TEACHING PHYSICS

a guide for the non-specialist

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Contents

Preface

If you are a non-physicist and are faced with the prospect of teaching physics, whether as a subject on its own, or within some form of integrated science, you may well be feeling a little overwhelmed.

Don't panic!![1]

This book is a guide to the teaching of physics. It will show how existing science teaching skills can be effectively deployed to tackle such things as the intricacies of series and parallel circuits, and how to startle your students, and not yourself, with a Van de Graaff machine.

There are two ways of using this book: you can read it all the way through or you can use it as a dip-in resource to use while planning programmes of work and individual lessons.

A book of this length cannot hope and does not intend to deal with all the physics that you might ever need, so a selection of useful textbooks is listed in appendix 2. If you don't feel secure in your grasp of some idea that we describe, it would be helpful to have one of these textbooks alongside you.

Research[2] has shown that many teachers report the prospect of teaching physics more difficult and worrying than the actuality. This book is designed to provide assistance with common problems perceived by newcomers to the teaching of physics. It aims to provide some insight into strategies for explaining difficult topics and the likely problems and misconceptions that arise from pupils.

Finally, we are not sufficiently arrogant to propose this book as *the solution* to the teaching of physics. There is a well-organised support structure for most teachers, including heads of department, science advisers and advisory teachers, the Association for Science Education, and local Teachers' Centres to whom teachers should turn for help and assistance.

Acknowledgements

We would like to thank Dr John Harris for his many helpful comments on the original draft of this book; in addition, the Max Planck Society for many hours of fruitful discussion which have contributed to the ideas in this book.

1 With apologies to Douglas Adams.
2 Millar R. (1987) Teaching physics as a non-specialist – A survey of the views of teachers without formal physics qualifications. Department of Education, University of York.

Introduction

Difficult concepts in physics

Why is physics so difficult? The mere mention that you earn your living from teaching the subject is sufficient to lead to rapid changes in conversation. Generally, people do not wish to explore a topic which has unhappy associations. Anybody picking up this book may be haunted by similar vague feelings of uncertainty about some of the ideas they are attempting to teach. Part of the answer lies in the fact that physics deals in abstractions. These ideas and laws represent our understanding of physical reality. However, other subjects such as mathematics are even more abstract. At least in physics there is the advantage of being able to illustrate arguments and ideas by demonstration or experimentation with real and concrete examples. It would be foolish to pretend that the answers are simple or evident. This book attempts to provide an insight into some of the problems of teaching physics and to provide some tentative solutions to communicating the subject.

The mature physicist has evolved a framework of associative ideas by which he or she simplifies the subject to a relatively few fundamental ideas. It is the process of assimilation and simplification that is so difficult for many. Partly this is due to the fact that we have all been scientists from a young age and, as such, we have constructed models of reality that help us to solve problems and survive. Much physics teaching attempts to tell the pupil that their firmly held ideas are erroneous, and not surprisingly, these intuitive notions are extremely tenacious. For example, in a recent A-level physics exam, candidates were asked to give possible explanations as to why a 2p coin might take 7.6 s to fall down a well, while a 1p coin took 7.5 s. Despite the fact that all pupils are taught from the age of 14 that the gravitational acceleration of all objects is the same, a substantial number of candidates commented that 'This was surprising as the heavier coin should fall faster'.

Does this evidence point to some major failing of modern physics teaching? Probably not, since this notion which was enshrined by Aristotle, survived 1600 years till the time of Galileo who demonstrated, in the infamous experiment in 1590, that this was fallacious for objects with negligible air resistance. Such ideas are remarkably tenacious because a superficial observation supports the evidence that heavier things do fall faster. Despite the ease with which Galileo's experiment can be repeated in the laboratory, the majority of pupil's everyday experience reinforces Aristotelian ideas.

A substantial body of research work has now established that pupils develop their own intuitive understanding of the physical phenomena which they experience from an early age.[1] These understandings are referred to by a variety of terms in the research literature as 'misconceptions', 'alternative conceptions', 'alternative frameworks' and 'children's science'. In addition, work done by the Assessment of Performance Unit (APU) has begun to show that we are not very effective at teaching science.[2] Solomon[3,4] has shown that another reason is that the meaning that we attach to works in physics is not by any means the same as the meaning commonly attached to such words in everyday life. A typical example would be the statement by a pupil that

> 'I've got bags of energy'

Here the child views the possession of energy in egocentric terms. Energy is seen as something which is associated with animals and humans. Pupils find it hard to imagine how energy could be stored. The physicist's understanding of the word is that 'Energy is transferred when work is done' which holds a quite different meaning. Energy for the physicist is a wholly abstract quantity which is a measure of the capacity of a body to do work. It is not a fluid and has no concrete form. Another example of a clash of concepts is

> Pupil: 'We pay for the electricity we use.'

The pupil clearly sees electricity as a finite material available from sockets for which somebody must be reimbursed. Again there is some basis for this in experience when most appliances are seen as having only one wire coming from the plug. However in a formal introduction to electricity, a teacher of physics will seek to establish quantitatively, with ammeters, that the current entering a device is the same as that leaving it. Electricity is not something which is 'used up'. Electric charge is a means of transferring energy. All the electric charge which flows out of one terminal of a battery returns to the other. In the a.c. mains supply the electric charges merely oscillate about a fixed point and the average flow of charge is zero. What does get 'used' in the sense implied by the word is the available electrical energy.

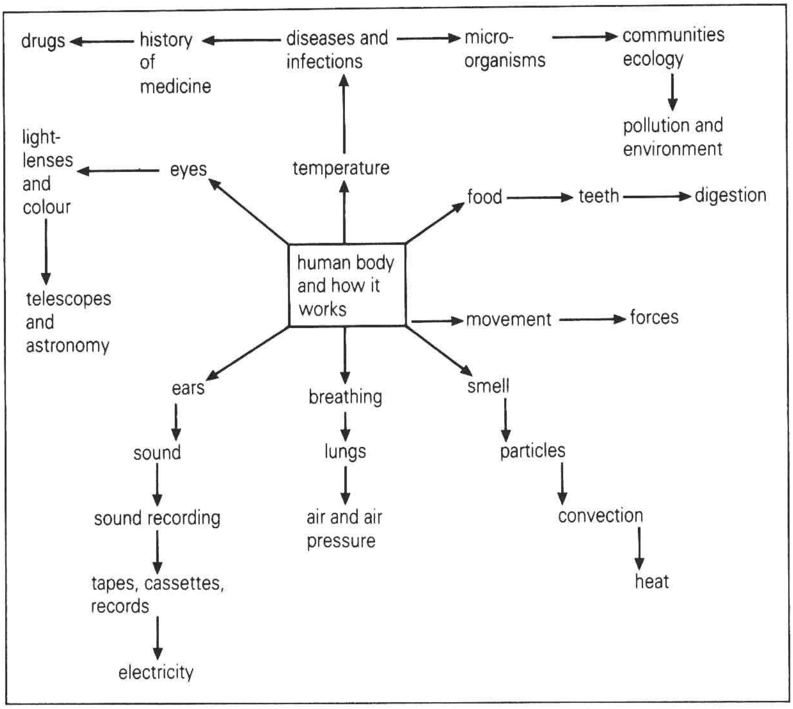
Claxton (1985)[5] has made the important point that pupils are quite capable of distinguishing science into three areas: 'gut science' which is the intuitive science used to estimate whether it is feasible to cross the road or not, 'lay science' which is the science gained from the media, comics and popular journalism and 'school science'. He argues that pupils seem to be quite capable of operating with three distinct conceptual realms between which they do not perceive a conflict. This does not make the life of the physics teacher any easier.

The purpose of this book is to outline some of the main difficulties likely to be experienced in the teaching of elementary physics and to suggest ways of approaching them. It is not the purpose of a book of this length to teach physics itself. A suitable list of books that will assist here is provided in appendix 2. We have chosen in this book to concentrate on the *concepts of physics* and the means by which we think they may be taught and learnt effectively. For non-physicists, who may be teaching physics for the first time as part of an integrated science course, these are often seen as the major area of difficulty. In a recent survey[6] of non-physicists teaching physics, two features of interest emerge. First, almost invariably fewer teachers reported difficulty when teaching a topic compared to the difficulty they anticipated beforehand. Secondly, the topics which gave the most difficulty were those that may have seemed simple because they are so fundamental, while topics that are more complex are in practice simpler to teach. For instance, voltage is the idea that most teachers reported difficulty in teaching while electronics which was predicted to be difficult turned out not to present too many problems.

A notable feature missing from this book is any emphasis on the 'processes' of physics, for example observing and hypothesising. These are important and it is impossible to teach content without process or vice versa[7]. It is perhaps ironic that in a decade when there is still considerable debate between different interpretations of the method of science, depending upon whether you agree with one philosopher or science or another[8], that the science teaching community seems to have decided that there is such a clearly defined thing as scientific method which can be clearly assimilated into the syllabus. What is perhaps a better statement is that scientists do engage in certain activities such as hypothesising, observing, classifying and testing, and that children in the laboratory should be provided with an opportunity to experience these activities if they are to gain a 'feel' for 'being a scientist'.

A style of teaching that relies heavily on demonstration and exposition does not encourage this. At its worst it presents physics as a well-defined body of knowledge with no potential for the new or unusual, ultimately giving the impression that 'physics is boring'. Unfortunately new teachers of the subject may be tempted to rely on this method since it provides a secure framework within which to explore the teaching of new content. However it is notable that experienced teachers of physics use a range of classroom activities consisting of practicals, demonstrations, home experiments, group discussions, games, computer software, videos and films to provide a range of different experiences and activities for children. Less-experienced teachers should be prepared to experiment with their methods a little to avoid a rather lifeless presentation and lots of suggestions are included in this book.

In future, physics will increasingly be taught as part of modular, integrated or coordinated science courses to meet the requirement for broad and balanced science courses. One of the effects of this is the need to give serious consideration to the methods of linking the separate subject disciplines. One such scheme devised by Barbara Smail[9] for lower school science courses which is based on the human body is shown in the figure.



Lower School science curriculum based on the human body

The advantage of this scheme is that the interest of girls and boys in the human body and their own selves provides a motivating context for teaching and learning. Such ideas deserve serious consideration, but ultimately the teaching of physics requires good, clear, lively and enthusiastic exposition using a variety of learning strategies. We hope that this book will provide some assistance to those searching for ideas.

Notes and references

1 Readers are referred to the following books and articles which are a good overview of this research.
Driver R., Guesne E. & Tiberghien A. (eds.) (1985) *Children's Ideas in Science.* Open University Press, Milton Keynes.
Osborne R. & Freyberg P. (1985) *Learning in Science.* Heinemann, London.
Gilbert J.K. & Watts D.M. (1983) 'Concepts, misconceptions and alternative conceptions: Changing perspectives in science education.' *Studies in Science Education,* **10**, 61–98.

2 The Assessment of Performance Unit (APU) has published four brief summary reports which give a detailed insight into the state of science education. These are

○ *Science at Age 11* 1984
○ *Science at Age 13* 1984

○*Science at Age 15* 1985
○*Electricity at Age 15* 1984
They are published by the Department of Education & Science and are available from HMSO, London.

3 Solomon J. (1982) 'How children learn about energy, or, Does the First Law come first?' *School Science Review* **63**, **224**, 415–22.

4 Solomon J. (1985) 'Energy for the citizen' in **Energy Matters** (eds. Driver R. & Millar R.). Centre for Studies in Science & Mathematics Education, Leeds University.

5 Claxton G.L. (1985) 'Teaching and acquiring scientific knowledge' in *Kelly in the Classrooms: Educational Aspects of Personal Construct Psychology*. Montreal, Cybersystems, Inc.

6 Millar R. (1987) *Teaching physics as a non-specialist. A survey of the views of teachers without formal physics qualifications*. Department of Education, University of York.

7 For a lengthy and interesting discussion of this issue, see the article 'Beyond processes' by Driver R. & Millar R. (1987) in *Studies in Science Education*, **14**, 32–62.

8 See Chalmers A. (1982) *What is This Thing Called Science?* (2nd ed.) Open University Press, for an interesting and readable account of many of the differences.

9 Smail B. (1984) *Girl-friendly Science: Avoiding Sex Bias in the Curriculum*. Longman Resources Unit, York.

1 Motion

Treatments of this topic generally start by introducing the concept of speed and velocity. Few pupils are aware of the difference between the two and speed is the word that they naturally use. Many of the more traditional introductions lack imagination and the topic often seems dry and abstract. Yet an understanding of the mechanics of movement is central to all physics, which is why the topic is introduced so early. So any initial treatment should point to the plethora of objects that move or are moving. It is well worth trying to arouse a sense of wonder with the world by starting from an astronomical perspective and posing the following questions.

> We live on a world that is round, yet we do not fall off. Many people used to believe the world was flat. Some still do. What evidence is there that it is round?
>
> We believe that the Earth is moving around the Sun but how do we know this? Before Copernicus, most people believed that the Earth was static, and the Sun moved around it.
>
> The Earth moves in a circular orbit and never slows down. Most objects in the world seem to travel in straight lines and slow down. Why is the Earth different?

The point of this is to pose some questions about motion and focus pupils' thinking. It is a good idea to give them the exercise of thinking out what their ideas are. Ask them to imagine that they are Newton and were beginning to write the *Principia*, Newton's great work. What rules of motion would they put in it?

A debate organised around the topic of flat Earth v. round Earth helps them to see that physics is a human activity where hypotheses are tested against the evidence. In everyday life we need to be able to measure how fast a car is going, the flow of blood through the heart and the speed of a runner. The development of modern science and technology started with a better understanding of force and motion based on the ideas of Galileo and Newton.

It is important to challenge long-cherished notions about the world. Most children's ideas are not explicit but intuitive. Using a brick and a small pebble, form the pupils into groups and ask the pupils to discuss which is going to get to the ground first when dropped from the same height. General experience reveals a substantial number who believe that the heavier object will arrive first. Try challenging the strength of this belief by gambling a bar of chocolate on the outcome! It is very unlikely that this will be a severe strain on your pocket!

The result does act as a powerful stimulus to experiment with other objects and to hypothesise as to why some objects do fall at the same rate, taking an equivalent time to reach the ground, and others do not. Pupils could be asked to devise an experiment that would test the effect of the air. The 'Guinea and Feather' experiment should be demonstrated if it has not been suggested by the pupils. This fascinating experiment can be further reinforced by showing a recording[1] of the experiment done on the Moon. The activity can be extended by asking pupils to investigate if an additional lateral motion makes any difference. Pupils are asked to throw one pebble sideways whilst simultaneously dropping another vertically.

Such experiments should lead the class through discussion to the idea that there is a need to be more objective and to measure the speed of the object. Teachers should be aware of the difference between velocity, which is a vector because it has speed *and* direction, and speed which is merely a scalar quantity because it only has size. The definition of velocity is

$$\text{velocity} = \frac{\text{change of displacement}}{\text{time}}$$

Displacement is a vector in that it represents distance travelled in a specific direction. Distance travelled, which is used in the definition of speed, is a scalar as it only has a magnitude which could be in any direction. Thus speed is defined by

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

Hence if the distance from London to Birmingham is 150 km and the time taken is 2 hours, then the speed is 75 km/hour. Such a statement says nothing about the direction and also reflects the fact that what is calculated is the average speed. The actual speed will vary considerably in those two hours. Far too often the following is observed

$$\text{velocity} = \frac{\text{distance}}{\text{time}}$$

The error may seem minor, but if language is used loosely by the teacher it is not surprising if the pupils fail to establish a clear understanding of these ideas. All disciplines are a way of knowing and one of the aims of the teacher is to introduce the pupils to the reserved language of the subjects, to attach meanings to words and to explore the excitement of new ways of seeing. Pupils invariably use speed, but as teachers we should attempt to be more rigorous with our vocabulary.

Most introductions lead to the measurement of speed. This is commonly introduced using the ticker timer. This noisy machine acts as a good exemplar of one of the problems of school science, that is the use of specialised pieces of apparatus that are not found elsewhere and that isolate the subject from the real world it purports to be exploring. This is where imagination must be demanded from children. They have jumped aboard Dr Who's Tardis and arrived in the 15th century. How would they attempt to measure the speed of the horse they are travelling on? Again this is best done as an activity in small groups where children discuss possible answers and then present their solutions. Small group work like this provides a chance for children to begin to use the language of physics which aids their understanding.

The teaching sequence can then move to the introduction of the ticker timer as the physics teacher's solution. Essentially it is an ingenious piece of apparatus that measures the distance travelled in successive small time intervals, for which there is no readily available, cheap substitute. At this stage it is necessary to issue a warning to those who would follow the standard treatment in many textbooks and introduce an approach that goes on to develop the equations of motion, *DON'T!*

Precise mathematical formulations of physics inevitably lead to rote learning, even amongst the brightest pupils. There is little chance that average pupils will then be able to relate abstract graphs to any form of qualitative experience they have and this is essentially what the ticker timer is good at doing. A qualitative treatment helps to focus on concepts and their association which is the prime aim of an introductory treatment. In addition, the recurring physics teachers' nightmare is likely to be experienced: that is the lack of any mathematical confidence in 13–14 year old pupils. It would be unfair to blame the maths teacher. The level of maths we expect is often quite sophisticated. Also it is important to realise that modern maths courses may approach equations in a different way to the formalism employed by most science teachers. Appendix 1 provides a fuller discussion of this.

A much better treatment is to combine the introduction to the subject with a substantial amount of practical work and demonstrations with a lot of discussion of the results and graphs. Graphs can be made of pupils walking, objects falling and running down inclined slopes. The statement 'Every picture tells a story' is one that is very applicable to graphs. They are records that provide information, and practice in their construction and interpretation is important if pupils are to build a sound understanding. This will take time. However, since much of this work is essential for later progress, it is pointless rushing on like a tourist doing a 10-day tour of Europe, seeing all and experiencing nothing. Later, it is important that children appreciate that the slope of a distance–time graph is a measure of the speed of an object while the area under a speed–time graph is equivalent to the distance travelled.

A preliminary introduction to the topic will have achieved a substantial amount if it has covered an understanding of speed, velocity and velocity–time graphs, Newton's First Law and the independence of gravitational acceleration from mass. From this most GCSE candidates will be expected to develop a knowledge and understanding of all Newton's laws, acceleration and momentum (this is now optional in many syllabuses), all of which have a number of differences.

Newton's Laws

The First Law

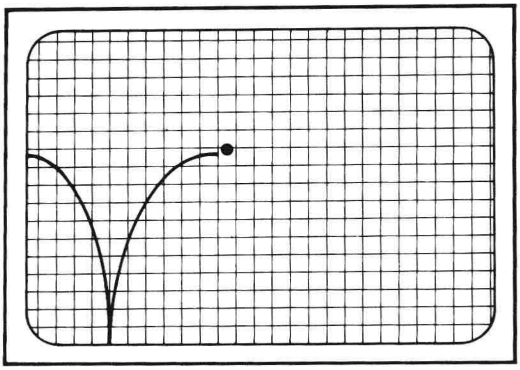
To many teachers this seems the simplest of all concepts in Newtonian mechanics. Yet in many ways it is the most difficult to accept. Gunstone & Watts (1986)[2] have reviewed the research findings and identified five intuitive rules that are commonly held by pupils:

- forces are to do with living things;
- constant motion requires constant force;
- the amount of motion is proportional to the amount of force;
- if a body is not moving there is no force on it;
- if a body is moving, there is a force acting on it in the direction of motion.

These are, of course, based on childrens' everyday perception of the world, but from the scientific viewpoint all are fallacious. Many of these can be described as Aristotelian concepts or are similar to Buridan's impetus theory which was that a moving object has an internal source of 'impetus' which it was given when first thrown or moved. A proper understanding of Newton's First Law challenges all these notions. These alternative concepts act as an obstacle to understanding. It would be presumptuous to believe that the superficial introduction to this found in many physics texts[3] will effectively dislodge these notions.

All that is commonly done in physics lessons to demonstrate our firmly held belief in Newton's First Law is to demonstrate the idea with carbon dioxide or air pucks on a glass table or to use a linear air track, both of which mimimise the effect of friction so that it is barely perceptible. Even so, neither of these demonstrations would really convince the normal sceptical audience of a group of 14 year olds. It is important to challenge pupils' views with more convincing evidence than this and make them realise that their intuitive ideas are not successful at explaining observations in a variety of situations. A useful stimulus for discussion is many of the videos that are available of motion in Space.[4] The question then should be posed as to why objects in Space keep going at constant velocity with no external force applied while those around us do not. Another example which can be used which is more likely to be part of the pupil's everyday experience is motion on an ice rink or on roller skates. This could be used to form the basis of a physics trip. There are also available several computer programs[5,6] that provide microworlds which allow the pupils to explore a Newtonian environment from the basis of a game. Papert[7] and di Sessa[8] have argued that such microworlds provide a dynamical environment that allows true heuristic discovery to take place. Figure 1.1 shows the screen from one of these. The pupil can apply thrusts in the horizontal and vertical directions, switch gravity and friction on and off independently and add a trace to illustrate the motion.

With the use of the structured materials accompanying them, such programs help to illustrate that the dynamics of objects on the surface of the Earth are affected by the presence of a gravitational field and friction. The program



1.1 Screen from computer program exploring Newton's laws

also comes with several microworlds where the rules governing the motion are not explicit and pupils are asked to explore and discover the rules governing the dynamics in these microworlds. There is no definitive evidence to point to the success of such materials as yet. However, it is quite clear that present methods are not succeeding and that new avenues need to be explored.

The Second Law

This is traditionally taught with two experiments that involve accelerating trolleys with elastics[9]. These are one set of experiments where it is essential to have the manufacturer's elastics. Substitutes tend to accelerate the trolleys and accompanying pupils to velocities where something dangerous happens to either the child or the equipment. The runways used in this experiment should be 'friction compensated' and, even then, do not expect to obtain results that clearly support Newton's Second Law. The apparatus is not sophisticated and there are many simple sources of error, such as the difficulty of maintaining a constant force and missing dots. However, summarising the class results in a table like table 1.1 on the board will allow wildly erroneous results to be discarded, and generally there are sufficient results to confirm the idea that *doubling the force, doubles the acceleration and tripling the force, triples the acceleration* (provided the mass is constant).

Table 1.1

Force (no. of elastics)	1	2	3
Acceleration (cm/tt^2)*	1.1	2.5	3.4
	1.5	2.2	3.7
	0.9	2.0	2.0
Average	1.16	2.23	3.33

*See appendix 3 on units

There is no point in doing this experiment, however, if it is merely being used to confirm theory, since it is not likely to be a great success and leaves pupils