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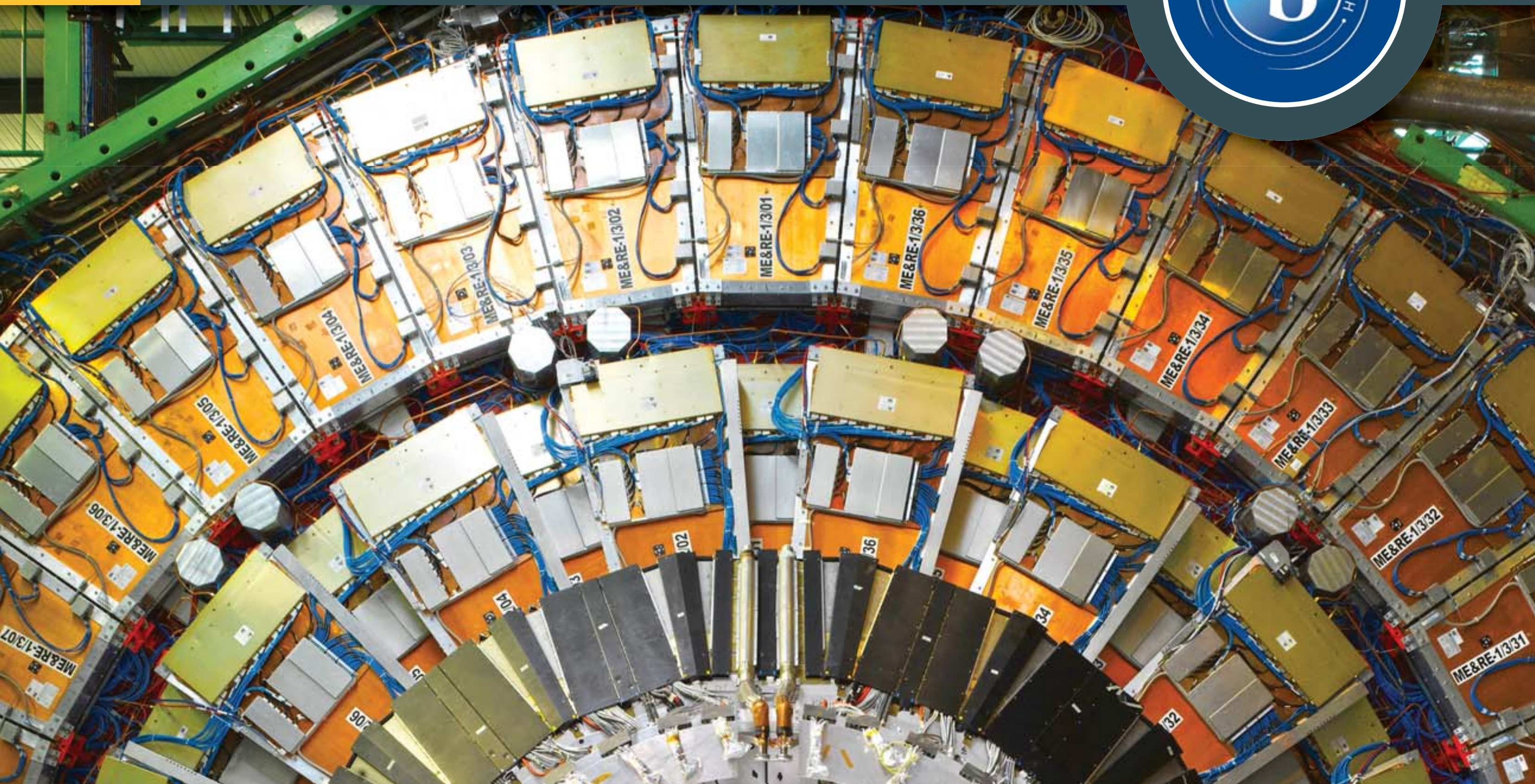

2014 EDITION

PHYSICS

COURSE COMPANION

David Homer
Michael Bowen-Jones

OXFORD

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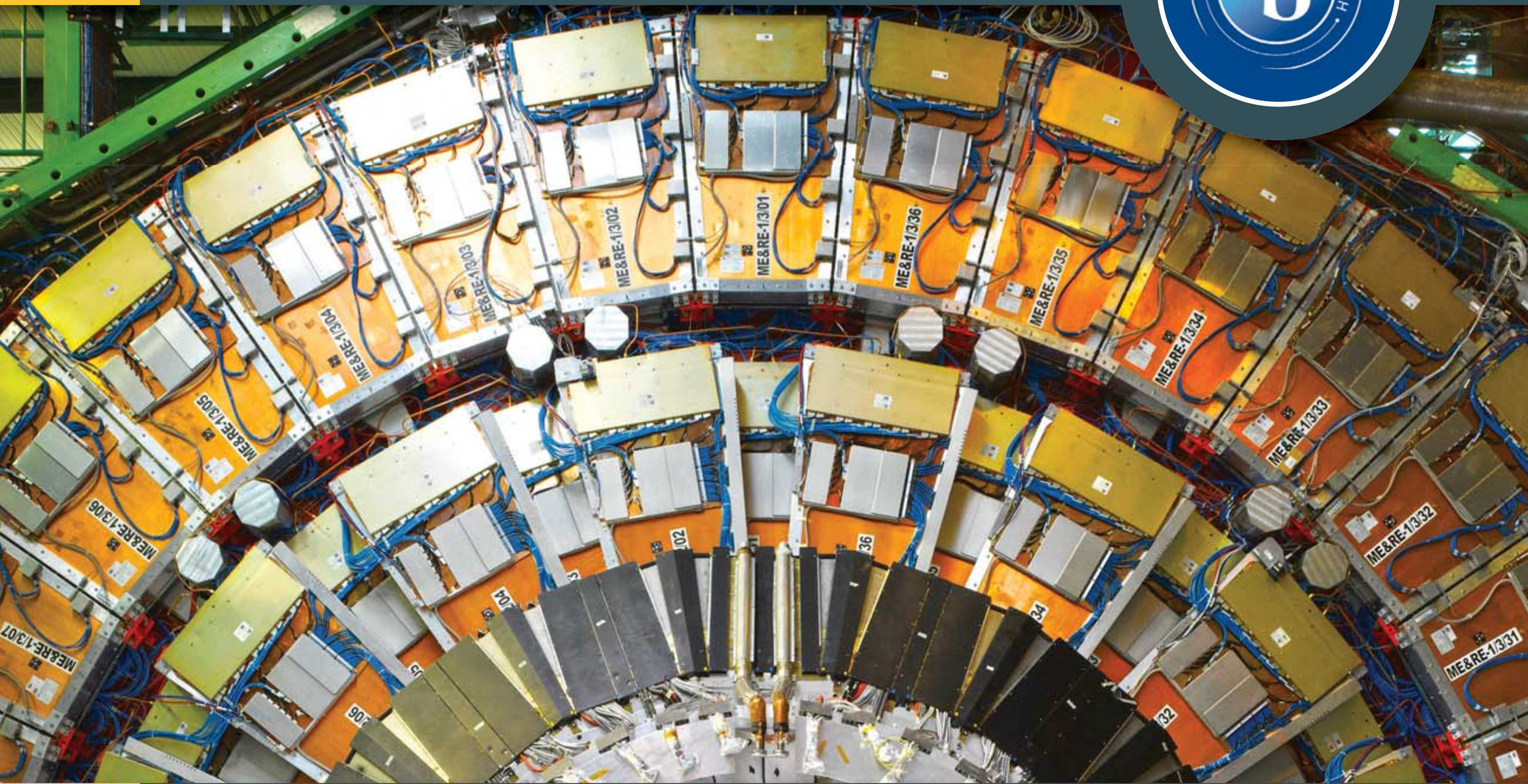
IN COOPERATION WITH ib



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p112 'Neutrino 'faster than light' scientist resigns', BBC News © 2013 BBC

Contents

Course book definition

The IB Diploma Programme course books are resource materials designed to support students throughout their two-year Diploma Programme course of study in a particular subject. They will help students gain an understanding of what is expected from the study of an IB Diploma Programme subject while presenting content in a way that illustrates the purpose and aims of the IB. They reflect the philosophy and approach of the IB and encourage a deep understanding of each subject by making connections to wider issues and providing opportunities for critical thinking.

The books mirror the IB philosophy of viewing the curriculum in terms of a whole-course approach; the use of a wide range of resources, international mindedness, the IB learner profile and the IB Diploma Programme core requirements, theory of knowledge, the extended essay, and creativity, action, service (CAS).

Each book can be used in conjunction with other materials and indeed, students of the IB are required and encouraged to draw conclusions from a variety of resources. Suggestions for additional and further reading are given in each book and suggestions for how to extend research are provided.

In addition, the course books provide advice and guidance on the specific course assessment requirements and on academic honesty protocol. They are distinctive and authoritative without being prescriptive.

IB mission statement

The International Baccalaureate aims to develop inquiring, knowledgeable and caring young people who help to create a better and more peaceful world through intercultural understanding and respect.

To this end the organization works with schools, governments and international organizations to develop challenging programmes of international education and rigorous assessment.

These programmes encourage students across the world to become active, compassionate and lifelong learners who understand that other people, with their differences, can also be right.

The IB Learner Profile

The aim of all IB programmes to develop internationally minded people who work to create a better and more peaceful world. The aim of the programme is to develop this person through ten learner attributes, as described below.

Inquirers: They develop their natural curiosity. They acquire the skills necessary to conduct inquiry and research and snow independence in learning. They actively enjoy learning and this love of learning will be sustained throughout their lives.

Knowledgeable: They explore concepts, ideas, and issues that have local and global significance. In so doing, they acquire in-depth knowledge and develop understanding across a broad and balanced range of disciplines.

Thinkers: They exercise initiative in applying thinking skills critically and creatively to recognize and approach complex problems, and make reasoned, ethical decisions.

Communicators: They understand and express ideas and information confidently and creatively in more than one language and in a variety of modes of communication. They work effectively and willingly in collaboration with others.

Principled: They act with integrity and honesty, with a strong sense of fairness, justice and respect for the dignity of the individual, groups and communities. They take responsibility for their own action and the consequences that accompany them.

Open-minded: They understand and appreciate their own cultures and personal histories, and are open to the perspectives, values and traditions of other individuals and communities. They are accustomed to seeking and evaluating a range of points of view, and are willing to grow from the experience.

Caring: They show empathy, compassion and respect towards the needs and feelings of others. They have a personal commitment to service, and to act to make a positive difference to the lives of others and to the environment.

Risk-takers: They approach unfamiliar situations and uncertainty with courage and forethought, and have the independence of spirit to explore new roles, ideas, and strategies. They are brave and articulate in defending their beliefs.

Balanced: They understand the importance of intellectual, physical and emotional balance to achieve personal well-being for themselves and others.

Reflective: They give thoughtful consideration to their own learning and experience. They are able to assess and understand their strengths and limitations in order to support their learning and personal development.

A note on academic honesty

It is of vital importance to acknowledge and appropriately credit the owners of information when that information is used in your work. After all, owners of ideas (intellectual property) have property rights. To have an authentic piece of work, it must be based on your individual and original ideas with the work of others fully acknowledged. Therefore, all assignments, written or oral, completed for assessment must use your own language and expression. Where sources are used or referred to, whether in the form of direct quotation or paraphrase, such sources must be appropriately acknowledged.

How do I acknowledge the work of others?

The way that you acknowledge that you have used the ideas of other people is through the use of footnotes and bibliographies.

Footnotes (placed at the bottom of a page) or endnotes (placed at the end of a document) are to be provided when you quote or paraphrase from another document, or closely summarize the information provided in another document. You do not need to provide a footnote for information that is part of a 'body of knowledge'. That is, definitions do not need to be footnoted as they are part of the assumed knowledge.

Bibliographies should include a formal list of the resources that you used in your work. 'Formal' means that you should use one of the several accepted forms of presentation. This usually involves separating the resources that you use into different categories (e.g. books, magazines, newspaper articles, internet-based resources, CDs and works of art) and providing full information as to how a reader or viewer of your work can find the same information. A bibliography is compulsory in the Extended Essay.

What constitutes malpractice?

Malpractice is behaviour that results in, or may result in, you or any student gaining an unfair advantage in one or more assessment component. Malpractice includes plagiarism and collusion.

Plagiarism is defined as the representation of the ideas or work of another person as your own. The following are some of the ways to avoid plagiarism:

- words and ideas of another person to support one's arguments must be acknowledged
- passages that are quoted verbatim must be enclosed within quotation marks and acknowledged
- CD-Roms, email messages, web sites on the Internet and any other electronic media must be treated in the same way as books and journals
- the sources of all photographs, maps, illustrations, computer programs, data, graphs, audio-visual and similar material must be acknowledged if they are not your own work
- works of art, whether music, film dance, theatre arts or visual arts and where the creative use of a part of a work takes place, the original artist must be acknowledged.

Collusion is defined as supporting malpractice by another student. This includes:

- allowing your work to be copied or submitted for assessment by another student
- duplicating work for different assessment components and/or diploma requirements.

Other forms of malpractice include any action that gives you an unfair advantage or affects the results of another student. Examples include, taking unauthorized material into an examination room, misconduct during an examination and falsifying a CAS record.

Using your IB Physics kerboodle Online Resources

What is Kerboodle?

Kerboodle is an online learning platform. If your school has a subscription to IB Physics Kerboodle Online Resources you will be able to access a huge bank of resources, assessments, and presentations to guide you through this course.

What is in your Kerboodle Online Resources?

There are three main areas for students on the IB Physics Kerboodle: planning, resources, and assessment.

Resources

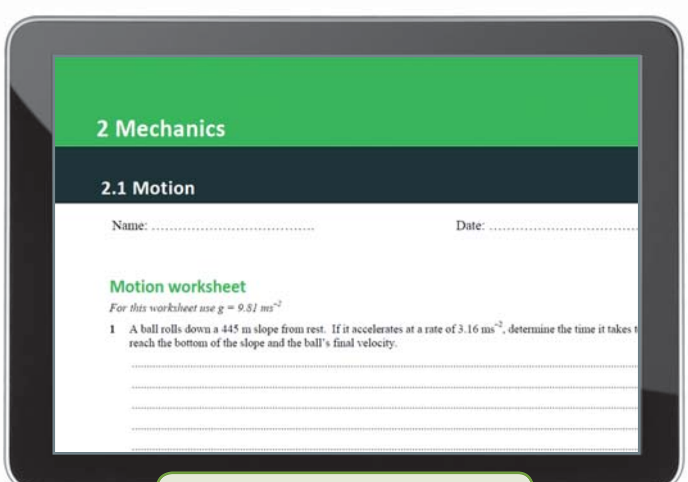
There a hundreds of extra resources available on the IB Physics Kerboodle Online. You can use these at home or in the classroom to develop your skills and knowledge as you progress through the course.

- Watch videos and animations of experiments, difficult concepts, and science in action.
- Hundreds of worksheets – read articles, perform experiments and simulations, practice your skills, or use your knowledge to answer questions.
- Look at galleries of images from the book and see their details close up.
- Find out more by looking at recommended sites on the Internet, answer questions, or do more research.

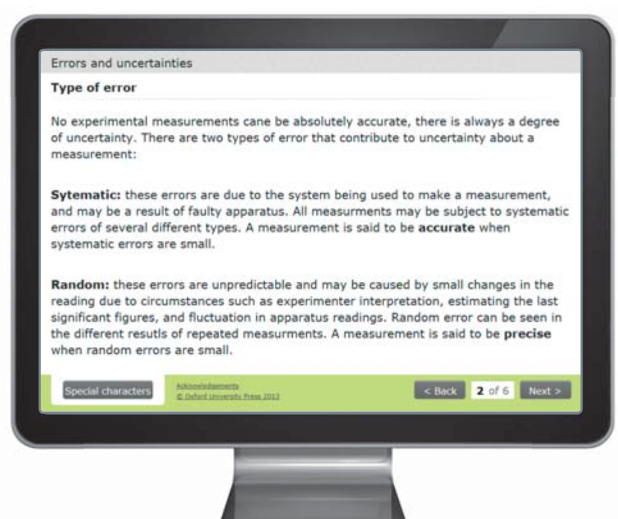
Planning

Be prepared for the practical work and your internal assessment with extra resources on the IB Physics Kerboodle online.

- Learn about the different skills that you need to perform an investigation.
- Plan and prepare experiments of your own.
- Learn how to analyse data and draw conclusions successfully and accurately.



One of hundreds of worksheets.

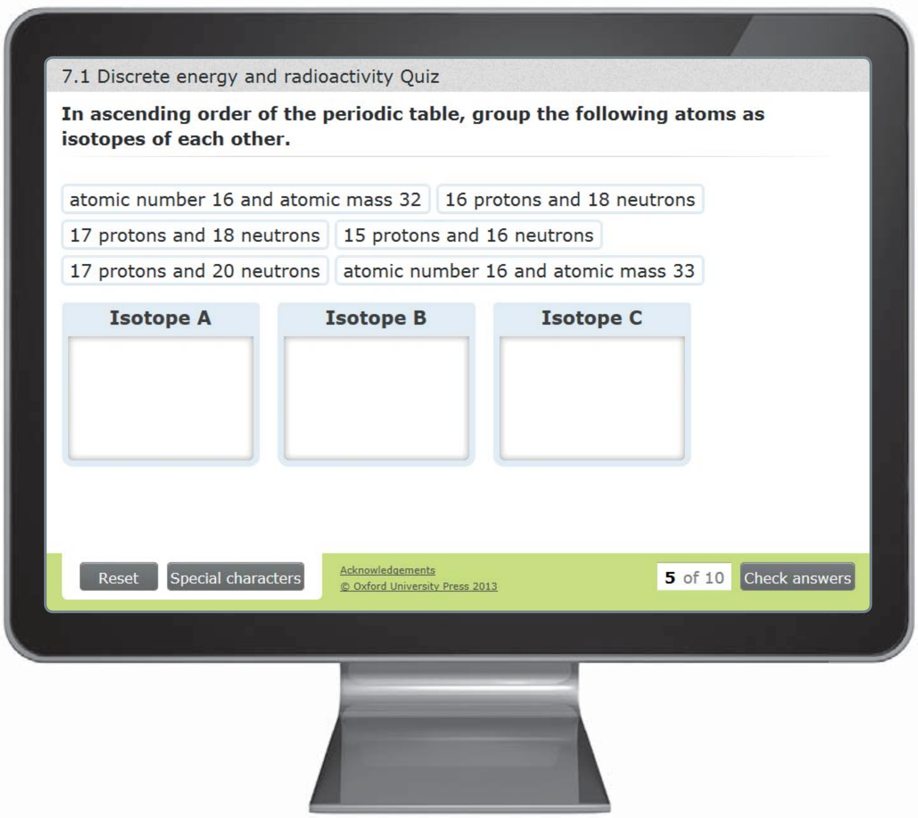


Practical skills presentation.

Assessment

Click on the assessment tab to check your knowledge or revise for your examinations. Here you will find lots of interactive quizzes and exam-style practice questions.

- Formative tests: use these to check your comprehension, there's one auto-marked quiz for every sub-topic. Evaluate how confident you feel about a sub-topic, then complete the test. You will have two attempts at each question and get feedback after every question. The marks are automatically reported in the markbook, so you can see how you progress throughout the year.
- Summative tests: use these to practice for your exams or as revision, there's one auto-marked quiz for every topic. Work through the test as if it were an examination – go back and change any questions you aren't sure about until you are happy, then submit the test for a final mark. The marks are automatically reported in the markbook, so you can see where you may need more practice.
- Assessment practice: use these to practice answering the longer written questions you will come across when you are examined. These worksheets can be printed out and performed as a timed test.



Don't forget!

You can also find extra resources on our free website

www.oxfordsecondary.co.uk/ib-physics

Here you can find all of the answers and even more practice questions.

Introduction

Physics is one of the earliest academic disciplines known – if you include observational astronomy, possibly the oldest. In physics we analyse the natural world to develop the best understanding we can of how the universe and its constituent parts interrelate. Our aim as physicists is to develop models that correspond to what is observed in the laboratory and beyond. These models come in many forms: some may be quantitative and based on mathematics; some may be qualitative and give a verbal description of the world around us. But, whatever form the models take, physicists must all agree on their validity before they can be accepted as part of our physical description of the universe.

Models used by physicists are linked by a coherent set of principles known as concepts. These are over-arching ideas that link the development of the subject not only within a particular physical topic (for example, forces in mechanics) but also between topics (for example, the common mathematics that links radioactive decay and capacitor discharge). In studying physics, take every opportunity to understand a new concept when you meet it. When the concept occurs elsewhere your prior knowledge will make the later learning easier.

This book is designed to support your learning of physics within group 4 of the IB Diploma Programme. Like all the disciplines represented in this subject group it has a thorough basis in the facts and concepts of science, but it also draws out the nature of science. This is to give you a better understanding of what it means to be a scientist, so that you can, for example, identify shortcomings in scientific topics presented to you in the media or elsewhere. Not everyone taking IB Physics will want to go on to be a physicist or engineer, but all citizens need to have an awareness of the importance of science in modern society.

The structure of this book needs an explanation; all of the topics include the following elements:

Understanding

The specifics of the content requirements for each sub-topic are covered in detail. Concepts are presented in ways that will promote enduring understanding.

Investigate!

These sections describe practical work you can undertake. You may need to modify these experiments slightly to suit the apparatus in your school. These are a valuable opportunity to build the skills that are assessed in IA (see page 687).

Nature of science

These sections help you to develop your understanding by studying a specific illustrative example or learning about a significant experiment in the history of physics.

Here you can explore the methods of science and some of the knowledge issues that are associated with scientific endeavour. This is done using carefully selected examples, including research that led to paradigm shifts in our understanding of the natural world.

Theory of Knowledge

These short sections have articles on scientific questions that arise from Theory of knowledge. We encourage you draw on these examples of knowledge issues in your TOK essays. Of course, much of the material elsewhere in the book, particularly in the nature of science sections, can be used to prompt TOK discussions.

Worked example

These are step-by-step examples of how to answer questions or how to complete calculations. You should review them carefully, preferably after attempting the question yourself.

End -of-Topic Questions

At the end of each topic you will find a range of questions, including both past IB Physics exam questions and new questions. Answers can be found at www.oxfordsecondary.co.uk/ib-physics

Authors do not write in isolation. In particular, our ways of describing and explaining physics have been honed by the students we have been privileged to teach over the years, and by colleagues who have challenged our ways of thinking about the subject. Our thanks go to them all. More specifically, we thank Jean Godin for much sound advice during the preparation of this text. Any errors are, of course, our responsibility.

Last but in no sense least, we thank our wives, Adele and Brenda, for their full support during the preparation of this book. We could not have completed it without their understanding and enormous patience.

M Bowen-Jones
D Homer

1 MEASUREMENTS AND UNCERTAINTIES

Introduction

This topic is different from other topics in the course book. The content discussed here will be used in most aspects of your studies in physics. You will come across many aspects of this work in the context of other subject matter. Although you may wish to do so, you would not be expected to read this topic in one go, rather you would return to it as and when it is relevant.

1.1 Measurements in physics

Understanding

- Fundamental and derived SI units
- Scientific notation and metric multipliers
- Significant figures
- Orders of magnitude
- Estimation

Applications and skills

- Using SI units in the correct format for all required measurements, final answers to calculations and presentation of raw and processed data
- Using scientific notation and metric multipliers
- Quoting and comparing ratios, values, and approximations to the nearest order of magnitude
- Estimating quantities to an appropriate number of significant figures

Nature of science

In physics you will deal with the qualitative and the quantitative, that is, descriptions of phenomena using words and descriptions using numbers. When we use words we need to interpret the meaning and one person's interpretation will not necessarily be the same as another's. When we deal with numbers (or equations), providing we have learned the rules, there is no mistaking someone else's meaning. It is likely that some readers will be more comfortable with words than symbols and vice-versa. It is impossible to avoid either methodology on the IB Diploma course and you must learn to be careful with both your numbers and your words. In examinations you are likely to be penalized by writing contradictory statements or mathematically incorrect ones. At the outset of the course you should make sure that you understand the mathematical skills that will make you into a good physicist.

Quantities and units

Physicists deal with **physical quantities**, which are those things that are *measureable* such as mass, length, time, electrical current, etc. Quantities are related to one another by equations such as $\rho = \frac{m}{V}$ which is the symbolic form of saying that density is the ratio of the mass of an object to its volume. Note that the symbols in the equation are all written in italic (sloping) fonts – this is how we can be sure that the symbols represent quantities. Units are always written in Roman (upright) font because they sometimes share the same symbol with a quantity. So "*m*" represents the quantity "mass" but "m" represents the unit "metre". We will use this convention throughout the course book, and it is also the convention used by the IB.

Nature of science

The use of symbols

The use of Greek letters such as rho (ρ) is very common in physics. There are so many quantities that, even using the 52 Arabic letters (lower case and capitals), we soon run out of unique symbols. Sometimes symbols such as *d* and *x* have multiple uses, meaning that Greek letters have become just one way of trying to tie a symbol to a quantity uniquely. Of course, we must consider what happens when we run out of Greek letters too – we then use Russian ones from the Cyrillic alphabet.

Greek

Α	α	alpha	Ν	ν	nu
Β	β	beta	Ξ	ξ	ksi
Γ	γ	gamma	Ο	ο	omicron
Δ	δ	delta	Π	π	pi
Ε	ε	epsilon	Ρ	ρ	rho
Ζ	ζ	zeta	Σ	σ	sigma
Η	η	eta	Τ	τ	tau
Θ	θ	theta	Υ	υ	upsilon
Ι	ι	iota	Φ	φ	phi
Κ	κ	kappa	Χ	χ	chi
Λ	λ	lambda	Ψ	ψ	psi
Μ	μ	mu	Ω	ω	omega

Russian

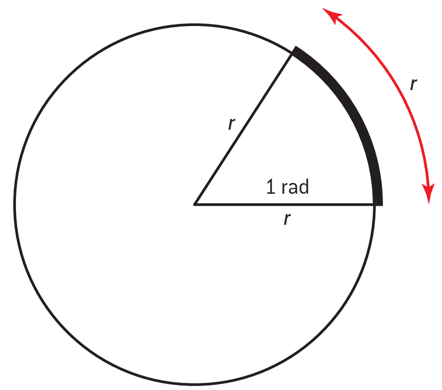
Аа Әә Бб Вв Гг Дд Ее
Жж Зз Ҙҙ Ии Йй Кк
Лл Мм Нн Ңң Оо Пп
Рр Сс Тт Уу Ўў Фф
Хх Цц Чч Шш Ыы
Юю Яя

Fundamental quantities are those quantities that are considered to be so basic that all other quantities need to be expressed in terms of them. In the density equation $\rho = \frac{m}{V}$ only mass is chosen to be fundamental (volume being the product of three lengths), density and volume are said to be **derived quantities**.

It is essential that all measurements made by one person are understood by others. To achieve this we use units that are understood to have unambiguous meaning. The worldwide standard for units is known as SI – *Système international d'unités*. This system has been developed from the metric system of units and means that, when values of scientific quantities are communicated between people, there should never be any confusion. The SI defines both units and prefixes – letters used to form decimal multiples or sub-multiples of the units. The units themselves are classified as being either fundamental (or *base*), derived, and supplementary.

There are only two supplementary units in SI and you will meet only one of these during the Diploma course, so we might as well mention them first. The two supplementary units are the radian (rad) – the unit of angular measurement and the steradian (sr) – the unit of "solid angle". The radian is a useful alternative to the degree and is defined as *the angle subtended by an arc of a circle having the same length as the radius*,

as shown in figure 1. We will look at the radian in more detail in Sub-topic 6.1. The steradian is the three-dimensional equivalent of the radian and uses the idea of mapping a circle on to the surface of a sphere.



▲ Figure 1 Definition of the radian.

Fundamental and derived units

In SI there are seven **fundamental units** and you will use six of these on the Diploma course (the seventh, the candela, is included here for completeness). The fundamental quantities are length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity. The units for these quantities have exact definitions and are precisely reproducible, given the right equipment. This means that any quantity can, in theory, be compared with the fundamental measurement to ensure that a measurement of that quantity is accurate. In practice, most measurements are made against more easily achieved standards so, for example, length will usually be compared with a standard metre rather than the distance travelled by light in a vacuum. You will not be expected to know the definitions of the fundamental quantities, but they are provided here to allow you to see just how precise they are.

metre (m): the length of the path travelled by light in a vacuum during a time interval of $\frac{1}{299\,792\,458}$ of a second.

kilogram (kg): mass equal to the mass of the international prototype of the kilogram kept at the Bureau International des Poids et Mesures at Sèvres, near Paris.

▲ Figure 2 The international prototype kilogram.

second (s): the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom.

ampere (A): that constant current which, if maintained in two straight parallel conductors of infinite length, negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newtons per metre of length.

kelvin (K): the fraction $\frac{1}{273.16}$ of the thermodynamic temperature of the triple point of water.

mole (mol): the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kg of carbon–12. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

candela (cd): the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of $\frac{1}{683}$ watt per steradian.

All quantities that are not fundamental are known as *derived* and these can always be expressed in terms of the fundamental quantities through a relevant equation. For example, speed is the rate of change of distance with respect to time or in equation form $v = \frac{\Delta s}{\Delta t}$ (where Δs means the change in distance and Δt means the change in time). As both distance (and length) and time are fundamental quantities, speed is a derived quantity.

TOK

Deciding on what is fundamental

Who has made the decision that the fundamental quantities are those of mass, length, time, electrical current, temperature, luminous intensity, and amount of substance? In an alternative universe it may be that the fundamental quantities are based on force, volume, frequency, potential difference, specific heat capacity, and brightness. Would that be a drawback or would it have meant that "humanity" would have progressed at a faster rate?

Note

If you are reading this at the start of the course, it may seem that there are so many things that you might not know; but, take heart, "Rome was not built in a day" and soon much will come as second nature. When we write units as $m\,s^{-1}$ and $m\,s^{-2}$ it is a more effective and preferable way to writing what you may have written in the past as m/s and m/s^2; both forms are still read as "metres per second" and "metres per second squared."

The units used for fundamental quantities are unsurprisingly known as fundamental units and those for derived quantities are known as derived units. It is a straightforward approach to be able to express the unit of any quantity in terms of its fundamental units, provided you know the equation relating the quantities. Nineteen fundamental quantities have their own unit but it is also valid, if cumbersome, to express this in terms of fundamental units. For example, the SI unit of pressure is the pascal (Pa), which is expressed in fundamental units as $m^{-1}\,kg\,s^{-2}$.

Nature of science

Capitals or lower case?

Notice that when we write the unit newton in full, we use a lower case n but we use a capital N for the symbol for the unit – unfortunately some word processors have default setting to correct this so take care! All units written in full should start with a lower case letter, but those that have been derived in honour of a scientist will have a symbol that is a capital letter. In this way there is no confusion between the scientist and the unit: "Newton" refers to Sir Isaac Newton but "newton" means the unit. Sometimes units are abbreviations of the scientist's surname, so amp (which is a shortened form of ampère anyway) is named after Ampère, the volt after Volta, the farad, Faraday, etc.

▲ Figure 3 Choosing fundamental units in an alternative universe.

Example of how to relate fundamental and derived units

The unit of force is the newton (N). This is a derived unit and can be expressed in terms of fundamental units as kg m s^{-2}. The reason for this is that force can be defined as being the product of mass and acceleration or $F = ma$. Mass is a fundamental quantity but acceleration is not. Acceleration is the rate of change of velocity or $a = \frac{\Delta v}{\Delta t}$ where Δv represents the change in velocity and Δt the change in time. Although time is a fundamental quantity, velocity is not so we need to take another step in defining velocity in fundamental quantities. Velocity is the rate of change of displacement (a quantity that we will discuss later in the topic but, for now, it simply means distance in a given direction). So the equation for velocity is $v = \frac{\Delta s}{\Delta t}$ with Δs being the change in displacement and Δt again being the change in time. Displacement (a length) and time are both fundamental, so we are now in a position to put N into fundamental units. The unit of velocity is $m\,s^{-1}$ and these are already fundamental – there is no shortened form of this. The units of acceleration will therefore be those of velocity divided by time and so will be $\frac{m\,s^{-1}}{s}$ which is written as $m\,s^{-2}$. So the unit of force will be the unit of mass multiplied by the unit of acceleration and, therefore, be $kg\,m\,s^{-2}$. This is such a common unit that it has its own name, the newton, ($N \equiv kg\,m\,s^{-2}$ – a mathematical way of expressing that the two units are identical). So if you are in an examination and forget the unit of force you could always write $kg\,m\,s^{-2}$ (if you have time to work it out!).

Significant figures

Calculators usually give you many digits in an answer. How do you decide how many digits to write down for the final answer?

Scientists use a method of rounding to a certain number of significant figures (often abbreviated to s.f.). "Significant" here means meaningful.

Consider the number 84 072, the 8 is the most significant digit, because it tells us that the number is eighty thousand and something. The 4 is the next most significant telling us that there are also four thousand and something. Even though it is a zero, the next digit, the 0, is the third most significant digit here.

When we face a decimal number such as 0.00245, the 2 is the most significant digit because it tells us that the number is two thousandth and something. The 4 is the next most significant, showing that there are four ten thousandths and something.

If we wish to express this number to two significant figures we need to round the number from three to two digits. If the last number had been 0.00244 we would have rounded down to 0.0024 and if it had been 0.00246 we would have rounded up to 0.0025. However, it is a 5 so what do we do? In this case there is equal justification for rounding up and down, so all you really need to be is consistent with your choice for a set of figures – you can choose to round up or down. Often you will have further digits to help you, so if the number had been 0.002451 and you wanted it rounded to two significant figures it would be rounded up to 0.0025.

Some rules for using significant figures

- A digit that is not a zero will always be significant – 345 is three significant figures (3 s.f.).
- Zeros that occur sandwiched between non-zero digits are always significant – 3405 (4 s.f.); 10.3405 (6 s.f.).
- Non-sandwiched zeros that occur to the left of a non-zero digit are not significant – 0.345 (3 s.f); 0.034 (2 s.f.).
- Zeros that occur to the right of the decimal point are significant, provided that they are to the right of a non-zero digit – 1.034 (4 s.f.); 1.00 (3 s.f.); 0.34500 (5 s.f.); 0.003 (1 s.f.).
- When there is no decimal point, trailing zeros are not significant (to make them significant there needs to be a decimal point) – 400 (1 s.f.); 400. (3 s.f.) – but this is rarely written.

Scientific notation

One of the fascinations for physicists is dealing with the very large (e.g. the universe) and the very small (e.g. electrons). Many physical constants (quantities that do not change) are also very large or very small. This presents a problem: how can writing many digits be avoided? The answer is to use scientific notation.

The speed of light has a value of 299 792 458 $\mathrm{m\,s^{-1}}$. This can be rounded to three significant figures as 300 000 000 $\mathrm{m\,s^{-1}}$. There are a lot of zeros in this and it would be easy to miss one out or add another. In scientific notation this number is written as $3.00 \times 10^8\ \mathrm{m\ s^{-1}}$ (to three significant figures).

Let us analyse writing another large number in scientific notation. The mass of the Sun to four significant figures is 1 989 000 000 000 000 000 000 000 000 000 kg (that is 1989 and twenty-seven zeros). To convert