Developing Models in Science Education

Edited by

John K. Gilbert and Carolyn J. Boulter

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DEVELOPING MODELS IN SCIENCE EDUCATION

Preface

This book arises from the collaborative work of a group of international researchers who are members of the Centre for Models in Science and Technology: Research in Education (CMISTRE). Based at The University of Reading in the UK, the Centre has a widely scattered membership, i.e. currently also in Australia, Brazil, Israel, New Zealand, Netherlands. Information about its present work can be accessed via The University of Reading's web pages on http://www.rdg.ac.uk/~ems97pc/MISTRE.

Formed in 1995, the first years of the group were spent in formulating a common language with which to talk about models and modelling and in negotiating the boundaries of the areas to be investigated. In this period of time the main themes which are addressed in this book started to be formulated, based on the interests and experiences of the collaborating members. All this was fuelled by academic visits by members to each others, by regular seminars where new papers and ideas were discussed, in conference symposia, both national and international, where these ideas were subjected to a wider audience and, more lately, by publications in journals. In most senses the Centre is typical of a research group in any field: a commitment by a group of academics to enquiry in a theme held in common. It might differ from many in two ways. First, it draws on the insights of a number of established disciplines: philosophy of science, historical studies of the development of science, the sociology and language of science, the psychology of the teaching and learning of science. Second, it has entailed a greater commitment to collaborative ways of working and to a reflection on the contextual nature of the understandings that are forged. Within the Centre, smaller sets of members often collaborate in particular areas of interest and expertise. This has given rise to the three main areas of interest that are reflected in the Sections of this book.

Although the common language is presented in detail in Chapter 1, it may be helpful to readers if the components of the framework and the agenda are summarised here. A model has been taken to be 'a representation of an idea, object, event, process, or system'. Mental modelling is defined as an activity undertaken by individuals, whether alone or within a group. The results of that activity can be expressed in the public domain through action, speech, writing or other symbolic form. Those expressed models, as we term them, which gain social acceptance following testing by the community of professional scientists play a central role in the conduct of both research and development, becoming consensus models. Whilst those consensus models which are currently in use at the frontiers of science may be termed scientific models, those produced in specific historical contexts may be called historical models. Curricular models are those versions of consensus models which are included in science curricula. Teaching models are those developed to assist in the understanding of curricular models and hence the phenomena that they represent. Hybrid models are those formed for teaching purposes by merging the characteristics of several distinct consensus models in a field of enquiry. A model of pedagogy is that used by a teacher in the planning and provision of science education in classrooms and laboratories.

Mental, expressed, and consensus models play key roles in the conduct and dissemination of the outcomes of science and technology. Together with curricular, hybrid, and teaching models, they play key roles in the teaching and learning of science and technology. CMISTRE is thus concerned with a broad question:

> What parts do models play in the production, dissemination, understanding, and use of knowledge in science and technology?

This question is being addressed by exploring:

1. The ways in which individuals construct and use mental models.
2. The ways in which these models are presented as expressed models.
3. The processes by which expressed models gain social acceptance to become consensus models.
4. The relationships between the historical models in an area of enquiry.
5. The processes by which teaching models are developed and used to facilitate the understanding of consensus models.
6. The uses made of models of all types both in science and technology and in science education and technology education.
7. Models of the curriculum in science and technology education.
8. The development and use of models of pedagogy by teachers.

The components of this common language and agenda of enquiry are returned to throughout the book, notably in the Preface to each Section and in Chapter 18. The work on the nature of models and the roles that they play in science and technology and in science and technology education is represented in Section One, 'On the Nature and Significance of Models'. The important differences between mental models in the private domain and expressed models in the public domain determined the area of research collected together in Section Two, on 'The Development of Mental Models'. From the development of the theoretical base represented in these two Sections, the work has progressed into the practical task of investigating models and modelling in settings where teaching and learning are the focus. This forms the content of Section Three, 'Teaching and Learning Consensus Models'.

Chapter 18, the last in the book, looks at the challenges of the position that has now been reached and at the various practical projects which are in operation using the theoretical framework developed. It then looks into the future to describe the areas for possible future research both in the theory of models and in their practical expression in situations of teaching and learning.

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The writing and production of this book have involved many people who have given their time and expertise generously. As the Editors, we would like to thank all who have contributed to the text and to its proof reading. Above all, we would like to thank Mrs. Helen Apted who has put this book together, struggling with templates and pagination to produce the text that you see. She has done this with great calmness and presence of mind for which all the contributing authors are most grateful.

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Section One: On the Nature and Significance of Models

Preface

This Section is concerned with the importance of models in both science and technology and in science and technology education. In the first Chapter, the place of modelling in the process of scientific investigation and in the production of technological artefacts and processes is discussed, together with how they relate to an understanding of authentic education in these disciplines. The terminology that has developed within the group of researchers represented in this book is described, providing a framework for subsequent Chapters. The second Chapter analyses the ways in which three prominent philosophers (Kuhn, Nersessian, Bunge) have used modelling to explore the relationships between models, theories and their understandings of the nature of the world-as-experienced. The case is made for the key role that models have in forging links between reality as perceived and reality as idealised. These links have implications for how constructivism can be interpreted in science and technology education. The representation of models expressed in classroom settings, an important component of constructivism, forms the basis for the third Chapter, which puts forward a typology for these expressed models. The range of possible models is defined through their 'aspects' and 'modes' of representation. This typology opens the door to future avenues for research into teaching and learning with and about models in classrooms. The final Chapter of the Section takes up the idea of mode of representation and connects this to the enactive, iconic and symbolic modes of Bruner, concentrating upon mathematical models. This Chapter defines the special way in which mathematical models represent real and theoretical objects. It shows how the rules, which can be applied to a mathematical model, facilitate the production of particularly important predictions and hence form a key link between experimentation and the making of theory. A strong case for the development and teaching of mathematical models as a core component of scientific understanding closes the Section.

Chapter 1

Positioning Models in Science Education and in Design and Technology Education

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INTRODUCTION

The purpose of this Chapter is to establish the place of modelling and models in science education and in technology education (the U.K. terminology of 'design and technology education' is introduced and used during the Chapter). It is argued that both the processes and outcomes of science and of technology *per se* have a great deal in common. 'Authentic' educations in science and in technology must reflect the natures of the parent disciplines as far as is practicable. Modelling and models are common to both, thus providing a potential bridge between science education and technology education. The basic terminology of modelling and models used throughout this book is presented.

THE ROLE OF MODELLING IN SCIENTIFIC ENQUIRY

The central roles that modelling plays in the processes of scientific enquiry and that models play as the outcomes of that enquiry are well established (e.g. Giere, 1988). As a consequence, modelling and models should make major contributions to 'authentic' (Roth, 1995) science education. This book is, primarily, an exploration of that potential contribution, for it is not yet fully realised in the classroom and laboratory. However, there is a secondary purpose. Barnes (1982) has argued that there are considerable similarities between the processes and outcomes of science and of technology. This suggests that some commonalities ought to exist between science education and technology education. Modelling and models should be capable of

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forming a bridge between the two. This book is a first step in constructing such a bridge. Whilst the emphasis is on the role of modelling and models in science education, because much of the relevant research and development work so far has been done there, this Chapter makes the case for such a bridge whilst Chapters 7,14, and 18 explore some of the issues involved.

The essence of much of the thinking that underlies this book is reflected in the report *Beyond 2000: Science Education for the Future* (Millar and Osborne, 1999). A recommendation made is that:

> The science curriculum from 5 to 16 (years) should be seen primarily as a course to enhance general 'scientific literacy'. (para. 4.2)

It is suggested that one structural element of such a curriculum should be 'explanatory stories', which are:

> The heart of the cultural contribution of science ... a set of major ideas about the material world and how it behaves ... (presented in) one of the world's most powerful and persuasive ways of communicating ideas ... narrative form. It is these accounts ... which interest and engage pupils. (Para. 5 2.1)

It is also proposed that

> Work should be undertaken to explore how aspects of technology and the applications of science currently omitted could be incorporated within a science curriculum designed to enhance 'scientific literacy. (para. 5.2.3)

We intend to establish that the theme of 'modelling and models' is both a highly suitable basis for the construction for many 'explanatory stories' and that it can provide a valuable link between science and technology in education.

THE CONDUCT OF SCIENCE AND OF TECHNOLOGY

Educational provision under the labels of 'science' and 'technology' should be as 'authentic' as possible (Roth, 1995), that is they should be as faithful to the intellectual structures of the parent disciplines as possible. Syllabuses should reflect three things. First, the processes by which science and technology are conducted (their epistemologies). Second, the value systems underlying such activities, the situations in which and the purposes for which they take place (their contexts). Third, the entities with which they deal and which are their outcomes (their ontologies).

This reflection of epistemologies, contexts, and outcomes should be as accurate as is possible under the circumstances within which education is conducted. For 'authenticity' to be possible, there must be a reasonable prior understanding of them by both practitioners and educators. The natures of these processes and outcomes are discussed in the sections below. These are complicated matters: for example, only simplified versions of 'processes' (given below) are even partially acceptable to their practitioners.

The Nature of Technology as Process and as Outcome

Pacey (1983) has defined 'technology-practice' as:

> ... the application of scientific and other knowledge to practical tasks by ordered systems that involve people and organisations, living things and machines...

The 'practical tasks' most commonly addressed focus on the improvement of the physical conditions of human life (UNESCO,1983). Pacey's (1983) 'technology-practice' consists of three, simultaneously operational, elements: the technical aspect, the organisational aspect, and the cultural aspect. The technical aspect consists of:

> ... knowledge, skill and technique; tools, machines, chemicals, liveware; resources, products, wastes...

In short, it is the aggregate of human resources brought to bear on these 'practical tasks', the means by which these are deployed, and the material focus and outcomes of this deployment. The organisational aspect is:

> economic and industrial activity, professional activity, users and consumers, trade unions.

These are the social organisations in which technology as an activity takes place, together with those which support, in one way or another, the conduct of that activity. The cultural aspect consists of relevant:

> ... goals, values and ethical codes, belief in progress, awareness and creativity.

within which solutions to practical problems are both framed and evaluated. In respect of the core idea of 'values', Pacey (1983) notes that:

> ... the culture of technology comprehends at least two overlapping sets of values, the ones based on rational, materialistic, and economic goals, and the other concerned with the adventure of exploiting the frontiers of capability and pursuing virtuosity for its own sake (p.89)

Striking a balance between the influence of these two sets of values in technology education is very difficult. It will be manifest in the outcomes of technological activity, the technologies that are produced, the solutions to the practical tasks arrived at: objects (products, e.g. cars, clothes) and systems (processes, e.g. ways of making cars, clothes). What emerges from Pacey's (1983) ideas is that technological process consists of thoughtful actions by individuals taken within social contexts to produce solutions to problems which it is intended will be valued.

The Nature of Science as Process

Science is about finding explanations for natural phenomena in the world-as-experienced. The document *Science for All Americans* (Rutherford & Ahlgren, 1990) states that:

> Science presumes that the things and events in the universe occur in consistent patterns that are comprehensible through careful, systematic, study. (p.3)

Matthews (1994) has identified ten philosophical theses which inform the view of science-as-a-process in *Science for All Americans*. These may be summarised as follows:

(1) Realism. The material world exists independent of human experience and knowledge.
(2) Fallibilism. Although human knowledge of the world is imperfect, it is possible to make reliable comparisons between competing theories about the nature of the world.
(3) Durability. Science modifies the ideas that are produced about the world, rather than abandoning them if they are found to be inadequate.
(4) Rationalism. The validity of scientific arguments is tested, sooner or later, against the criteria of inference, demonstration, and common sense.

(5) Antimethodism. There is no fixed set of steps in a scientific enquiry, for knowledge involves an element of human creativity rather than emerging directly from experiment.
(6) Demarcation. Although there is no fixed method for scientific enquiry, it does involve a series of features which enable it to be distinguished from other, non-scientific, endeavours.
(7) Predictability. Successful science predicts observations which are then made.
(8) Objectivity. Although science is a human activity, it attempts to rise above subjective interests in the pursuit of truth.
(9) Moderate Externalism. The direction of scientific research is influenced by prevailing views on what questions are worth addressing, and what methods will prove productive.
(10) Ethics. Ethical considerations determine what topics are researched and arise in the actual conduct of research.

The outcomes of science are the broadly-conceived notion of 'scientific methodology', together with descriptions of how the material world behaves, ideas about the entities of which the world is believed to consist or with which it can be reliably analysed (concepts), proposals for how these entities are physically and temporarily related to each other in the material world (models), and general sets of reasons why these behaviours, concepts, and models can be thought to occur (theories). Science then consists of thoughtful actions by individuals within social contexts producing explanations of the natural world which it is hoped will be valued. The similarity of these overviews of science and technology suggests that there is a relationship between them.

The Relationship Between Science and Technology

The ways that science and technology relate, which cover both the processes involved and the outcomes achieved are undoubtedly complicated. It is possible to argue that the processes of technology first provide solutions to problems. Science afterwards explains the reasons for the success of these solutions. For example, steel was initially developed empirically as a way of producing harder iron, whilst the consequences for the structure of iron of the addition of small amounts of other elements, e.g. cobalt, were only explained long afterwards. It is possible also to argue that science precedes technology in time, such that technology is the application of science. For example, that enquiries into the sequences of amino acids within genetic material are leading to the rapid development of the industry of biotechnology.