The Association for Science Education

Teaching Secondary Physics

Third Edition

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Contents

1 The principles behind secondary physics teaching

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This book is one of a series of three Association for Science Education (ASE) handbooks, the others being parallel volumes in chemistry and biology. The 1st edition of this book was published in 1999, over 20 years ago, the 2nd edition in 2011, almost a decade ago. This 3rd edition has been substantially revised and brought up to date.

The author team has kept in mind a secondary teacher confronted with the task of teaching a specific topic, for example forces, and the plans and preparation they need to do. What does such a teacher need to produce a series of effective lessons that will also engage learners, and both enhance and sustain their curiosity? Some teachers will approach this task with an excellent understanding of the topic. However, we have kept in mind that not all teachers of secondary physics have a degree in the subject and that, even if they do, very few degrees cover all of secondary physics. We hope that all teachers of secondary physics, even if they have been teaching the subject for some time, will find much of value in here.

In this book, our aim is to encourage and support teachers to use approaches that convey the essential features of physics and the nature of science. This is important so that students learn not just the content of physics, but also what physics is and how it relates to their world. As such, this chapter reflects on the discipline of physics and approaches to teaching that enable students to engage in that discipline and build an identity that connects them to physics. Our hope is that considering the nature of physics, and teaching it, will also support teachers in reflecting on and developing their own identities as teachers of physics, whatever their background.

In the chapters that follow we will look at some of the main topics covered in the study of physics: forces, electricity and magnetism, energy, matter, atomic physics, waves and the Earth in space. In each of these chapters the author team will cover the content that we feel will be useful for a teacher to plan a series of effective lessons in that topic, highlighting specific examples of the ideas and thinking that will help develop and strengthen understanding of physics.

1.1 What is physics?

Physics develops and provides deep and satisfying explanations of phenomena; often those explanations will be based on what the world is made of and how those constituents behave. Furthermore, these explanations will be built on consistent and well tested relationships between identified and carefully defined quantities. As a discipline, physics is concerned with the smallest things we can conceive, and the largest, and everything in between; from the behaviour of individual electrons to galaxies containing millions of stars, not to mention the nature of time and even how social networks develop. This is one reason why it is helpful to frame physics around the development of explanations, to provide coherence to all these areas of physics.

The enormous scope of what physics tries to do presents challenges around how to 'see' complex and sometimes abstract ideas. To help, physicists often use models as ways to make particular aspects of what they are studying easier for them and others to conceptualise and communicate. As such, the use of models is a central part of the study and development of physics. Models in physics can have descriptive, explanatory and often predictive power; they are useful abstractions about an aspect of the world that can be elegant and that help us understand how and why phenomena happen. The kinds of models we consider in physics are incredibly diverse: they include simple linguistic analogies that could be spoken or written (such as 'a force is a push or a pull') to more sophisticated narrative explanations such as describing the formation of a star in terms of a balance of gravitational and nuclear forces. Other models include various representations such as schematics, diagrams, animations and graphs, as well as physical and computational models, often involving mathematics. In every case the model will have value for the physicist. For a magnet sitting on a table, we cannot 'see' field lines that come out of it but imagining these helps us describe what would happen if another magnet was brought near it. Equally, when considering the design of an aeroplane wing, a complex computational model of air flow can help optimise the design of the wing shape, so that it will generate the upwards force on the bottom of the wing needed to lift the plane.

Another strength of physics is how models of one phenomenon can be applied to other situations. For example, a model that provides an explanation of waves can be used in considering light, radio communications, earthquakes and waves in the ocean. At an advanced level, waves are also important in understanding electron orbitals and quantum phenomena. Models in physics can go beyond the description of a single phenomenon in one context to the same phenomena in other contexts and sometimes (but not always) different phenomena altogether. Models in physics can have a 'generalisable' nature but we must also recognise the limitations of all models in perfectly describing aspects of the world. Models in physics also have the power to link different scales of analysis, often microscopic and macroscopic. For example, a sub-atomic account of electrons helps us understand the current in a circuit and the phenomenon of electricity, and this can be developed further to include electromagnetism. An explanation of gravitation helps us to understand both why a ball falls to the Earth and how stars are formed.

However, the use of models is only part of the nature of physics as a discipline and it is true that biology and chemistry also use and develop models that link phenomena and scales: think of DNA and phenotypes, or atomic structure and elements. We suggest that it can be problematic to present students with hard distinctions between the traditional school sciences of biology, physics and chemistry, and that this doesn't reflect the work of professional scientists anyway, in which collaboration among specialists is common practice. Physics is frequently described as 'abstract' and this is often given as a reason why some find studying it hard. It is true that physicists attempt to reduce the details of a situation to describe fundamental processes and relationships. This is because physics has been successful in finding a way to describe natural phenomena with a small number of formulae that describe the relationship between physical quantities ('universal laws') and that can be applied in multiple situations.

The way in which mathematical formulae are used in physics is a key aspect of the discipline: relationships and equations are at the heart of many areas of physics. We hope you agree that this in itself is appealing: the elegance of being able to describe aspects of the Universe through simple mathematical relationships. Yet, appreciating the elegance of a mathematical relationship requires linking the mathematics to conceptual understanding; knowing the equation is a far cry from relating it to phenomena in the world and only once the mathematics is given meaning does it become elegant. This also links back to the need for recognising the limitation of models. A mathematical formula might describe a relationship that appears to hold anywhere in the Universe, but bringing this to bear on a particular situation requires an understanding of those particulars, knowing when the model is not sufficient and whether it needs to be refined or superseded by a different one.

It can be easy to see the formulae that students need as a list that just has to be memorised and recalled in an exam. It would be a shame to simply commit these equations to memory rather than use them to develop and strengthen understanding. In many cases they describe how nature works, giving order to the Universe and identifying what causes things to happen. Ohm's law can help us to calculate a current, but knowing that current will flow *because* there is a difference in potential across a conductor is part of conceptual understanding contained in that equation. We can convert mass to weight by multiplying it by 10, but realising that near the surface of the Earth an object will fall *because* its mass is attracted towards the centre of the Earth is more important as this is something that happens with all objects.

In physics, things happen for a reason and events occur as a result of the previous situation. Physicists attempt to break down events in order to understand causal chains, although these can be complex. In this way, physicists are concerned with exploring what has happened and why, often using derived ideas to make further predictions about the future.

In summary, physics provides descriptions and explanations of phenomena and helps scientists make predictions. It does so through models that can take many forms, but are often abstractions which try to get at the mechanisms that link different scales of phenomena, and different phenomena. As well as being beautiful and refined, the power in these models is that they are often generalisable and can be applied to multiple contexts and situations. Many of the fundamental equations of physics provide elegant ways to understand the world on whichever scale you choose to look at it, from the level of an atom to a galaxy.

1.2 Doing physics

Characterising physics as a domain is part of showing young people what role physics may play in their lives and how it can help them understand how the world around them works. Another aspect of this is painting a picture of what it means to do physics. This is not to assume that all students should aspire to become professional physicists, but many careers, hobbies and interests involve 'doing physics'. Watching the International Space Station pass overhead with a pair of binoculars and working out how fast it is travelling, considering how a higher temperature might cook the outside of a cake more, working out the most stable position when riding a horse or how best to scale a climbing wall and keep your balance all involve some understanding and use of the laws of physics. As teachers we should look to find and highlight these connections in students' everyday lives whenever we can, and build from these an appreciation of what professional physicists do, but also that many aspects of life involve 'doing physics'.

Because physics is about elegant and often abstract models that are generalisable, then it is perhaps understandable that it might be mistakenly considered to involve a set of fixed truths. The language of physics may not help here. For example, instead of using the term 'generalisable' we could have used 'universal', and rather than 'models' and 'fundamental equations', we might have focused on 'laws'. It is an often painted caricature that physicists are concerned with uncovering universal laws that describe the secrets of the Universe. Indeed, this is appealing to some young people and many physicists still talk in these terms. However, very few physicists still hold this view of the nature of physics.

A further confounding factor here is that school curricula still refer to the canon of classical physics for the most part, and might be seen to feature almost exclusively the academic triumphs of the dead, wealthy, white men who span history, from Galileo to Newton to Stephen Hawking. Doing physics was never really like this, and it certainly is not today. Helping your students to see the role that Jocelyn Bell Burnell played in discovering pulsars, or Lisa Meitner's research on atomic physics and radioactivity, or Shirley Ann Jackson's pioneering work in telecommunication or how Persian scientist Avicenna had developed ideas around motion hundreds of years before Newton demonstrates that physics is valued and done by all genders and ethnicities. Each of these physicists worked within a community and built on the ideas of others. We suggest that widening the appeal of physics involves giving students a sense of what it is really like to do physics.

If we are to contend that physics is about explanatory models therefore, it follows that teaching secondary physics should convey the nature of how models develop in physics and the processes involved in this. Physicists recognise that models change over time, and that models are often the answers to the specific questions asked in research. Part of physics is about the development, testing and modifying of ideas and models. Many of the ideas presented in school physics have been updated, and this involves more sophisticated models rather than the direct replacement of many theories. For example, we suggest that it is still incredibly important for students to learn about Newtonian physics and this forms a key part of Chapter 2 Forces. Nevertheless, we know that Einstein's theory of relativity and quantum mechanics can describe and explain aspects of the world that Newtonian physics cannot.

Physics changes over time because models are continually tested and revised. However, it is worth noting that many models are robust and have survived a great deal of testing over the years. At any one time, there are often competing theories to explain something, for example how the Moon was formed. What physicists (and other scientists) do is develop models that take into account the available evidence at that time and can then be used to make hypotheses that can be tested in the future. This often involves collaborations between scientists from multiple disciplines and backgrounds, with each of these categories containing a huge number of different specialisms (e.g. biophysicists, geophysicists, electrical engineers). The international collaborations around particle physics at CERN, the European Organization for Nuclear Research, or around space missions are examples of this, in which theoretical physicists who deal with abstractions work in collaboration with experimental physicists and engineers who have to build and operate the equipment to test the predictions and theories.

The scale of large projects can make it easy to forget that physics is used on smaller, more local scales. For example, a radiographer uses physics to provide images of the body, as does a dentist when taking X-rays. Engineering is very closely related to physics, although it also has its own characteristics as a range of disciplines with more emphasis on design, testing, creating objects and solving real-world problems. In many countries, including the UK, engineering is not a school subject in its own right at secondary level, so the role of physics in engineering is worthwhile highlighting to students and also looking for places where these connections could be made. For example, the study of force and extension of materials could be followed by an activity using glue guns and spaghetti to build the strongest structures or widest span bridges. When you can, try and include in your lessons information about the careers that might include physics, to strengthen the feeling that students see physics as 'for them' (organisations such as the Institute of Physics have resources and guidance to help here). Authors have included links to careers throughout the chapters in this book. Studying physics teaches critical and logical thinking, problem solving and understanding complex systems, skills that can make students highly successful in careers such as finance, software design, plumbing, being an electrician, product design, architecture, journalism and broadcasting, and in the armed forces, for example.

Many students you teach are unlikely to study physics after the age of 16 and so it's worthwhile highlighting the role that physics plays in their everyday lives to help them feel the subject is relevant and worth studying. Many of your students will be interested in the role that physics plays in new developments in technology, understanding sport or how rollercoasters work; using these everyday contexts allows students to understand and value physics. This is where there can be benefit in looking beyond the formal curriculum, even if you don't explore the detail. For example, analysis of vectors, momentum and friction will help describe the optimal path of a ten-pin bowling ball (the one that is likely to get a strike) and explain why a curved trajectory is likely to be more successful that a straight-line trajectory. GPS systems would not work without incorporating Einstein's theories of relativity and even the humble LED is a quantum physics device rather than just a direct replacement for the filament light bulb. Physics often leads to technological advances that permeate our lives: the internet and Wi-Fi, mobile phones, cameras, music production, ballpoint pens, seatbelts, solar panels and many other everyday technologies owe their existence to physics ideas.

There are also questions to which physics cannot yet provide an answer, such as what happened before the Big Bang, what happens inside a black hole or how gravity and quantum physics link together. The impact of physics on the world is not always positive though, and this needs to be explored too. Nuclear physics has provided an alternative to fossil fuels and helped us understand how the Universe was formed, but has also led to the development of atomic weapons and sometimes damage to our environment, such as the nuclear power plant disaster at Chernobyl. So looking at the impact of physics from a societal viewpoint is important and it might be useful to bring in aspects of debate and discussion around topical issues such as the pros and cons of cars, or the expansion of internet technologies or the choice and siting of alternative energy plants. There are questions that physics may never be able to answer though, and ethical and social questions can, at best, only be informed by physics. Not only does physics have a 'cutting edge', which shows students that the discipline is ever moving, but it also has 'permeable boundaries' requiring physicists to engage with broader social and ethical debates.

1.3 Learning physics

When learning physics, it is important that students don't just learn the conceptual ideas like a shopping list or song lyrics; we want them to see the physics all around them in their daily lives and see how studying physics can make the world seem more beautiful. As well as the laws, theories and experiments that help us and students to understand how the Universe works, one of the joys of teaching physics is that you can pick almost anything lying around and find a physics lesson in it or use it to show a physics principle. Air resistance can be taught with cupcake (muffin) cases, electrical resistance with a pencil line and the nature of transverse waves can be shown using cocktail sticks and jelly babies. One of the habits that physicists and physics teachers get into is that they start to see physics everywhere and relish asking questions, even if they don't know the answers. This inquisitive nature about how the world works and how we might be able to find answers is something that is worth trying to foster in class. The fact that asking the right questions can be as important as finding the answers means that we shouldn't worry too much if we don't know all the answers ourselves. We hope that your lessons can enable students to 'do' physics, as well as develop a sense that it is something that extends well beyond their classroom.

Like all worthwhile pursuits, the path to success isn't always easy and in this section we will highlight some of the common challenges that students (and their teachers) can face when learning physics. We will include some suggestions for how to deal with these in the classroom and the chapters that follow will provide more specific examples. The main areas we address here are:

- students' prior conceptions and how these may differ from the accepted scientific view
- the challenges of visualising and working with abstract ideas
- the role of language and multiple representations in the teaching and learning of physics
- the role of mathematics in the teaching and learning of physics.

In some areas of physics, for example in aspects of nuclear physics, pupils may not have strong preconceptions around how things work. However, often, students come to classrooms with their own ideas about how the world works, and sometimes these differ from the way that physics describes and explains the world. This can sometimes cause problems in the physics classroom as their experiences and interpretations may run counter to the scientifically accepted explanations. Most students will have seen heavier things fall faster than lighter ones, tell you that they cannot see anything moving inside wires and observe that it does not look like anything comes out of a remote control. As the ideas they hold have often emerged from their experiences of the world around them, just telling them that they are wrong and 'this is how the world works' is not necessarily the best teaching strategy.

Prior conceptions and how they may differ from the accepted scientific view

Part of being a good physics teacher is being aware of, and sympathetic to, the views and intuitions that students have about how the world works. Students need opportunities to make their ideas explicit, to encounter alternative ideas and to evaluate these ideas in relation to their own. Social interaction between teacher and students allows such processing of ideas, and rich dialogue also helps students engage with their own preconceptions by drawing on different funds of knowledge. When learners' prior ideas are very different to scientifically accepted knowledge, these ideas have classically been labelled as 'misconceptions', although many educators now prefer to refer to these as 'alternative conceptions', recognising that such ideas are simply learners' attempts to make sense of their world using common sense. It is difficult for students to give up their alternative conceptions, so lessons and learning activities need careful design.

Before teaching any topic, we strongly recommend that you explore the alternative conceptual ideas that students commonly hold in that topic. The book *Making Sense of Secondary Science* (see Resources at the end of this chapter) provides a comprehensive overview of many of the views that you may encounter, but other resources are available. In many physics topics, diagnostic assessment questions have been developed to help. These types of questions are tightly focused on a particular conceptual idea. They are often multiple choice with the incorrect responses representing common alternative conceptions that students have. The power of these questions is that they do more than just tell us who is right and who is wrong; we can get an idea of what an individual student is thinking. There are a number of online repositories of these types of questions (see Resources for links to the Institute of Physics, IOPSpark, and Best Evidence Science Teaching, BEST). The physics education research (PER) community has produced many of these, often referred to as concept inventories, many of which are hosted on the PhysPort site.

Having access to and using these types of questions can be a key part of planning and teaching and they can be powerful tools, not just at the start and end of a topic, but through using them in teaching to generate discussion activities. As well as knowing the 'right' answer, if we are forewarned of the most common conceptual problems, then we can adapt what we do in order to help to support students to move from their current thinking and towards accepted ideas in physics. Helping students realise that their ideas may be naive, by showing the differences between their own ideas and the evidence, is one approach to begin changing their ideas. For example, a teacher may ask students to make a prediction before a piece of practical work or simulation, based on their prior ideas. This makes those ideas explicit to the teacher, but also to the students themselves, and the data they collect may conflict with the students' initial ideas (White and Gunstone, 1993). Concept cartoons can help achieve the same aims, but through dialogue (Keogh and Naylor, 1999). A concept cartoon provides a picture of a scientific phenomenon, with different people giving inferences about or alternative explanations of that phenomenon. By inviting students to say what they think or decide how much they agree with various statements, and then justify their positions to each other, you can create dialogue that can help students to unpick their current understanding.

The challenges of visualising abstract ideas

The role that modelling plays in physics has been highlighted as a key one in the discipline. One of the reasons why it is also relevant at the school level is that much of what we ask students to study is based around abstract ideas. Concepts and ideas such as forces, magnetic fields, energy and atomic stability are not tangible in the way that an apple falling from a tree is and this can cause challenges for students. One of the reasons we use representations in these situations is to help us connect between the tangible world and the ideas and explanations that sit behind them, but it is important that we distinguish between reality and theory.

In the electricity chapter, the rope model is explored in detail and we hope a case is made for its value, but it's important to remember that there is not actually a rope inside the wires. This may seem like an obvious thing to say, but it can be easy to slip from the model: 'as I pull harder on the rope, it will move faster', into reality: 'the increased potential difference causes a greater flow of electrons' and back again, without highlighting this transition between model and reality. The difference is not always obvious to students. Physics teachers develop their own ways to present this difference, for example standing on one side of the room and saying '*I am in model world*' when discussing the model and then, when talking about the real world moving to the other side of the room, sharing '*I am now in the real world*'. This may seem a little over the top but, for the novice, the distinction is not always clear and so we need to signpost it as clearly as we can.

This provides one strategy to support students in helping them visualise some of the abstracted ideas they meet in physics. Others include the use of 'forces glasses' (see Chapter 2 Forces, Section 2.1 page 21) and marbles on ramps to appreciate potentials and nuclear scattering (see Chapter 6 Atomic physics, Section 6.1 page 173). The important thing for physics teachers to consider is that there is often a certain leap of imagination that we ask of students in lessons and we should consider what we ask of them and look for ways to help.

The role of language and multiple representations

Language presents a specific issue in physics education, because many of the terms used in physics in a very specific way are used in a different way in everyday life. Words like 'force' and 'energy' have everyday uses that are, in some way, connected to their correct use in physics, but sometimes not with the level of preciseness needed in physics. Sometimes physicists are criticised for being pedantic, but some words have very specific meanings and it is critical to use them appropriately to avoid confusion. For example, in Chapter 2 Forces we'll suggest ways to help students correctly use the terms 'speed', 'velocity', 'acceleration' and 'momentum', which are often conflated. Similarly, in Chapter 3 Electricity and magnetism, we'll explain how to help students be clear about the difference between 'current' and 'potential difference', and why it matters.

As well as the examples above, other technical words used in physics can cause problems and so it can help when introducing or using words in science to consider how and if students may have encountered them before. If one considers the words we use in physics, they may have a very specific technical meaning (for example, diffraction) or one that is more common (such as energy). Sometimes the common usage of the word can be close to the way it is used in physics (as in the case of repel), but sometimes the meaning is quite different (for example, field) and can cause problems. The ways in which mass/weight and speed/velocity are often used interchangeably in everyday life is also problematic. Providing clear definitions with examples and insisting on their correct use is an important part of teaching and learning physics well and in the individual chapters we will suggest ways to help students become fluent and confident in using the correct language.

As well as the precise use of technical terms, physics also has the tools to communicate details about the same situation in multiple ways, each having their own strengths and limitations. For example, a question about the acceleration of a bird in flight may be presented in multiple ways including:

- ➜ in words; 'a peregrine falcon, flying at 20 m/s accelerates to 80 m/s in 10 s'
- ➜ with a labelled photograph
- ➜ a diagram of the bird, with labelled force arrows
- ➜ a speed–time or velocity–time graph
- ➜ in equation form with symbol algebra or with numerical values $a = (v - u)/t$.

The expert physicist will find it easy to navigate fluently between each of these representations. However, students often find this a greater challenge. When working with students we suggest that you pay particular attention when moving between representations and emphasise that they are only one way of communicating the situation being considered. In some cases, it may be that questions can be successfully answered by using more than one representation and so consideration should be given to promoting more than one 'right way' of answering questions.

The role of mathematics

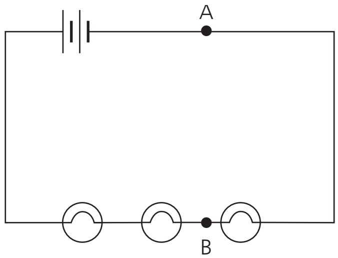
The critical role that mathematics has in the doing and learning of physics can sometimes send a message to students that much of physics is about using equations and doing calculations. While this is an important part of the subject in school, the difficulties that some students have with their mathematical skills can create a barrier for success in physics that needs some careful navigation.

There are three aspects of mathematics that commonly cause difficulties for learning physics, which you may wish to consider in your teaching:

- ➜ a balance between conceptual understanding and calculations
- ➜ algebra and memorising formulae
- ➜ drawing and interpreting graphs.

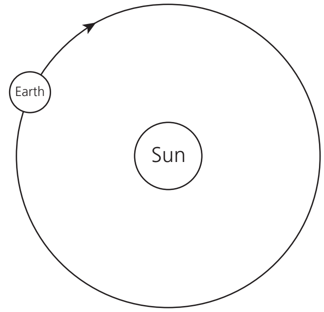
A balance between conceptual understanding and calculations

While formulae play a pivotal role in the teaching and learning of physics, they are used to describe the relationships between quantities in real-life situations rather than just representing numbers that need to be combined in some mathematical fashion. As such it's important not to lose sight of these concepts and slip into a 'plug-and-chug' mode in which students become skilled at getting the correct numerical answer while bypassing any consideration for what the numbers actually represent and the interrelationship between the variables. Fluency with the associated calculations is desirable, but we suggest that a stress on the conceptual understanding of the ideas needs to be highlighted in your teaching. Try and strike a balance between practice with the numerical questions and questions that will allow students to discuss their thinking and ideas. Physics *is* mathematical but if the focus is too much on the computational side of things, then the real meaning and heart of the discipline can be lost or obscured. Using questions that cannot be answered mathematically in small group discussions can provide an environment where students may be more confident in expressing their ideas and challenging each other's openly without the potential embarrassment of 'getting it wrong in front of the whole class'. There is a large collection available free online, called Next Time Questions and they can be a powerful resource for you to check your own understanding before any lesson.



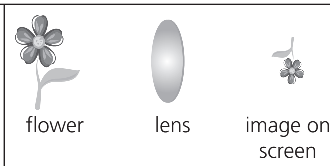
In this series circuit, three identical lamps are connected to a battery and they all light up. Without making any other changes, a wire is connected between points A and B.

- What happens to the brightness of each lamp?
- Does the current from the battery increase, decrease or stay the same?



The Earth is kept in orbit around the Sun by the gravitational attraction of the Sun on the Earth. If the mass of the Earth was to suddenly double:

- What would happen to the gravitational force on the Earth from the Sun?
- What would happen to the motion of the Earth?



A convex lens is used to make an image of a flower in a screen.
If the bottom half of the lens was covered, what would happen to the image?

Figure 1.1 Questions designed to promote conceptual thinking

Algebra and memorising formulae

As we have discussed, equations are powerful and elegant simplifications of how quantities in the Universe are related. Students can see letters in an equation represent missing numbers, but in most cases the letters represent quantities that are related. This is one of the reasons why always including units with measurements in physics is so important. Adding the unit is what transforms the numbers into quantities. As a teacher, always insisting on units is not about convention or exam marks, it is about giving these numbers meaning. Students may use an equation to find one particular answer but part of the power of equations in physics is that they are often generalisable: they do not just apply to the situation in question, but *all* situations.

The formula $\mathrm{KE} = \frac{1}{2}mv^2$ might be used by a student for a runner, but the same formula can work out the kinetic energy of a bicycle, an aeroplane or a meteorite.

It is a good habit when introducing new relationships to begin with a word equation so that you can talk about the relationship in conceptual terms. If you jump straight to the shortened, algebraic form, then the connection between the letters and symbols and the real world can be lost or weakened. Once the conceptual ideas and the relationships are established, you can then move on to mention the quantities, units, symbols and the equation that links them all together. We have included a table of all the quantities, units and symbols used in this book as an appendix.

Drawing and interpreting graphs

Students are likely to have had some experience of drawing and interpreting graphs from their primary education in mathematics and other science topics. Table 1.1 shows some of the common difficulties that students face relating to graph drawing in physics, with suggestions for how you might address them.

Table 1.1 Common difficulties related to graph drawing in physics

Difficulty	Suggestion
Students may be able to read data points on a graph, but it can be more challenging to interpret and explain relationships and trends in such points.	Developing narratives about the story that the graph might be telling can be a way to communicate that the graph is representing a relationship.
When asked to draw a graph, students can often find it quite challenging to select the scales needed on each axis.	Initially, you may wish to consider providing graphs with pre-drawn axes or providing different scales to choose from, to help them develop confidence in doing this.
Students can often omit the units on the labels of the axes. As with equations, these are as important as the quantity.	Always insist on these in graphs and, initially, you may want to provide pre-drawn scales, with units.
Their experience of drawing best-fit lines can be limited, and some may simply join the dots on a line graph. If students have to try and develop their procedural skills in graph drawing at the same time as learning new conceptual ideas in physics from the graph, that can be a large cognitive load.	Allocating time to support and develop a student's graph drawing skills using decontextualised or everyday data can be a good investment.
Some find language such as 'Draw a graph of a versus b' confusing, not being sure which variable goes on which axis.	Liaising with the maths department to find common language and being consistent in physics and, if possible, across the sciences can help here.
Many students struggle to correctly calculate the gradient of a line graph, even if they have done so successfully in maths.	Try to develop a consistent protocol for how you do this, making it easier for students to develop confidence and fluency.
Students do not always appreciate that the gradient of a graph and the area under it can be meaningful and allow them to work out extra information about the situation.	It is common for physics to deal with rates of change (e.g. velocity, power, current) and accumulations (e.g. displacement, gravitational potential energy) and so these may be ideas that you wish to introduce and regularly refer back to when using graphs.
Some students do not realise that calculated values for the gradient of a graph and the area under graph have units.	When calculating gradients or areas under graphs, include the units of each axis in the calculation to show that they are an important and relevant part of the calculation.

The Association for Science Education (ASE) publication *The Language of Mathematics in Science* provides much more detail about these and other issues with examples of best practice. It can also be really valuable in talking to your maths department and, when possible, developing common strategies or approaches.

Practical work

Physics is a practical subject, from the work of massive experimental facilities such as CERN and the Laser Interferometer Gravitational-Wave Observatory (LIGO) to students exploring the behaviour of a diode in a classroom. Practical work hugely enriches the understanding of students when done well and can be a powerful tool in helping students connect the ideas that physics is built on and the reality of what they can see, touch and measure in front of them.

For any practical activity, it is important to be clear about what you hope students will learn from it and, once this is established, you can then help steer the situation to support that learning. There will be a manipulative demand related to the use of the equipment, setting things up and taking precise measurements. There is also a procedural demand relating to the order in which things need to be done, the control of variables, and the processing and analysis of data. Finally, there will be a conceptual demand that is related to the physics ideas behind the experiment. Each demand can be important but it's worth being clear in your mind which is your primary focus in the practical work you choose to do.

If the focus is conceptual, then you may want to provide partly set-up equipment (for example, providing a set-up with a ruler and a spring attached to a weight holder on a clamp) so the student only has to add 'weights' and take measurements of the spring extension and can focus on the relationship between load and extension. In other cases, collecting accurate and reliable data may be your focus. As such, you will need to get the students to consider potential errors and how confident they are in their findings. Graph drawing and analysis is another core skill in physics and so, in some cases, you may provide exemplar data to allow enough time for the analysis. Like so many things in teaching there is rarely a clear 'right' or 'wrong' thing to do; what matters is that you are clear in your focus for the learning and steer the lesson that way, with consideration for the competing demands you place on students.

A useful way to consider the purpose of practical work in physics is to see it as a way to connect the domain of ideas with the domain of observables, helping students 'see' what might be abstract ideas in the ways in which objects behave and interact. When planning or evaluating the effectiveness of practical work, it can be easy to consider it as successful if the students do or see the things we want them to, rather than considering whether they actually connect the conceptual ideas to what they were observing. These ideas are explored in more depth by Robin Millar and Ian Abrahams in their paper 'Practical work: making it more effective' (see Resources at the end of this chapter). A simple but powerful phrase from that paper which can help us keep an eye on what matters is that effective practical work should be 'hands on and minds on'. Specific suggestions for how this approach can be applied to many of the common practicals carried out in secondary physics lessons can be found in the book *Enhancing Learning with Effective Practical Science 11–16* (See Resources at the end of this chapter).

You might also wish to develop an enquiry approach in your physics teaching so that students experience, to some extent, how research physicists work and how science knowledge is built and challenged through practical work. There is a range of enquiry activities developed through EU funding in recent years and these can be found on the Scientix website.

Using digital technologies

The development of new technologies has provided all kinds of tools to support teaching and learning in physics. Sensors and measurement devices that were once confined to research laboratories now sit in students' pockets. Most smartphones contain accelerometers, GPS, magnetic field sensors, compasses, light and sound meters from which you can take direct readings in the classroom. When studying earthquakes, the readings from accelerometers can help students to appreciate how a seismometer works and, at the same time, show them why vectors are important. Students can take their smartphones on theme park rides and measure the forces they experience; they can track their speed and acceleration on their journey to school and use high speed camera settings to capture things that happen in fractions of a second. Conversely, astronomy simulations can help them explore changes that happen over long periods of time in a few seconds and imagine 'what if' situations when exploring the orbital speeds and height of satellites. Spreadsheets can allow them to process large data sets into meaningful graphs almost instantly, such as the experiment in Chapter 6 Atomic physics in which a class of students use coins, sweets or dice to model half-life and draw a graph representing hundreds of random events.

Advances in technologies are often so rapid that any specific detail included here could easily be superseded, but there are some messages to draw out that will remain true. When possible, it is important to collect data to be analysed and explore relationships in physics lessons. Simulations and visualisation tools can help us to see the massive and the microscopic, play with relationships and vary things we could not do in a practical situation. However, they can build on, but not replace, real practical work.

1.4 Final thoughts

We hope that this chapter helps provide a foundational understanding of what physics is, what physicists do and some key issues to consider in your teaching. Hopefully we have made a strong case that physics is not just a collection of facts and equations, rather the study of how the Universe works and the connections within that. We have tried to lay out clear narratives around how physics describes, explains and predicts aspects of the world and how it uses a variety of different types of models to do this. We have also advocated that teachers develop a sense of what it means to 'do physics' within their students: showing how physics is relevant to everyday life, impacts society and provides skills which will help students in their careers and lives. Finally, we have given some guidance on the aspects of teaching physics which can be challenging, and what might be done to ease these challenges. In this introductory chapter therefore, we hope that we have stimulated thoughts about what it means to convey physics as a discipline. Readers may not agree with all the suggestions made here, and that is very much part of the developmental process in becoming a teacher of physics. Our aim is to support that development and give you confidence as physics teachers. In the chapters that follow, the authors further lay out their thinking on how to convey a particular area of physics to students, and what is important in doing so. We hope that readers will engage with these chapters critically also, as they develop their own ideas around teaching physics.

1.5 Resources

Online resources

Please go to ***spark.iop.org/asebook*** for a set of curated resources from the IOP Spark website to match this chapter.

The Best Evidence Science Teaching (BEST) from the University of York has many diagnostic questions, follow-up activities and detail on the progression of conceptual ideas in this and other topics: www.stem.org.uk

The Institute of Physics provides a comprehensive set of teacher support curated through their spark website: www.spark.iop.org

Next Time Questions are a set of conceptual thinking questions: www.arborsci.com

The PhysPort site features many resources and papers from the physics education research (PER) community: www.physPort.org

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Further reading

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2 Forces

James de Winter

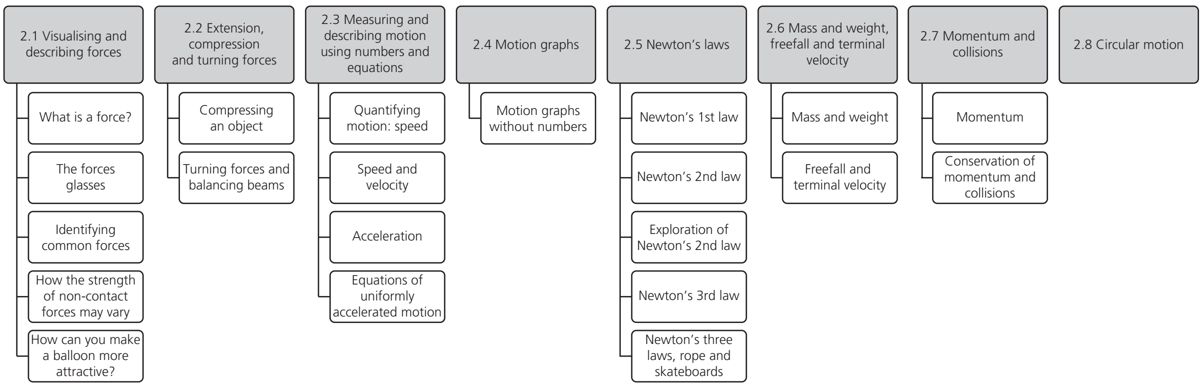
Introduction

One of the wonderful things about physics is how efficiently it can describe the Universe. With a few measurements and some rules that will fit on a postcard we are able to describe and predict the motion of most things on the planet and even travel to the Moon. This chapter looks at those measurements and rules and, while many situations can get complex, the underlying principles are accessible to all students in their study at this level. It starts with primary education experiences and then moves on to developing a sense of what forces are and how we can 'see' them, as well as understanding how forces can change the motion and shape of objects. It then looks at how we describe and quantify the motion of objects, paying particular attention to the terms 'speed', 'velocity' and 'acceleration', together with their associated equations and graphs which represent motion. Once these ideas are established, the chapter will look at how Newton's laws connect everything together. Other sections deal with how forces are linked to changing the shape of objects, freefall, momentum and circular motion. Examples are taken from many different contexts and you can reinforce the idea that forces and physics are everywhere and not confined to a single situation.

Teams designing the latest sports clothing to reduce air resistance, aeronautical engineers working on supersonic flight, medical physicists developing replacement body parts and many others who use physics in their everyday jobs will find the ideas that underpin this topic relevant and important in their work. From the forces between planets to those between atoms and everything in between, an understanding of how forces change the motion of an object is one of the most powerful ideas in physics that permeates our daily lives and hopefully we can communicate this to students.

A teaching sequence

It is unlikely that all of the ideas relating to forces and motion will be dealt with in a single set of lessons at secondary level. It is more likely that these topics will be returned to a number of times as students pass through their physics education. Rather than trying to provide a route that will tightly map to any particular curriculum or exam specification, the flowchart below shows a route through the whole topic in a sequence that is designed to build up ideas and concepts in a logical order that broadly increases in conceptual challenge as the chapter progresses. Topics such as momentum, circular motion and more detailed analyses of motion, such as freefall and terminal velocity, are usually studied by older students (14–16 years old) building on work covered in earlier years. The hope is that you can use this when planning for your specific context and classes.



Prior experiences

Forces are commonly studied during primary education and students will have had the experience of thinking about them in everyday situations. This work is likely to have begun in an exploratory or structured play situation, such as pulling, pushing, stretching or squashing objects or experimenting with floating and sinking, and dealing with contact and non-contact forces (such as weight and magnets). Although there is likely to be a limited formalised use of language, they may have talked about the 'heaviness' of things, how 'stretchy' a material is or how 'rough' or 'slippery' a surface is and connected forces to what happens. This might include exploring questions like 'How much force does it take to push the table across the floor?' or statements such as 'there is an upwards force making the boat float'. Students are likely to have had some experience of measuring forces directly with a simple force meter. In many cases the analysis of numerical data will be more comparative (e.g. the force to lift X was more than needed to lift Y), although it is likely that some students will have seen or presented experimental data graphically.

As many of their experiences will link pulling and pushing to movement, a direct connection between forces and motion is almost inevitable. Although initially helpful, this causes problems later on, particularly when students have to consider the forces on an object in equilibrium. Helping students appreciate that there may be multiple, but balanced, forces acting on stationary objects and those moving at a constant velocity is a significant challenge and this is addressed later in this chapter.

There are a number of alternative conceptions that students hold about forces and motion. Some of the ideas taught in this topic seem to be counter to intuitive understanding, such as the naive ideas that without air resistance, objects fall with the same speed towards the ground or need a force to make them carry on moving in a straight line at constant speed. Collections of these alternative conceptions from research are widely available, the book *Making Sense of Secondary Science* (Driver, Squires, Rushworth, and Wood-Robinson, 2014) is highly recommended. As we can only see the effect of forces and not the force itself, forces are difficult to visualise and so students may need help to do so. Strategies covered later in this chapter, such as the use of force arrows and 'forces glasses', are designed to help. Many examples and questions that students are given are simplified (for example, 'assume that there is no air resistance') and, while this can help, it can be a struggle for some to imagine the 'ideal' situation, such as one without friction.

Good quality diagnostic questions can be valuable in identifying what students already know or believe. Rather than traditional, generic questions, these are targeted at a particular, single conceptual idea. The questions are often multiple choice with the distractor answers representing common alternative conceptions, which allow teachers to identify if a student understands that idea but also if not, what they do think. The Best Evidence Science Teaching (BEST) and AAAS project 2061 and the *Concept Cartoons* books are particularly helpful here (see the end of this chapter for more details). This evidence about students' current ideas can then be used to inform what you do next for the whole class or on an individual level.

Science literacy

The correct use of language can create challenges for some teachers and students. In physics, we use words deliberately to express complex ideas efficiently and clearly. Examples are mass and weight; it is true that in everyday conversation these are interchangeable terms, but they have precise and different meanings that we need to use in the physics classroom, even if this may contradict what students hear elsewhere. A language teacher would not accept 'apple' to be an appropriate substitute for 'banana' on the grounds that they are both fruit. We should take our lead from them and, when it matters, insist on the correct language and take care to use it ourselves.

Teaching and learning challenges

In this topic, there are a number of common and persistent alternative conceptions that students can hold and which cause difficulties. In the rest of this chapter, we will try and provide sufficient background and activities to support you in addressing these alternative conceptions with your students. However, at this point it is perhaps worth identifying some of the most common conceptual challenges faced by students studying this topic.

- Students often think that if an object is moving then there must be a force acting to keep it in motion. For example, they might think that when you push or throw an object there must still be a force in the direction of motion once you let go.
- Students often think that moving objects will slow down and come to a stop by themselves without a force being needed.
- Students often conflate words that have similar meanings, not always realising the important differences between them. The most common ones are speed/velocity, distance/displacement, mass/weight and force/pressure.
- Students often think that acceleration means speeding up only, when in fact the term can also describe slowing down or changes in direction. This is particularly important when considering circular motion (covered later in the chapter).
- Students often think that all forces require objects to be in contact, not appreciating that some can act at a distance (for example, magnetic or electrostatic attraction and repulsion, gravitational attraction) and that the strength of these forces can vary with distance.

2.1 Visualising and describing forces

In physics, some quantities that we are interested in have a magnitude (size) and a direction, and these are called vectors, whereas other quantities only have a magnitude and they are called scalars. Examples of vectors are velocity, force and acceleration. Examples of scalars are speed, mass, temperature and time. Vectors are common in this topic and sometimes vector and scalar quantities are easily confused, such as velocity and speed. Although you may not wish to use the terms 'vector' and 'scalar' or differentiate between 'speed' and 'velocity' in early lessons on forces, appreciating that many quantities in this topic have size *and* direction and that both are significant pieces of information should be a consideration in your teaching.

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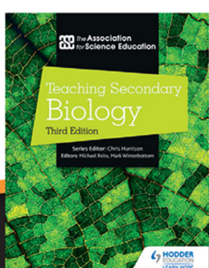

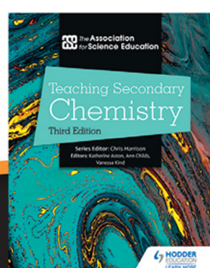

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