French 'Système International'). SI units will be used throughout this course.

Nature of Science

Common terminology

For much of the last 200 years many prominent scientists have tried to reach agreement on a metric (decimal) system of units that everyone would use for measurements in science and commerce. A common system of measurement is invaluable for the transfer of scientific information and for international trade. In principle this may seem more than sensible, but there are significant historical and cultural reasons why some countries, and some societies and individuals, have been resistant to changing their system of units.

The SI system was formalized in 1960 and the seventh unit (the mole) was added in 1971. Before that, apart from SI units, a system based on centimetres, grams and seconds (CGS) was widely used, while the imperial (non-decimal) system of feet, pounds and seconds was also popular in some countries. For non-scientific, everyday use, people in many countries sometimes still prefer to use different systems that have been popular for centuries. Confusion between different systems of units has been famously blamed for the failure of the Mars orbiter in 1999 and has been implicated in several aviation incidents.

The fundamental units of measurement

There are seven **fundamental (basic) units** in the SI system: kilogram, metre, second, ampere, mole, kelvin (and candela, which is *not* part of this course). The quantities, names and symbols for these fundamental SI units are given in Table 1.1.

They are called 'fundamental' because their definitions are not combinations of other units (unlike metres per second, for example). You do not need to learn the definitions of these units.

Table 1.1 Fundamental units

Quantity	Name	Symbol	Definition
length	metre	m	the distance travelled by light in a vacuum in 1/299 792 458 seconds
mass	kilogram	kg	the mass of a cylinder of platinum-iridium alloy kept at the International Bureau of Weights and Measures in France
time	second	s	the duration of 9 192 631 770 oscillations of the electromagnetic radiation emitted in the transmission between two specific energy levels in caesium-133 atoms
electric current	ampere	A	that current which, when flowing in two parallel conductors one metre apart in a vacuum produces a force of 2×10^{-7}N on each metre of the conductors
temperature	kelvin	K	1/273.16 of the thermodynamic temperature of the triple point of water
amount of substance	mole	mol	an amount of substance that contains as many particles as there are atoms in 12 g of carbon-12

Nature of Science

Improvement in instrumentation

Accurate and precise measurements of experimental data are a cornerstone of science, and such measurements rely on the precision of our system of units. The definitions of the fundamental units depend on scientists' ability to make very precise measurements and this has improved since the units were first defined and used.

Scientific advances can come from original research in new areas, but they are also driven by improved technologies and the ability to make more accurate measurements. Astronomy is a good example: controlled experiments are generally not possible, so our rapidly expanding understanding of the universe is being achieved largely as a result of the improved data we can receive with the help of the latest technologies (higher-resolution telescopes, for example).

Derived units of measurement

All other units in science are combinations of the fundamental units. For example, the unit for volume is $\mathrm{m^3}$ and the unit for speed is $\mathrm{m\,s^{-1}}$. Combinations of fundamental units are known as **derived units**.

Sometimes derived units are also given their own name (Table 1.2). For example, the unit of force is $\mathrm{kg\,m\,s^{-2}}$, but it is usually called the newton, N. All derived units will be introduced and defined when they are needed during the course.

Table 1.2 Some named derived units

Derived unit	Quantity	Combined fundamental units
newton (N)	force	$\mathrm{kg\,m\,s^{-2}}$
pascal (Pa)	pressure	$\mathrm{kg\,m^{-1}\,s^{-2}}$
hertz (Hz)	frequency	$\mathrm{s^{-1}}$
joule (J)	energy	$\mathrm{kg\,m^{2}\,s^{-2}}$
watt (W)	power	$\mathrm{kg\,m^{2}\,s^{-3}}$
coulomb (C)	charge	$\mathrm{A\,s}$
volt (V)	potential difference	$\mathrm{kg\,m^{2}\,s^{-3}\,A^{-1}}$
ohm (Ω)	resistance	$\mathrm{kg\,m^{2}\,s^{-3}\,A^{-2}}$
weber (Wb)	magnetic flux	$\mathrm{kg\,m^{2}\,s^{-2}\,A^{-1}}$
tesla (T)	magnetic field strength	$\mathrm{kg\,s^{-2}\,A^{-1}}$
becquerel (Bq)	radioactivity	$\mathrm{s^{-1}}$

Note that students are expected to write and recognize units using superscript format, such as $\mathrm{m\,s^{-1}}$ rather than m/s. Acceleration, for example, has the unit $\mathrm{m\,s^{-2}}$.

Occasionally physicists use units that are not part of the SI system. For example, the electronvolt, eV, is a conveniently small unit of energy that is often used in atomic physics. Units such as this will be introduced when necessary during the course. Students will be expected to be able to convert from one unit to another. A more common conversion would be changing time in years to time in seconds.

ToK Link

Fundamental concepts

As well as some units of measurement, many of the ideas and principles used in physics can be described as being 'fundamental'. Indeed, physics itself is often described as the fundamental science. But what exactly do we mean when we describe something as fundamental? We could replace the word with 'elementary' or 'basic', but that does not really help us to understand its true meaning.

One of the central themes of physics is the search for *fundamental particles* – particles that are the basic building blocks of the universe and are not, themselves, made up of smaller and simpler particles. It is the same with *fundamental laws and principles*: a physics principle cannot be described as fundamental if it can be explained by 'simpler' ideas. Most scientists also believe that a principle cannot be really fundamental unless it is relatively simple to express (probably using mathematics). If it is complicated, maybe the underlying simplicity has not yet been discovered.

Fundamental principles must also be 'true' everywhere and for all time. The fundamental principles of physics that we use today have been tested, re-tested and tested again to check if they are truly fundamental. Of course, there is *always* a possibility that in the future a principle that is believed to be fundamental now is discovered to be explainable by simpler ideas.

Consider two well-known laws in physics. *Hooke's law* describes how some materials stretch when forces act on them. It is a simple law, but it is not a fundamental law because it is certainly not always true. The *law of conservation of energy* is also simple, but it is described as fundamental because there are no known exceptions.

Scientific notation and metric multipliers

Scientific notation

When writing and comparing very large or very small numbers it is convenient to use **scientific notation** (sometimes called '*standard form*').

In scientific notation every number is expressed in the form $a \times 10^b$, where a is a decimal number larger than 1 and less than 10, and b is a whole number (**integer**) called the **exponent**. For example, in scientific notation the number 434 is written as 4.34×10^2; similarly, 0.000 316 is written as 3.16×10^{-4}.

Scientific notation is useful for making the number of significant figures clear (see the next section). It is also used for entering and displaying large and small numbers on calculators. $\times 10^x$ or the letter E is often used on calculators to represent 'times ten to the power of…'. For example, 4.62*E*3 represents 4.62×10^3, or 4620.

The worldwide use of this standard form for representing numerical data is of great importance for the communication of scientific information between different countries.

Table 1.3 Standard metric (SI) multipliers

Prefix	Abbreviation	Value
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}

Standard metric multipliers

In everyday language we use the words 'thousand' and 'million' to help represent large numbers. The scientific equivalents are the prefixes kilo- and mega-. For example, a kilowatt is one thousand watts, and a megajoule is one million joules. Similarly, a thousandth and a millionth are represented scientifically by the prefixes milli- and micro-. A list of standard prefixes is shown in Table 1.3. It is provided in the *Physics data booklet*.

ToK Link

Effective communication needs a common language and terminology

What has influenced the common language used in science? To what extent does having a common standard approach to measurement facilitate the sharing of knowledge in physics?

There can be little doubt that communication between scientists is much easier if they share a common scientific language (symbols, units, standard scientific notation etc. as outlined in this chapter). But are our modern methods of scientific communication and terminology the best, or could they be improved? To what extent are they just a historical accident, based on the specific languages and cultures that were dominant at the time of their development?

Significant figures

The more precise a measurement is, the greater the number of significant figures (digits) that can be used to represent it. For example, an electric current stated to be 4.20 A (as distinct from 4.19 A or 4.21 A) suggests a much greater precision than a current stated to be 4.2 A.

Significant figures are all the digits used in data to carry meaning, whether they are before or after a decimal point, and *this includes zeros*. But sometimes zeros are used without thought or meaning, and this can lead to confusion. For example, if you are told that it is 100 km to the nearest airport, you might be unsure whether it is approximately 100 km, or 'exactly' 100 km. This is a good example of why scientific notation is useful. Using 1.00×10^3 km makes it clear that there are three significant figures. 1×10^3 km represents much less precision.

When making *calculations*, the result cannot be more precise than the data used to produce it. As a general (and simplified) rule, when answering questions or processing experimental data, the result should have the same number of significant figures as the data used. If the number of significant figures is not the same for all pieces of data, then the number of significant figures in the answer should be the same as the least precise of the data (which has the fewest significant figures). This is illustrated in Worked example 1.

Worked example

1 Use the equation:

$$P = \frac{mgh}{t}$$

to determine the power, P, of an electric motor that raises a mass, m, of 1.5 kg, a distance, h, of 1.128 m in a time, t, of 4.79 s. ($g = 9.81\,\mathrm{m\,s^{-2}}$)

$$P = \frac{mgh}{t} = \frac{1.5 \times 9.81 \times 1.128}{4.79}$$

A calculator will display an answer of 3.4652…, but this answer suggests a very high precision, which is not justified by the data. The data used with the least number of significant figures is 1.5 kg, so the answer should also have the same number:

$$P = 3.5\,\mathrm{W}$$

'Rounding off' to an appropriate number of significant figures

'Rounding off', as in Worked example 1, should be done at the *end* of a multi-step calculation, when the answer has to be given. If further calculations using this answer are then needed, *all* the digits shown previously on the calculator should be used. The answer to this calculation should then be rounded off to the correct number of significant figures. This process can sometimes result in small but apparent inconsistencies between answers.

Orders of magnitude

Physics is the fundamental science that tries to explain how and why everything in the universe behaves in the way that it does. Physicists study everything from the smallest parts of atoms to distant objects in our galaxy and beyond (Figure 1.1).

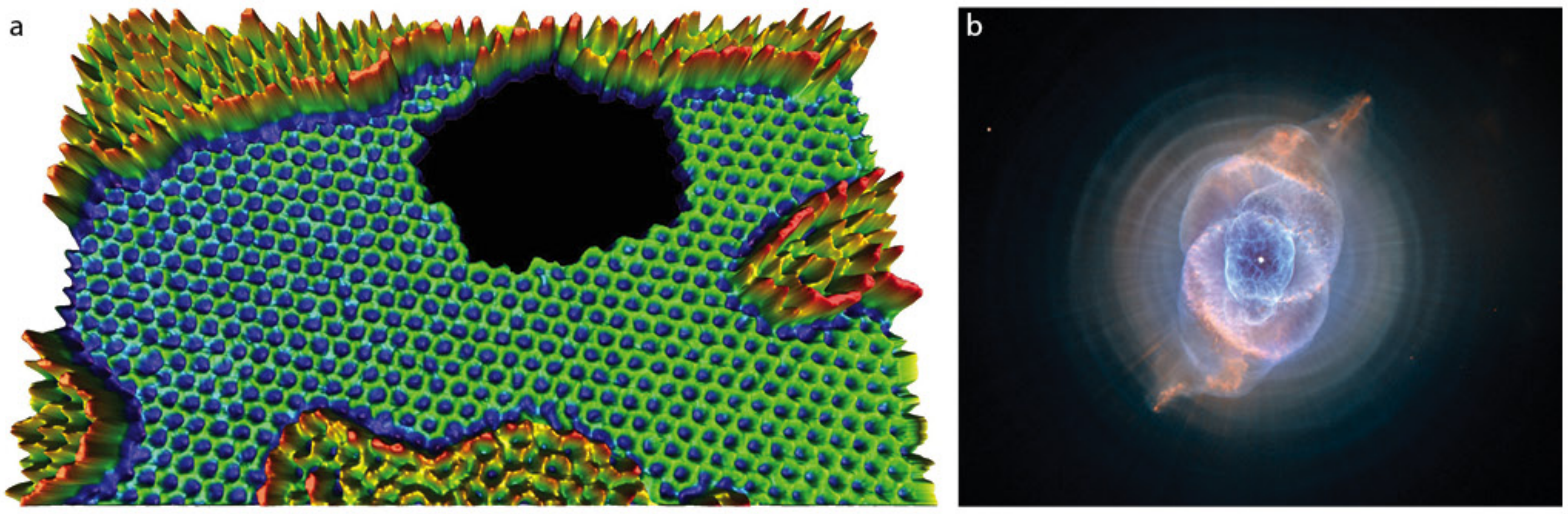

Figure 1.1
a The behaviour of individual atoms in graphene (a material made from a single layer of carbon atoms) can be seen using a special type of electron microscope
b Complex gas and dust clouds in the Cat's Eye nebula, 3000 light years away

Physics is a **quantitative** subject that makes much use of mathematics. Measurements and calculations commonly relate to the world that we can see around us (the **macroscopic** world), but our observations may require **microscopic** explanations, often including an understanding of molecules, atoms, ions and sub-atomic particles. **Astronomy** is a branch of physics that deals with the other extreme – quantities that are very much bigger than anything we experience in everyday life.

The study of physics therefore involves dealing with both very large and very small numbers. When numbers are so different from our everyday experiences, it can be difficult to appreciate their true size. For example, the age of the universe is believed to be about 10^{18} s, but just how big is that number? The only sensible way to answer that question is to compare the quantity with something else with which we are more familiar. For example, the age of the universe is about 100 million human lifetimes.

When comparing quantities of very different sizes (**magnitudes**), for simplicity we often make approximations to the nearest power of 10. When numbers are approximated and quoted to the nearest power of 10, it is called giving them an **order of magnitude**. For example, when comparing the lifetime of a human (the worldwide average is about 70 years) with the age of the universe (1.4×10^{10} y), we can use the approximate ratio $10^{10}/10^2$. That is, the age of the universe is about 10^8 human lifetimes, or we could say that there are eight orders of magnitude between them.

Here are three further examples:

- The mass of a hydrogen atom is 1.67×10^{-27} kg. To an order of magnitude this is 10^{-27} kg.
- The distance to the nearest star (*Proxima Centauri*) is 4.01×10^{16} m. To an order of magnitude this is 10^{17} m. (Note: log of $4.01 \times 10^{16} = 16.60$, which is nearer to 17 than to 16.)
- There are 86 400 seconds in a day. To an order of magnitude this is 10^5 s.

Tables 1.4 to 1.6 list the ranges of mass, distance and time that occur in the universe. You are recommended to look at computer simulations representing these ranges.

Table 1.4 The range of masses in the universe

Object	**Mass/kg**
the observable universe	10^{53}
our galaxy (the Milky Way)	10^{42}
the Sun	10^{30}
the Earth	10^{24}
a large passenger plane	10^5
a large adult human	10^2
a large book	1
a raindrop	10^{-6}
a virus	10^{-20}
a hydrogen atom	10^{-27}
an electron	10^{-30}

Distance	**Size/m**
distance to the edge of the visible universe	10^{27}
diameter of our galaxy (the Milky Way)	10^{21}
distance to the nearest star	10^{16}
distance to the Sun	10^{11}
distance to the Moon	10^8
radius of the Earth	10^7
altitude of a cruising plane	10^4
height of a child	1
how much human hair grows by in one day	10^{-4}
diameter of an atom	10^{-10}
diameter of a nucleus	10^{-15}

Table 1.5 The range of distances in the universe

Time period	**Time interval/s**
age of the universe	10^{18}
time since dinosaurs became extinct	10^{15}
time since humans first appeared on Earth	10^{13}
time since the pyramids were built in Egypt	10^{11}
typical human lifetime	10^9
one day	10^5
time between human heartbeats	1
time period of high-frequency sound	10^{-4}
time for light to travel across a room	10^{-8}
time period of oscillation of a light wave	10^{-15}
time for light to travel across a nucleus	10^{-23}

Table 1.6 The range of times in the universe

Estimation

Sometimes we do not have the data needed for accurate calculations, or maybe calculations need to be made quickly. Sometimes a question is so vague that an accurate answer is simply not possible. The ability to make sensible estimates is a very useful skill that needs plenty of practice. The worked example and questions 2–5 below are typical of calculations that do not have exact answers.

When making estimates, different people will produce different answers and it is usually sensible to use only one (maybe two) significant figures. Sometimes only an order of magnitude is needed.

Worked example

2 Estimate the mass of air in a classroom. (density of air = 1.3 kg m^{-3})

A typical classroom might have dimensions of 7 m × 8 m × 3 m, so its volume is about 170 m^3.

mass = density × volume = 170 × 1.3 = 220 kg

Since this is an estimate, an answer of 200 kg may be more appropriate. To an order of magnitude it would be 10^2 kg.

1 Estimate the mass of:
- **a** a page of a book
- **b** air in a bottle
- **c** a dog
- **d** water in the oceans of the world.

2 Give an estimate for each of the following:
- **a** the height of a house with three floors
- **b** how many times a wheel on a car rotates during the lifetime of the car
- **c** how many grains of sand would fill a cup
- **d** the thickness of a page in a book.

3 Estimate the following periods of time:
- **a** how many seconds there are in an average human lifetime
- **b** how long it would take a person to walk around the Earth (ignore the time not spent walking)
- **c** how long it takes for light to travel across a room.

4 Research the relevant data so that you can compare the following measurements. (Give your answer as an order of magnitude.)
- **a** the distance to the Moon with the circumference of the Earth
- **b** the mass of the Earth with the mass of an apple
- **c** the time it takes light to travel 1 m with the time between your heartbeats.

1.2 Uncertainties and errors *– scientists aim towards designing experiments that can give a 'true value' from their measurements, but because of the limited precision in measuring devices, they often quote their results with some form of uncertainty*

Nature of Science

Certainty

Although scientists are perceived as working towards finding 'exact' answers, an unavoidable uncertainty exists in any measurement. The results of *all* scientific investigations have uncertainties and errors, although good experimentation will try to keep these as small as possible.

When we receive numerical data of any kind (scientific or otherwise) we need to know how much belief we should place in the information that we are reading or hearing. The presentation of the results of serious scientific research should always have an assessment of the uncertainties in the findings, because this is an integral part of the scientific process. Unfortunately the same is not true of much of the information we receive through the media, where data are too often presented uncritically and unscientifically, without any reference to their source or reliability.

No matter how hard we try, even with the very best of measuring instruments, it is simply not possible to measure anything *exactly*. For one reason, the things that we can measure do not exist as perfectly exact quantities; there is no reason why they should.

This means that *every* measurement is an approximation. A measurement could be the most accurate ever made, for example the width of a ruler might be stated as 2.283 891 03 cm, but that is still not perfect, and even if it was we would not know because we would always need a more accurate instrument to check it. In this example we also have the added complication of the fact that when measurements of length become very small we have to deal with the atomic nature of the objects that we are measuring. (Where is the edge of an atom?)