How Much Should We Tell The Learners?
Some Reflections On Modelling In Physics Education

Colm O'Sullivan, Department of Physics, National University of Ireland Cork, Ireland (ctosull@ucc.ie).

Abstract

Traditionally physics teachers and textbook authors have tended to avoid telling students and readers very much about the fundamental role played by mathematical modelling in explaining physical phenomena. This paper argues that learning can be made easier if the teacher is more forthright about the nature and status of the underlying models. Care should be taken when using words like 'law' to describe a model/theory. Macroscopic models need to be clearly distinguished from microscopic ones. Ideas will be illustrated by reference to particular models encountered in school physics.

Introduction

> *La science est l'asymptote de la vérité. Elle approche sans cesse et ne touche jamais.*
>
> (Victor Hugo, *William Shakespeare*, 1864)

In its attempt to 'approach the truth', the most powerful tool available to the physicist is that of mathematical modelling which, in more recent years, has been enhanced by computational tools. The central role of mathematics in physics has been understood for at least four centuries.

> *Philosophy is written in this grand book. I mean the universe which stands continually open to our gaze. But it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics ……. without which it is humanly impossible to understand a single word of it; without [this] one is wandering about in a dark labyrinth.*
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> GALILEO GALILEI, ***The Assayer***, 1623.

No one needs to be reminded that Newton's development of differential calculus was primarily to provide him with the tools for the formulation of analytical dynamics. The extraordinary advances in man's understanding of the material universe since Newton's time have been strongly driven by mathematical modelling, a fact widely recognised by those who contributed to the developments.

> *The enormous usefulness of mathematics in the natural sciences is something bordering on the mysterious and there is no rational explanation for it...... The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve.*
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> EUGENE P. WIGNER, ***Communications in Pure and Applied Mathematics***, 1960.

Feynman has expressed these ideas in his own inimitable style.

> *Every one of our laws is a purely mathematical statement. Why? I have not the slightest idea. ..... It is impossible to explain honestly the beauties of the laws of nature in a way that people can feel, without their having some deep understanding of mathematics. I am sorry, but this seems to be the case.*
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> RICHARD P. FEYNMAN, ***The Character of Physical Law***, 1965.

Notwithstanding the central role of mathematical modelling in physics, teachers and textbook authors have tended to be rather reserved in communicating this to pupils and students. It is important to find ways of explaining to learners at all levels the importance of modelling as an indispensable tool in science and to be more forthcoming and explicit concerning the nature of the underlying model involved in each topic within introductory physics courses. These points were highlighted in a number of the plenary lectures at this conference, for example Mikelskis-Siefert (2006) and Lijnse (2006).

The use of the word 'law'

In the *Principia*, Newton enumerats the axioms of dynamics as Lex I, Lex II, etc. The term ‘laws of nature’ to describe the basic clockwork of the material universe is indeed effective. As physics developed, however, the term ‘law’ began to be used in a looser sense and these differences can be found to be confusing by beginner students. There appears to be at least four distinct categories in the use of the word ‘law’ in introductory physics texts and emphasis on such distinctions can lead to greater clarity.

1. *Fundamental ‘laws of nature’*

   For example,

   Newton’s laws of motion, Law of universal gravitation
   Second law of thermodynamics
   Coulomb’s law (Gauss’ law), Ampère’s law
   Planck/Einstein law
   …. etc.

2. *Equations of state*

   For example,

   ‘Ideal gas law’ $pV = nRT$
   ‘Ohm’s law’ $V = RI$
   ‘Curie law’ $\chi_m = C/T$
   Constitutive equations in electromagnetism such as $\boldsymbol{D} = \varepsilon\boldsymbol{E}$, $\boldsymbol{B} = \mu\boldsymbol{H}$
   …. etc.

3. *Phenomenological mathematical models*

   For example,

   ‘laws of friction’
   ‘laws of collisions’, i.e. a coefficient of restitution model (O’Sullivan, 2006)
   …. etc.

4. *Basic general principles*

   For example,
   ‘law of conservation of momentum’
   ‘law of conservation of energy’
   Archimedes’ principle
   …. etc.

In standard sequencing of material in most introductory physics courses, basic general principles like those listed are derived from other laws applied to specific contexts and are better entitled ‘Principle of conservation of momentum’, etc.

Macroscopic *versus* microscopic models

Another common source of confusion for beginning learners arises when clear distinction is not made between models which are intrinsically microscopic and those which are essentially of a macroscopic nature. A case in point is where electric circuit theory is taught from the perspective of current flow (an analogy with fluid motion) but is *simultaneously* interpreted in terms of localized current carriers (electrons, ions, charged particles, holes, etc.). Of course, the ‘fluid’ involved in electric current flow does not have all of the properties of real fluids, such as viscosity. Herrmann et al (2006), at this conference, have suggested the name ‘electronium’ for this substance.

In another paper at this conference, Konicek and Mechlova (2006) pointed out the difficulties that arise in making the transition from the simple fluid model to models that can describe phenomena observed in superconducting materials. This emphasizes the need for models to be ‘upward compatible' if easy transition of student learning between introductory and more advanced levels is to be facilitated. In the context of conduction in metals, therefore, it would seem prudent for students to be introduced in sequence to a hierarchy of appropriate models, for example,

fluid flow model → free electron gas mode → Drude model → quantum mechanical model

It is important that, at each transition between models, the limits of the model being replaced be pointed out explicitly to students and, where possible, the replaced model should be interpreted within the new framework.

A more troubling example of mixing of models involves the teaching of surface tension. Common misconceptions in this area were highlighted by Kazachkov (Moore et al, 2005) at the GIREP 2005 seminar in Ljubljana. The underlying model here envisages a liquid surface as a stretched membrane, the surface tension of the material being defined as the tensile force per unit length or, equivalently, as the surface energy per unit area. Sources of confusion arise if this treatment is supplemented by reference to cohesive and adhesive intermolecular forces which, while not incorrect, cannot be related to the surface tension quantity in any easy way.

A very useful model for explaining everyday phenomena to pupils learning about physics for the first time is that of magnetic poles (or point magnetic charges). Surprisingly, this model is often neglected in elementary textbooks despite the ease with which it can be used to explain a wide range of common phenomena involving permanent magnets, such as the magnetic compass. Reasons for this neglect probably include the facts (i) that free magnetic monopoles do not exist and (ii) that magnetic phenomena can be 'more realistically' explained in terms of electric current loop; neither of these reasons would seem to be a particularly convincing argument for avoidance of the model..

Dvorak (2006) has shown how the observed voltage induced in a coil arising from the rotation of a nearby bar magnet can be explained in detail by modelling the magnet as a rotating magnetic dipole with equal and opposite point charges (poles). An equivalent explanation based on a model involving microscopic current loops would prove much more daunting for students. Similarly, the behavior of a magnetic compass is much easier for beginners to understand in terms of forces on two equal and opposite poles as distinct from torques on a very large number of microscopic current loops.

There is one further advantage to the use of the magnetic pole model in introductory courses. The model happens to be a rare example of a case where it can be introduced and used effectively while, *within the same course*, can be shown to be superseded by a more sophisticated model. Thus the nature of and limits to scientific models can be brought home to student in a clear and instructive way.

Ockham's razor

Given the absolutely central role it plays in scientific practice, it is extraordinary that Ockham's Razor gets so little mention in textbooks. The usual Latin form of the aphorism, traditionally attributed to the 13th century scholastic William of Ockham

Entia non sunt multiplicanda praeter necessitatem,

which may be translated as 'A multiplicity of concepts is not to be proposed without necessity', was originally formulated in the 17th century by John Ponse of Cork (Thorburn, 1918). The concept, however, is very much older. The following statement is said (Garrett, 2000) to be a translation of a declaration by Ptolemy in the 2nd century, writing in the context of changes in the solstices and equinoxes.

> *It is a good principle to explain the phenomena by the simplest hypotheses possible, insofar as there is nothing in the observations to provide a significant objection to such a procedure.*

The injunction in the Razor to choose the simplest theory consistent with the observations is universally recognised as a central criterion for the acceptances of a scientific theory. By 'simplest' here is meant the avoidance of any redundant concepts or parameters. The postulation of quarks prior to the 1950s, for example, would clearly have been scientifically unacceptable.

It is precisely the constraint imposed by Ockham's Razor that distinguishes true science from para-science and other systems of thought purporting to explain the real world. For this reason alone, it is surely essential that all learners be made aware of its importance.

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