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Towards a Curricular Model of the Nature of Science

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Abstract

The nature of science is a complex theme, and continues to be the subject of advanced and ongoing scholarship, drawing upon a range of disciplines. Therefore, whatever is presented in school science as being 'the' nature of science must at best be a simplification, and so there is a need to form judgements about which simplifications are most appropriate. Effective 'curricular models' of science concepts are designed simplifications of scientific models that guide teachers by indicating target knowledge that is deemed appropriate in terms of the prior learning and conceptual development of a group of learners, and which is both 'intellectually honest' and a suitable basis for further learning. A similar approach can guide teaching about the nature of science. A consideration of the English National Curriculum offers an example of how aims relating to the teaching of the nature of science may not be realised in the absence of a suitable explicit curricular model to guide teaching.

Key terms:

nature of science in school science; curricular models; target knowledge; optimum level of simplification; models: scientific-curricular-teaching

Transforming knowledge through science teaching

Intentionally or otherwise, school science teaching presents an image of the nature of science (Millar, 1989). Students will come to views about what science is about, and how it takes place, that are influenced by the way science is presented in their science classes. The argument in this paper is that effective teaching about the nature of science does not only involve teachers themselves having well developed knowledge and understanding of the nature of science, but also depends upon managing how knowledge is transformed in teaching and learning. It is well accepted that significant meaningful knowledge cannot be transmitted directly from teacher to student, but rather that learning is a process of reconstruction of knowledge (*e.g.*, Bransford, Brown, & Cocking, 2000; Taber, 2000a), that can be more or less effectively 'scaffolded' by teaching (Driver, Asoko, Leach, Mortimer & Scott, 1994).

In this paper the transformation of scientific knowledge into student learning is modelled in terms of a series of discrete steps involving the learning about (*i.e.*, forming mental models of) publicly expressed models; then reconceptualising those models to make them fit for a new purpose; followed by the 'publication' of personal understanding through representation as new expressed models. This process involves both deliberate and unintentional modifications (*i.e.,* reconstructions) of the original knowledge.

This paper presents an argument that research into teaching about scientific content is allowing science educators to make explicit, and to evaluate, the nature of the 'curricular models' that act as proxies for scientific models, *i.e.*, as the 'target' knowledge in science teaching. It is agued that the same type of analysis is needed when considering teaching about the nature of science: *i.e.*, that scholarship in science education needs to inform designed curricular models so that they derive from careful planning that incorporates consideration of how to teach and assess learning outcomes specified in curriculum aims and objectives. There is now a considerable body of research exploring aspects of teaching and learning about the nature of science, which can inform the design of curricular models. The case of teaching about the nature of science under the English National Curriculum (1991-2006) is discussed to show how, in the absence of designed curricular models, laudable curriculum goals may not be sufficient to ensure the intended teaching and learning.

The nature of science in school science

Science education may be considered to have a number of facets. These include teaching science concepts; developing students' attitudes towards science; giving instruction in practical skills; providing a context for teaching thinking skills, or a means for preparing citizens for adult life in technologically advanced democracies (*e.g.*, Ziman, 1980; Roberts, 1988; Bybee & DeBoer, 1994; Parkinson, 1994; Turner, 2000). One aim of science education, which has been the focus of increasing attention in recent years, is that of teaching students about the nature of science itself (*e.g.*, Duschl, 2000; Turner, 2000; Parkinson, 2004). This has been a theme of key literature (*e.g.*, Matthews, 1994), and is reflected in national curriculum documents, such as those in New Zealand (MoE, 1993), the UK (*e.g.* DfEE/QCA, 1999) and the National Academy of Science's science education standards in the US (NAS, 1996).

As suggested above, science teaching has always, inevitably - if implicitly (*e.g.*, Linder, 1992) - presented a view of what science is: its purpose(s), its values, its norms, its role(s) in society *etc.* When teaching about the nature of science has been incidental, even accidental, it has likely often reflected the tacit views of teachers that in many cases have received little thought (Justi & van Driel, 2005). This is not meant as a criticism of teachers – in view of their own educational experiences (McNally, 2006) and in the absence of any explicit specification for teaching about the nature of science in the curriculum they are employed to teach, it is not reasonable to expect anything different. However, when teaching about the nature of science is a deliberate, intended part of a curriculum, it becomes part of the explicit teaching 'content' to be specified (modelled) in curriculum documents and teaching schemes. Teachers, and those who develop the curriculum, must make explicit their assumptions and beliefs about the nature of science, as these inform teaching objectives. Existing research suggests that students often have very vague ideas about aspects of the nature of science (Driver, Leach, Millar & Scott, 1996), and that teachers may themselves be unclear about their own beliefs in this area (Eick, 2000).

The nature of science is a complex theme (Hipkins, Barker & Bolstad, 2005). It could be argued that science itself is in any case not best understood as an entity with a single unitary nature, and this disciplinary structure needs to be addressed when considering the image of science presented though the school curriculum (Kind & Taber, 2005). Even when the different science disciplines are conceptualised as part of an overarching meta-programme, the nature of that endeavour is multifaceted. The nature (or natures) of science (or, of the sciences) continues to be the subject of advanced and ongoing scholarship, drawing upon such disciplines as history, philosophy, sociology and psychology (*e.g.*, Ziman, 1980; Matthews, 1994). It is clearly not possible, even if it were considered appropriate, to reflect the full range and subtlety of contemporary thought about the nature of science(s) in school or college science. 'School science' is a politically constructed entity (that is, constructed by those groups with institutional power and influence), and cannot be a neutral reflection of 'professional science' (Kind & Taber, 2005). Therefore, whatever is presented in school science programmes as being the nature of science must be - at best - a simplification. The extent to which that simplification should represent these manifold perspectives is one issue that needs to be addressed in the light of continuing research into teaching and learning in this area.

As is the case in teaching about many complex science topics, any particular simplification presented to students may be judged by some 'experts' as oversimplified, distorted, or simply as just incorrect. Achieving a total consensus within the science education community about the most appropriate simplifications on which to base teaching may be unrealistic – this will be the situation whether we are discussing simplifications of photosynthesis or the nature and role of 'laws' in science.

The argument made in the present paper is that

(a) over several decades, science educators have developed ways of thinking about scientific concepts – photosynthesis, energy, redox, *etc.* – that allow us to made judgments about the most appropriate simplifications to use in teaching;

(b) similarly, over an extended period of time, there has been considerable work exploring the teaching of aspects of the nature of science;

(c) other scholarship has helped to clarify distinctions between scientific models, and the different types of models used and developed (deliberately or otherwise) in teaching and learning science;

(d) these distinctions between scientific, curricular, teaching *etc.* models are now being usefully applied to help understand the way scientific knowledge is transformed during the teaching process;

(e) a similar analytical approach may be useful in thinking about how teaching about the nature of science transforms scholarly understandings, and so can be useful in informing curriculum design and teaching.

In particular, it is suggested that the notion of a 'curricular model' (Gilbert, Boulter & Elmer, 2000) as designed 'target knowledge' is useful in thinking about the way the nature of science is represented in the intended curriculum (*i.e.*, as presented in official documentation and teaching schemes).

Models in science, and models in education

Given that we do not expect students in school courses to be at the 'cutting-edge' of scholarship in academic fields, there needs to be a way of deciding what should be included in a school curriculum, and what level of presentation of material is appropriate for the learners at any particular age or stage. This is the situation faced when teaching about scientific concepts, *i.e.*, when teaching the 'knowledge' that might be considered as the products of the scientific endeavour. When teaching about food webs, or acids and bases, or electrical circuits in school the 'target knowledge' in the curriculum represents a simplification of the knowledge presented in scientific journals. The target knowledge is a curricular model of the science itself.

As much scientific knowledge can itself be considered to be a set of models (for interpreting and exploring the natural world), it is important here to distinguish between the different types of models that are involved in the process of teaching students material based on current scientific knowledge (Gilbert, Osborne & Fensham, 1982). Indeed there are two distinctions of importance: concerning the 'location' of the models we can discuss, and their status in relation to science.

Some classes of model important in science education

The first distinction is between those internal, mental, models that an individual holds as representations in their minds (Johnson-Laird, 1983), and those expressed models that are in the public domain, and so open to critique and discussion (Gilbert, 1998; Gilbert et al, 2000). Although we are still some way from understanding how mental representations are formed, stored and used in cognition, it is reasonable to assume that scientists, science teachers and students 'hold' mental models of energy, burning, or blood circulation. Indeed such assumptions are central to the rationale for a great deal of research into the learning of science (Taber, 2006a). These mental models should be clearly distinguished from the formal public models that are represented in media, such as published texts (Phillips, 1987). To a close approximation, these different types of models may be considered to be located in different 'places', *i.e.*, the mental models in Popper's (1979) World 2 (of subjective thought), and the expressed models in Popper's World 3 of 'objective' knowledge.

Figure 1 is a simplistic way of representing the two 'dimensions' of models considered here. The distinction between the 'location' of a model (in an individual's mind, or expressed in the public domain) is seen as being dichotomous, and also impermeable. By this, I mean that models are not moved from one domain to another: rather they must be re-represented (more or less perfectly) across the divide - expressing a personal model; or learning about a public one. However, within either of these domains models can exist with vastly different status in terms of the extent to which the model is widely accepted. The two extremes would in principle be a model that only one individual would consider viable, to a model that everyone considered to be a reliable way of thinking about some target concept. Although neither extreme would seem likely in practice, both personal and public models can be found along much of this continuum.

Type of model	Location	Status
Mental	Individual mind (World 2)	Idiosyncratic … … … … … … … … … Consensual
Expressed	Public domain (World 3)	Idiosyncratic … … … … … … … … … Consensual

Figure 1: Models located in two domains

Figure 1 completely ignores the temporal dimension - the status of models clearly changes over time - and is a simple heuristic device to highlight how the 'location' (personal-public) and status (idiosyncratic-consensual) dimensions are related.

The expressed models in World 3 (the public domain) can be generated by scientists, teachers or students, but are likely to accordingly have very different status. The expressed models developed by scientists as part of their professional 'output' are 'scientific models', and are 'products' of scientific activity. In time, these models may lose their currency, but will remain in the literature as 'historical models' (Gilbert, 1998). As scientific models are, in part at least, tools for thought and research, an historical model that is no longer accepted may still be considered important and successful if it contributed to the programme of empirical and/or theoretical work that led to its own replacement (*e.g.* Lakatos, 1970). Indeed, it is possible for models that may be considered to be historical for those working in an area to still be used as if current scientific models outside of the specialist field (Sánchez Gómez & Martín, 2003).

Students may produce expressed models as by-products of completing their set assignments, or more deliberately if set a modelling task as an assigned activity. These models have significance for the educative process - for example, having diagnostic value to the teacher (*e.g.*, Taber, 2001a) - but do not have the same recognised public status as the scientist's models. Very occasionally, students may make authentic contributions to professional science through assignments set in educational programmes (Alsop, forthcoming), but this is very rare, and in general the purpose of most school and college assignments is developing personal knowledge, not contributing to wider public knowledge systems.

More significant for the present paper are two levels of expressed model that are intermediate between those of scientists and students (Gilbert *et al.*, 1982). Curricular models are the representations of scientific models found in formal curriculum documents and other indications of the intended curriculum, and teaching models are the models expressed by teachers in classroom exposition or though teaching materials produced for their classes.

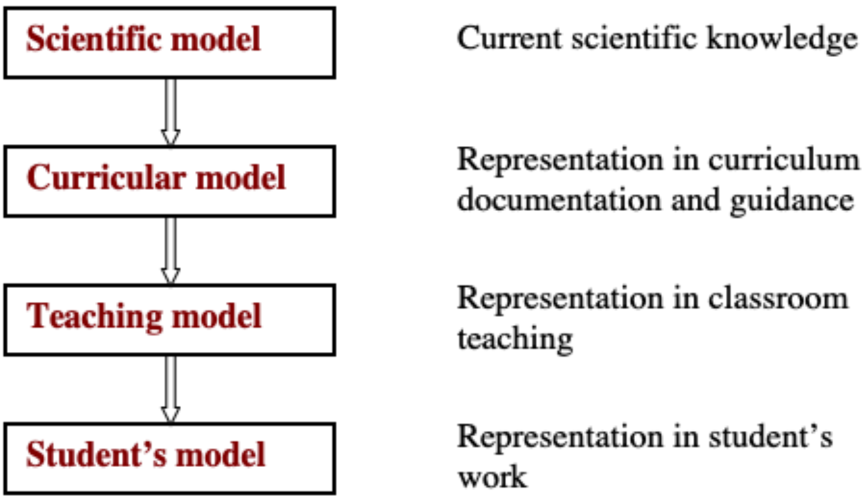

Figure 2: Transformation of knowledge through a succession of models

Figure 2 provides a simple representation of how scientific knowledge is transformed through several stages of re-representation before it may be 'learnt' in a school science setting (*cf.* Gilbert *et al.*, 1982). The succession of models shown in figure 2 are all expressed models – those in the scientific literature; those presented in the official curriculum documents; those presented during the teaching (statements, notes given, answers to student questions *etc.*); and those expressed in the students' 'behaviour' (*i.e.*, comments, written work, test answers *etc.*). In principle, science educators would claim to be interested in student knowledge and understanding, but in practice this can only be judged by the students' behaviour (*e.g.*, talk, written work). Mental models must be expressed before they can be communicated.

Indeed a very significant point in interpreting figure 2 is recognising that the arrows cannot imply a direct process of transferring between levels of models. Expressed models may be duplicated (mechanically reproduced, as in photocopying a diagram) but an expressed model at one level cannot be directly transformed into another expressed model. Any expressed model (in the public domain, World 3, see figure 1) must first be re-represented (learnt, understood) in mind (World 2) before being re-expressed (back to World 3). This is shown in simplified form in figure 3, where expressed models are internalised – *i.e.*, through the formation of a new mental model (Greca & Moreira, 2001) before they can be re-expressed. Figure 3 is still a simplification in many ways: *e.g.* in practice, curriculum development may involve many people; teachers may work from textbooks (and so reinterpret the expressed model of an author's interpretation of a curricular model); students read texts, bring ideas from the media, and discuss ideas with other students.

The key point to be taken from the diagram relates to the notion of the lack of permeability (see above) of the barrier between the private and public domains: that each of the arrows moving from expressed to mental model involves the interpretation of the expressed model, and that each of the arrows moving from mental to expressed models involves an attempt to represent personal understanding. 'Knowledge' (information) is likely to be distorted in this reconstruction process.

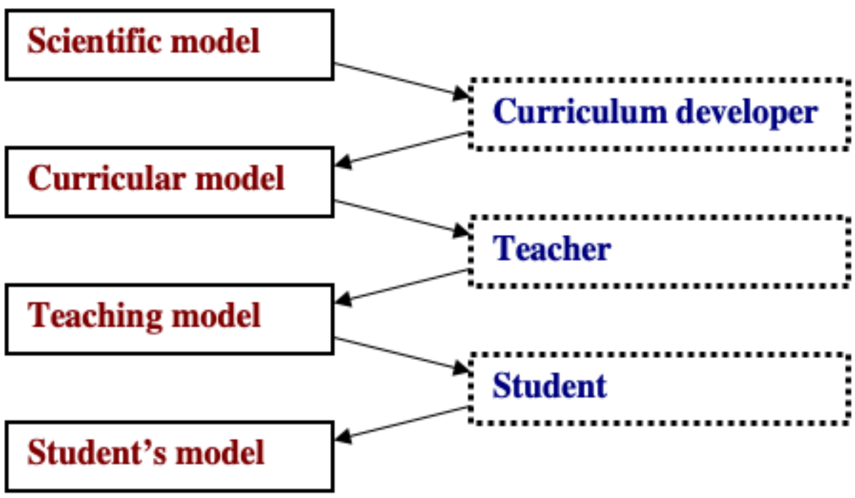

Figure 3: Mediation of scientific knowledge through curriculum design, teaching, and learning

The overall process of knowledge transformation in figure 3 therefore consists of two distinct aspects:

- the deliberate ways in which (within the minds of curriculum developers) scientific knowledge is simplified in curriculum development, and (within the minds of teachers) that target knowledge is re-conceptualised (structured, sequenced, linked with anticipated prior knowledge, compared with analogues from common experience, *etc.*) to be suitable for classroom teaching;
- the inevitable unintended 'degradation' and distortion of meanings associated with any form of translation process (*cf.* Gilbert *et al.*, 1982).

Effective science teaching is not a process of transferring knowledge, but rather concerns the guided construction of knowledge (Edwards and Mercer, 1987; Mercer, 1995), a dialectic process involving the re-construction of the entities of science (Ogborn, Kress, Martins & McGillicuddy, 1996) through dialogic processes (Mortimer & Scott, 2003) mediated by language (Lemke, 1990) and social interaction (Solomon, 1992; Scott, 1998). Although the epistemological (*i.e.*, relativist) basis of 'constructivism' as a perspective on knowledge creation has been the subject of debate and criticism (Matthews, 1998; Scerri, 2003), constructivist descriptions of how individuals learn are supported by research from cognitive science (*e.g.*, Bransford, Brown, & Cocking, 2000; Taber, 2000a) and are widely accepted in science education (Taber, 2006b).

By the time scientific knowledge becomes student knowledge it has been transformed by several deliberate stages of modification (to meet pedagogic purposes), and had many opportunities for 'mis-translation' (due to the negotiation inherent in the dialectic of the classroom, as well by the limitations of communication, and the way in which all learners construct understanding by re-interpreting information in terms of existing 'schema' or conceptual frameworks).

Curriculum design and the transformation of knowledge

This analysis suggests that the creation of curricular models involves a transformation of scientific knowledge; and the planning of teaching and presentation of curricular models may lead to further transformation. Where responsibility for 'setting' a curriculum (often specified in terms of content and learning outcomes) is located centrally, and precedes distinct local decisions about how to teach, there is considerable scope for teachers to misinterpret the intentions of curriculum planners. 'Good practice' in curriculum design would be reflected by a much more holistic and integrated approach (Zacharias & White, 1964/1968), where curriculum planning includes consideration of learning outcomes, appropriate teaching approaches, and assessment. Where curriculum is produced through such an approach, it is more likely that teaching will reflect curriculum intentions – although this does not of itself ensure the extent to which the target knowledge set out in the curriculum reflects the scientific models.

The role of curricular models in teaching about the nature of science will be illustrated below in terms of the introduction of a National Curriculum (NC) in England and Wales (henceforth referred to as the English NC). This requires all school students to be taught about the nature of science as part of a mandated school science curriculum.

Before the introduction of this NC it was common for curriculum development in the UK to involve science education researchers, teaching authority advisory teams and teachers (and sometimes examining boards) working together to consider courses in a holistic way. For example, the Nuffield Foundation led the development of a range of influential courses during the 1970s and 1980s. The Nuffield chemistry course for 16-18 year olds was "set up to produce a teaching scheme, and an appropriate method of assessment…the impetus for the curriculum changes… came largely from chemistry teachers in schools" (quoted in Ingle & Ranaweera, 1984, p.55). Groups of teachers could develop courses to meet the needs and interests of their own students, that could be examined under arrangements known as 'mode 3', as part of the 'certificate of secondary education' at age 16 (QCA, website). A research group based at Leeds University undertook an extended programme of classroom research, curriculum development and evaluation, working with local teachers (Driver & Oldham, 1986). If not the 'norm', such cooperative, integrated approaches to curriculum development were not unusual.

Under the English NC system several independent examination boards set and administer external examinations, but subject to having their specifications (of syllabus and assessments) approved by a central Authority that ensures NC and other requirements are satisfied. Whatever the merits of the intended purposes of the introduction of a NC (for example that all students would study broad and balanced science to age 16), this development also led to fragmentation of the curriculum process: curriculum content and assessment principles being established through central government and its agencies; the independent examination boards then devising their own examination specifications to fit the mandated curriculum; and teachers in schools largely left to develop teaching schemes to fit (or following the interpretations of text book authors). In more recent years there has been a post-hoc attempt to integrate curriculum and teaching: however this has taken the form of central government agencies offering teachers increasingly detailed 'guidance' on the sequencing of and approaches to teaching the material specified in the mandated curriculum (see Kind & Taber, 2005).

Difficulties in implementing the English NC for science have been widely recognised (STC, 2002), and the first phase of a substantial revision takes effect from September 2006. One of the courses being offered to meet the requirements of the revised curriculum for 14-16 years olds ('21st Century Science', see below) reflects a return to a more integrated approach to curriculum development. The present paper sets out to draw lessons from teaching about the nature of science in England during a period of fifteen years during which curriculum, assessment and teaching have largely been planned in a fragmented manner.

Expressed models designed for teaching science

The mental models of teachers and students are clearly very important to science educators. Indeed, the exploration of students' conceptions of a wide range of science topics has been a major research enterprise for several decades (*e.g.,* Duit, 1991; Driver, Squires, Rushworth & Wood-Robinson, 1994). Learners' mental models of the natural world are often at odds with scientific models and the curricular models that make up the target knowledge learners are expected to 'acquire'. There is a an active debate within the science education community about how teaching can and should take into account student ideas; regarding when such ideas are best understood as barriers or potential bridges to scientific understanding; and the extent to which it is appropriate and desirable to expect students' constructions of knowledge to progress towards matching such target knowledge (Taber, 2006a).

There are expectations that expressed models should be represented clearly, and meet certain criteria (of internal consistency, *etc.*) - but students' internal mental models may often be incoherent, partial, fluid and inconsistently applied. Whilst this often reflects the student's status as a novice, it is probably also characteristic of many mental models. That is, scientists' own personal mental models may often share such characteristics (*e.g.,* Bachelard, 1968/1940; Claxton, 1993), especially in areas where they are not responsible for expressing those models in forms acceptable to their peers.

Of more central importance to the concern of the current paper are expressed models. To clarify the different levels of model relevant to this discussion, consider an example from biology - the plant cell.

- A scientific model of a plant cell would represent currently accepted scientific knowledge of plants cells. Clearly, scientific knowledge in this area is vast, and so would in practice be represented by a set of distinct but largely consistent complementary models (of organelle types and structures, of metabolic pathways, *etc*.)
- A curricular model of a plant cell would be an expressed model (perhaps in the form of a paragraph of text) formally set out as the level of knowledge expected of learners at a certain stage and level (the 'target knowledge'). Clearly, we would expect that this would draw upon, but not be identical with, the scientific models available.
- A teaching model would be something used by a teacher to teach the knowledge represented in the curriculum to students. This might be a list of key points drawn up to be addressed during classroom dialogue; an overhead transparency showing 'typical' cell structure with key organelles represented and labelled; or it could be a three dimensional plastic model, or perhaps a computer-based simulation allowing students to 'zoom in' on structures or change their angle of view.
- A students' model, in this case, might be a physical model of cell structure, perhaps compiled from various modelling materials (or in one variation often used in schools, different sweets set in jelly). In this example the student is making a personal model based on interpretation of presented teaching models, as an exercise to aid understanding and reinforce new learning. (Student models can also be creative attempts to develop new ways of understanding data, phenomena *etc.* – in such a case the modelling may be more concerned with appreciating the nature of science than learning specific conceptual 'content'. However, as indicated below, this is less common.)

In this 'plant cell' example, the student's expressed model should reflect the teaching models presented, which should illustrate aspects of the curricular model, which itself should reflect selected features of the scientific models. As suggested above, it is important to appreciate the step-wise process here, as clearly – like the parlour game of Chinese whispers - there is the possibility of distortions entering at each step. Knowledge is transformed so that the students' learning about plant cells may lead to knowledge quite different from that scientific knowledge which is being taught about [*sic* – taught about, not taught].

A student may fail to build a model that resembles the teaching models presented. Similarly, it is also possible for a teacher to use teaching models that do not effectively represent the target knowledge of the curricular model. Such problems arise on an individual classroom basis, and may be considered as largely a failing of the teaching. It is, however, also possible for the most conscientious teacher and capable student to produce expressed models that distort scientific knowledge if the curricular model itself does not effectively reflect the scientific models. Where this occurs the problem can be more widespread, and indeed even systematic

Questioning curricular models

It is likely that most scientists or science teachers would have reservations about some aspects of the target knowledge set out in some officially sanctioned curricula and teaching schemes. As mentioned above, complete consensus is an unrealistic goal. Scientific concepts may often be subtle and abstract, and there may be genuine disagreements about how to best reflect them in school or college teaching.

Consider an example from physics teaching. Energy is a fundamental concept in physics (and indeed science more widely) and an appreciation of the concept is essential in all areas of the subject. However, even the most respected physicists may find it a difficult concept to explain a physicist's notion of energy to the layman, except through metaphor or analogy (Feynman, 1967). There has been a debate in physics education for some years (e.g., Driver & Millar, 1986; Ogborn, 1986; Solomon, 1992; Millar, 2003) on how to present this concept in school science, and discussion continues.

This debate is reflected in curriculum support materials issued by the UK government (DfES, 2003), where two curricular models are offered as the basis for ways of talking about energy in the lower secondary classroom:

- energy transfer - the energy is located in one place, and when something happens energy is transferred from that place to another; and
- energy transformation - energy is transformed or changed from one form or type to another when a change occurs.

However, it is possible to highlight other areas of the curriculum where established models exist that do not reflect current scientific thinking. In chemistry, the topic of atomic structure and bonding is rich with such dubious models, represented in official curricula and the textbooks intended to support them.

The very notion of the atom, as presented in some junior secondary curricula, may be a distortion of current scientific knowledge – often implying atoms are elementary, indivisible particles that are the smallest particles of matter possible, and the smallest particles to retain the properties of chemical substances (Taber, 2003). At higher grade levels, the atoms discussed in science classes suddenly acquire structure, and this structure is often presented in several distinct stages. A planetary model may be used for several years/grades, before suddenly being deposed by a model with electronic orbitals. The 'progression' between these apparently inconsistent models may be very challenging for students (*e.g.*, Taber, 2004).

It is unhelpful that these models are often presented to students as if simple reflections of THE structure of the atom (one example of where science teaching may misrepresent the nature of science). Justi and Gilbert (2000a) have discussed how the actual curricular model set up as target knowledge may not be based on any coherent current or historical scientific model, being instead a hybrid, drawing on several distinct and inconsistent models from the history of science. Scerri (1991) has pointed out that the 'spdf' orbital model of the atom, which is basis of the main curricular model at senior high/college level, is not actually generally valid in terms of current scientific knowledge (although in this case students will find themselves sharing the questionable model with many professional chemists).

Chemical bonding is a topic where students commonly experience learning difficulties, and often develop alternative conceptions (Taber & Coll, 2002). A common alternative conceptual framework for making sense of bonding (Taber, 1998) seems in part to develop from curricular models (the octet rule as an explanation for bonding) used to plan teaching (where atoms are often implied to 'want' or 'need' full electron shells, which leads to them becoming involved in reactions). For example, ionic bonding is often identified with electron transfer between atoms (a curricular model), commonly using the example (as a teaching model) of a sodium atom donating an electron to a chlorine atom. This model encourages students to develop the common notion that NaCl consists of 'molecules' comprising ion-pairs (Butts and Smith, 1987; Taber, 1994; Barker & Millar, 1999). In practice, students will prepare NaCl by a process of neutralisation from solutions already containing Na+ and Cl- ions, a reaction process that does not involve any electron-transfer 'events' of the type commonly represented in curricula, textbooks and teacher's presentations (Taber, 2002).

The boundaries between science disciplines may also present complications. A curricular model used in biology is that of the 'energy rich phosphate bond', which students often interpret (or may have explicitly presented) as the notion that a bond in the metabolic compound ATP is so rich in energy that when it is broken a great deal of energy is released. This model may be helpful at the level of explanation required in some biology classrooms, but is at odds with the principle taught in the physical sciences that all bond breaking is endothermic. In this case the curricular model does seem to reflect a widely used model in some science disciplines – for example in the work for which Fritz Lipmann (1953) won a Nobel prize – again illustrating the problematic nature of designing effective curricular models.

Designing curricular models

Clearly, scientific concepts can be abstract and complex, and it is easy to find examples of curricular models that are flawed: oversimplifications - or worse. However, the science education literature is also well populated with reports of student learning difficulties where the target knowledge may not be a distortion of scientific ideas, but is too abstract or complicated for the learners concerned (*e.g.,* Shayer & Adey, 1981). Designing curricular models is about finding an optimum level of simplification (Taber, 2000b) where the curricular model is simple enough for students to understand (in terms of their prior knowledge) but reflecting scientific understanding well enough to provide a suitable foundation for progression to more sophisticated understandings.

An important role for research in science education, then, is to support the development of curricular models, for different topics and grade levels, which present the optimum level of simplification for the learners. Clearly such a research programme must explore a) the structure of the scientific subject matter; b) learning processes; c) teaching approaches; d) sequencing and pacing of teaching presentations, *etc.* (see Taber, 2006a). The components of such a research programme (albeit not necessarily conceptualised as such) can clearly be found in the science education literature. Developing effective curricular models of scientific concepts, then, draws upon knowledge from both the disciplines of science themselves, and pedagogic content knowledge (Gess-Newsome & Lederman, 1999) deriving from scholarship within science education (see figure 4).

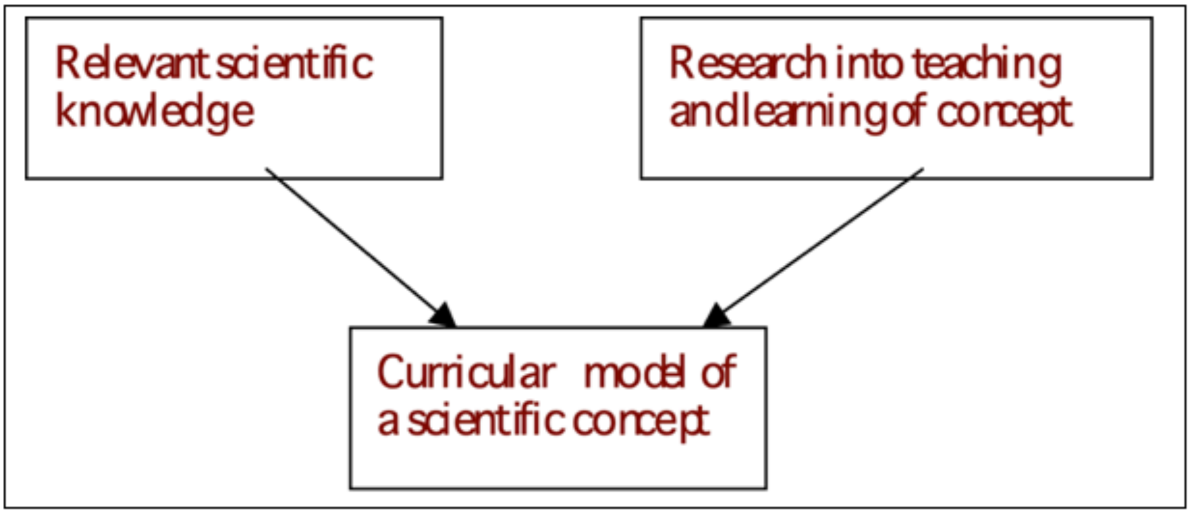

Figure 4: Informing curricular models of science concepts

Research exploring learners' understanding of curriculum topics has been an active area of enquiry for several decades now. Much of this work has been undertaken within a 'constructivist' perspective (*e.g.*, Matthews, 1998), but some predates the widespread adoption of this perspective, and was discussed in the seminal papers that largely initiated the constructivist movement within science education (*e.g.*, Driver and Erickson, 1983; Gilbert and Watts, 1983). A great deal is now known about learners' thinking about scientific topics, before, during and after formal teaching. The science education literature also offers examples of how subject matter can be analysed to inform teaching (*e.g.*, Herron, Cantu, Ward & Srinivasan, 1977), and - increasingly - studies of the processes of teaching and learning (*e.g.*, Petri & Niedderer, 1998; Harrison & Treagust, 2000).

As well as research exploring (in effect) students' mental models of science concepts at various ages, there has also been a substantial amount of enquiry into teachers' (*e.g.*, Lawrenz, 1986; Kruger, Summers & Palacio, 1990) and trainee teachers' understandings of science topics (*e.g.*, Nakiboglu, 2003; Summers, Corney & Childs, 2004). This is a logical 'next step', as

(a) teachers will have been students and so may have shared (or indeed still share) many of the reported alternative conceptions found in studies of learners; and
(b) it is teachers' own mental models of science concepts which will determine how they understand the curricular models, and so inform the teaching models they use.

These different areas of research can contribute to curriculum development in science education, and inform the selection and design of the curricular models presented in new and revised curricula.

The nature of science in the curriculum

In recent years, there has been an increasing recognition of the importance of explicitly teaching school and college level students something of the nature of science (*e.g.*, Matthews, 1994; Sorsby, 2000; Osborne, 2002). In the US, the nature of science was the subject of the first chapter of 'Science for all Americans' (Rutherford & Ahlgren, 1991), the influential report from Project 2061, the American Association for the Advancement of Science's initiative to support literacy in science, mathematics and technology. The National Academy of Sciences subsequently published National Education Standards (NAS, 1996). Although the US does not have a 'national curriculum', the standards were developed with support from the National Academy of Engineering, the Institute of Medicine, the National Science Foundation, the US Department of Education, the National Aeronautics and Space Administration and the National Institutes of Health. Along with 'benchmarks' developed by the American Association for the Advancement of Science (AAAS, 1993), the NAS standards are influencing the establishment of comparable standards at State level. The standards include 'science as inquiry' (content standard A), part of which is 'understanding about scientific enquiry' (content standard A2) and 'history and nature of science' (content standard G) which is divided into 'science as human endeavour' (G1), 'nature of scientific knowledge' (G2), and 'historical perspectives' (G3).

In New Zealand the development of the science curriculum has been the subject of considerable public debate (Bell, Jones & Carr, 1995). The curriculum is organised through six 'learning strands'. Four of these, labelled 'contextual strands', are related to areas of science content (basically biology; physics; chemistry; earth science/astronomy). The other two 'integrating strands' concern 'making sense of the nature of science and its relationship to technology' and 'developing scientific skills and attitudes'. The curriculum document emphasises how learning science and learning about science should be linked in teaching and learning.

The teaching of the nature of science in the English National Curriculum

In the English National Curriculum (NC) teaching about the nature of science is specified under the heading 'scientific enquiry' (DfES/QCA, 1999). A NC was first established in England and Wales by a law passed in 1989. The nature of science was intended to part of the curriculum from the beginning. In July 1987 the responsible ministers in the UK government set up a working group to advise on a NC for science for England and Wales. The resulting proposals (DES/WO, 1988) made recommendations for what should be included in such a curriculum under a set of headings designed to represent 'attainment targets' (AT). The last of these 22 AT was labeled 'The Nature of Science', and under this heading it was recommended that:

> "pupils should develop an understanding that science is a human activity, that scientific ideas change through time, and that the nature of scientific ideas and the uses to which they are put are affected by the social and cultural contexts in which they are developed."
>
> (DES/WO, 1988, p.vi)

Whilst something as complex and nebulous as the nature of science cannot be readily encapsulated in such a brief description, this statement will be accepted here as a fair starting point for considering how the nature of science could be reflected in school science.

The intention was that each of the 22 AT would be assessed, although there would be some aggregation for the purposes of reporting. When the NC was passed into law the following year, the number of AT had been reduced to 17 (with the Nature of Science as AT17). However, by the time teaching and assessment under the NC had been implemented, teachers were working to a revised (1991) document with only 4 AT (Parkinson, 1994). These were

- Sc1: Scientific Investigation;
- Sc2: Life and living processes;
- Sc3: Materials and their properties;
- Sc4: Physical processes

Although teachers were still expected to teach about the Nature of Science, its explicit presence in the 'Programme of Study' had been considerably diminished. In principle, 'scientific investigations' concerned how scientists come to knowledge, and along with the other three AT (which are basically biology, chemistry and physics with a little earth science and astronomy) provided contexts for teaching about the nature of science as a human activity.

The NC was later revised again (DfEE/QCA, 1999), in part recognising that the nature of science aspects were not being widely taught, and Sc1 was broadened to become 'scientific enquiry' and to include specification of 'ideas and evidence' as well as 'scientific investigations'. As in the NZ case (see above), teachers were told that this should be integrated within the teaching of science topics content:

> "Teaching should ensure that scientific enquiry is taught through contexts taken from the sections on life processes and living things, materials and their properties and physical processes"
>
> (DfEE/QCA 1999)

However, in practice "teachers often regarded Sc1 work as a 'bolt-on' assessment activity rather than work to be integrated into the teaching and learning of Sc2-Sc4" (QCA, undated/a). The evolution of the NC makes it sensible to consider the two main subdivisions 'scientific investigations' and 'ideas and evidence' separately.

Teaching the nature of science through 'scientific investigations'

The original Sc1 ('scientific investigations') was used as the basis of awarding a significant percentage (20%) of marks for coursework towards the school leaving examination (the General Certificate of Secondary Education, GCSE). The national curriculum documents never laid down how much practical work schools should undertake, which experiments and demonstrations should be undertaken, how practical work ought to be organised, or any other such details of how the curriculum should be 'delivered'. Indeed, the model of investigations in the current version of the curriculum (at the time of writing, a revision is about to be implemented for KS4), offers a broad image of science (see Table 1) including reference to fieldwork. However, through the influence of the Curriculum and Qualifications Authority, which approves all examination specifications, a system evolved for evaluating student coursework. This coursework is undertaken by students in their final years of compulsory schooling, is marked by teachers in the schools, and then moderated by the examination boards. Students' work would be marked using hierarchical grade criteria in four areas: relating to planning practical work, collecting data, analysing data and evaluating the practical work.

In principle, schools had total freedom to set as wide a range of scientific investigations as they thought appropriate, and for this to be as small a component of student practical work in science as they wished. However it soon became clear that only certain types of 'investigations' allowed credit to be awarded towards the examinations, and that much of the practical work traditionally undertaken in schools had little direct value in preparing students for the coursework assignments.

A 'suitable' investigation would involve the control of variables, and the collection of data that could be presented as a line graph. If students were to be given the opportunity to score high marks, then the investigation had to be based on a familiar area of science that allowed them to refer to appropriate theory in their account. In order to give students a chance of collecting the 'right' sort of data, and completing the work in reasonable time, teachers recognised that it was important that tasks allowed precise quantitative data to be collected, and that not too much time was spent in exploring the kinds of factors that could be controlled or varied.

Table 1: The English National Curriculum requirements for teaching about scientific investigations for 14-16 year olds (DfEE/QCA, 1999)

2. Pupils should be taught to:
a) use scientific knowledge and understanding to turn ideas into a form that can be investigated, and to plan an appropriate strategy
b) decide whether to use evidence from first-hand experience or secondary sources
c) carry out preliminary work and make predictions, where appropriate
d) consider key factors that need to be taken into account when collecting evidence, and how evidence can be collected in contexts [for example, fieldwork, surveys] in which the variables cannot readily be controlled
e) decide the extent and range of data to be collected [for example, appropriate sample size for biological work], and the techniques, equipment and materials to use
f) use a wide range of equipment and materials appropriately, and manage their working environment to ensure the safety of themselves and others
g) make observations and measurements, including the use of ICT for datalogging [for example, to monitor several variables at the same time] to a degree of precision appropriate to the context
h) make sufficient observations and measurements to reduce error and obtain reliable evidence
i) judge the level of uncertainty in observations and measurements [for example, by using the variation in repeat measurements to judge the likely accuracy of the average measured value]
j) represent and communicate qualitative and quantitative data using diagrams, tables, charts, graphs and ICT
k) use diagrams, tables, charts and graphs, and identify and explain patterns or relationships in data
l) present the results of calculations to an appropriate degree of accuracy
m) use observations, measurements or other data to draw conclusions
n) explain to what extent these conclusions support any predictions made, and enable further predictions to be made
o) use scientific knowledge and understanding to explain and interpret observations, measurements or other data, and conclusions
p) consider anomalous data giving reasons for rejecting or accepting them, and consider the reliability of data in terms of the uncertainty of measurements and observations
q) consider whether the evidence collected is sufficient to support any conclusions or interpretations made
r) suggest improvements to the methods used
s) suggest further investigations.

note - these objectives are grouped under headings: planning (a-e); obtaining and presenting evidence (f-j); considering evidence (k-o); evaluating (p-s).

Initially, some schools were quite creative in designing investigations. However, when moderators reports were received marking students down, and suggesting that certain set investigations would limit the mark ceiling, most schools moved towards a small number of 'investigations' that could easily be set-up and successfully completed: *e.g.*, investigating resistance of wire, rates of familiar reactions, or factors determining the rate at which bubbles of gas are produced from illuminated pondweed. As the government's qualifications and curriculum authority reported "it was observed that investigative work at KS3, and especially at KS4, was narrow in range" (QCA, undated/a, p.2)

So, for example, in 'investigating' the resistance of wire a student might be steered towards finding out how the length of wires, or the diameter, affected resistance when the other variable was kept constant. Changing the material of the wire would be considered less suitable – as this does not give a continuous variable suitable for plotting on a line graph! In another class students might chose to change either the temperature or concentration of acid reacting with strips of magnesium. In other words, standard 'investigations' became common, with minimum choice in planning, and with outcomes that the students should have already expected. Despite the intention that scientific investigations would be met through the context of learning about substantive science topics, many teachers, were in effect 'teaching to the test',

> "Amongst secondary schools, some integrated Sc1 into the teaching and assessment of Sc2-Sc4; but an equal number also reported that Sc1 was addressed separately through whole investigations, with an assessment focus, and/or that individual Sc1 skills were taught and assessed separately, particularly [from age 14]".
>
> (QCA, undated/b, p.6)

The grade criteria for marking GCSE coursework have acted as an implicit curricular model for the nature of scientific investigations. Student investigations took a standard form (usually deciding which of two obvious factors to vary), and other practical work often tended to be downplayed or even marginalised – with teachers arguing that there is limited time to teach all the topics, and no other type of practical work is directly awarded merit.

This curricular model is inappropriate, because it is an oversimplification of the way scientists undertake investigations (Kind & Taber, 2005). Control of variables is an important feature of much scientific work, but not all. Other empirical work in science does not follow standard experimental paradigms. This curricular model offers students little insight into the work of 'naturalists' like Darwin. (I would include geologists and astronomers as naturalists in this sense: Kepler did not control variables when he investigated the orbit of Mars.)

Those scientists whose work does involve hypothesis-testing base their conjectures on what seem theoretically viable ideas. However the need to meet the assessment criteria has led to students looking for what their textbooks already tell them they should find: "Generally, there appeared to be a continued over-emphasis on knowledge/content-based science at KS2 and KS3, with insufficient time given to real enquiry" (QCA, undated/a, p.2)

The representation of 'scientific investigations' deriving from the coursework requirements of the English examination system is a poor curricular model of a key aspect of the nature for science. Assessment criteria can be very influential when they only reflect part of the teaching programme. The marking criteria, and their interpretation through the work of examination boards, has taken on the status of an implicit, but highly influential, curricular model that has led to students in English schools being presented with a limited and distorted view of science. The widespread recognition of these shortcomings (*e.g.*, Roberts & Gott, 2004) has been partly responsible for the major overhaul of the science curriculum for 14-16 years that is about to be implemented. The issue attracted comment at the highest levels, with a parliamentary select committee commented that,

> "The way in which coursework is assessed for GCSE science has little educational value and has turned practical work into a tedious and dull activity for both students and teachers"
>
> (STC, 2002, p.21)

In the UK, the perceived [*sic*] maintenance and improvement of standards (as measured by formal indicators such as examination pass rates, *e.g.*, Gibson & Asthana, 1998) has been a cornerstone of successive government education policies. In a system where summative assessment outcomes are key foci, if not an obsession, among schools, students, parents and other educational shareholders, it is understandable how assessment criteria came to form the default curricular model.

Whilst the factors that dominate education may well be different in other systems, this story - of the accidental evolution of a problematic curricular model for scientific investigations - can act as a cautionary tale. This example demonstrates the importance of presenting teachers with explicit curricular models that have been carefully designed, rather than allowed to evolve in response to various institutional, political and pragmatic pressures (Gaskell, 2003; Kind & Taber, 2005).

Teaching the nature of science through 'ideas and evidence'

The role of scientific investigations in science is clearly only one aspect of the nature of science. It is too early to know whether other aspects of the nature of science will become oversimplified through the evolution of unintended curricular models in England. For most of the period since the introduction of the NC (in 1989) there was little attention given to other aspects of the nature of science in the national tests (*e.g.*, at age 14) or school leaving examinations (at age 16). The assumption was that this aspect of science would be infused through teaching about Sc2-4 (*i.e.*, basically biology, chemistry and physics) and did not need explicit attention in terms of formal assessment.

However, it became clear that in the absence of explicit curriculum specification and formal assessment, the nature of science was often not being explicitly and deliberately taught. The curriculum was revised (DfES/QCA, 1999), so that 'ideas and evidence' became one of two strands within a rewritten Sc1, (alongside 'scientific investigations'), and teachers were notified that this area would increasingly be a focus for formal assessment (QCA, 2002).

Table 2: The English NC requirements for teaching about ideas and evidence in science to secondary age students.

Key Stage	Pupils should be taught:
KS3 (ages 11-14)	a) about the interplay between empirical questions, evidence and scientific explanations using historical and contemporary examples [for example, Lavoisier's work on burning, the possible causes of global warming]
	b) that it is important to test explanations by using them to make predictions and by seeing if evidence matches the predictions
	c) about the ways in which scientists work today and how they worked in the past, including the roles of experimentation, evidence and creative thought in the development of scientific ideas.
KS4 (ages 14-16)	a) how scientific ideas are presented, evaluated and disseminated [for example, by publication, review by other scientists]
	b) how scientific controversies can arise from different ways of interpreting empirical evidence [for example, Darwin's theory of evolution]
	c) ways in which scientific work may be affected by the contexts in which it takes place [for example, social, historical, moral and spiritual], and how these contexts may affect whether or not ideas are accepted
	d) to consider the power and limitations of science in addressing industrial, social and environmental questions, including the kinds of questions science can and cannot answer, uncertainties in scientific knowledge, and the ethical issues involved.

The current English NC curriculum (DfES/QCA, 1999) now specifies what students are expected to learn about ideas and evidence in science (see Table 2). These teaching objectives are accompanied by level descriptors that are meant to guide teachers in assessing pupils progress and planning progression in their teaching (DfES/QCA, 1999). Some of the examples presented in these level descriptors suggest that teachers are being encouraged to offer an authentic image of the nature of science in their teaching (see Table 3).

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Table 3: Level descriptors relating to the nature of science in the English NC

NC Level	What is expected of pupils
Level 4	Pupils recognise that scientific ideas are based on evidence.
Level 5	Pupils describe how experimental evidence and creative thinking have been combined to provide a scientific explanation [for example, Jenner's work on vaccination at key stage 2, Lavoisier's work on burning at key stage 3].
Level 6	Pupils describe evidence for some accepted scientific ideas and explain how the interpretation of evidence by scientists leads to the development and acceptance of new ideas.
Level 7	Pupils describe some predictions based on scientific theories and give examples of the evidence collected to test these predictions.
Level 8	Pupils give examples of scientific explanations or models that have had to be changed in the light of additional scientific evidence.
Exceptional performance	Pupils give examples of scientific explanations and models that have been challenged by subsequent experiments and explain the significance of the evidence in modifying scientific theories.

However, following monitoring exercises in 2000-2, the UK's Qualifications and Curriculum Authority reported that

> "The extent to which 'ideas and evidence' is being taught in science varied … schools stated that limited resources were making it difficult to deliver this aspect adequately."
>
> (QCA, undated/a, p.3)

> "Some primary and secondary schools were successfully integrating 'ideas and evidence' into their lessons/schemes of work, *e.g.* as part of discussions, debates, research projects, investigative work *etc.* However, many other primary and secondary teachers were unfamiliar with/uncertain about the nature and purpose of this strand"
>
> (QCA, undated/b, p.7).

The Qualifications and Curriculum Authority noted that "many teachers requested guidance and support in this area, particularly good stimulus materials, providing examples set in the real world and addressing some of the historical aspects" (QCA, undated/b, p.7).

In summary, the introduction of explicit requirements for teaching about the nature of science as a result of the 1989 NC and its revisions has not automatically led to widespread and effective classroom teaching that helps students understand "that science is a human activity, that scientific ideas change through time, and that the nature of scientific ideas and the uses to which they are put are affected by the social and cultural contexts in which they are developed" (DES/WO, 1988, p.vi). Table 4 summarises the situation that has developed over this period of one and half decades.

The view taken here is that in the absence of careful planning of deliberate curricular models for teachers to adopt, assessment requirements provided a very limited curricular model for teaching about 'scientific investigation', whilst the lack of any established curricular models to mediate teacher understanding of 'ideas and evidence' led to this aspect first being largely ignored (when not assessed), and then being identified by inspectors and teachers as an area where more support was needed to enable effective teaching.

Table 4: The nature of science reflected in the English National Curriculum (1989-2006).

Aspects of the nature of science	Scientific method (epsistemology)	History of science, Sociology of science, etc.
Representation in the English curriculum	Scientific enquiry – scientific investigations	Scientific enquiry – ideas and evidence
Assessment	Significant compulsory aspect of school leaving examination	Originally not formally assessed; explicitly assessed in national tests and school leaving examinations in recent years
Extent of implementation	Near universal adoption of curriculum requirements from curricular introduction (in 1989)	Originally limited when not formally assessed.
Nature of implementation	Evolution of formulaic 'fair testing' exercises; which in many schools distorted the nature of much school practical work in science.	Reported by Inspectors to be of very variable quality.
Comment	Assessment led: assessment criteria take on status of an implicit curricular model	Teachers report lack of preparation, expertise, and support materials

It is interesting to note that this analysis parallels commentary on the implementation of teaching about the nature of science in the New Zealand curriculum (Bell, Jones & Carr, 1995). Haigh, France & Forret report how "investigative problem-solving science has been promoted … as a means of linking process with an understanding of the nature of the scientific enterprise", but that "at the primary level, open investigative practical work has largely been interpreted as 'fair testing'… an approach encouraged by much of the Ministry produced teacher support material" (2005, p.218). Hipkins, Barker & Bolstad, comment that "the lack of specificity of the NOS content of the curriculum is indeed an issue for the teachers who must interpret it" (2005, p.246), and go on to suggest that "in the absence of clear directives about NOS in the New Zealand science curriculum, other more implicit curriculum messages continue to hold sway" (p.246).

The need for a curricular model of the nature of science

To some extent, it is not surprising that teachers are often not well prepared to teach students about the nature of science. Until recently, the nature of science has not been an explicit concern of most school and college curricula, and degree level preparation in science has usually focused on learning the subject matter and experimental techniques of a particular science discipline. Learning about 'science' itself was likely to be incidental and tacit, or the result of extramural interests. Whilst some degree courses have long included options in aspects of 'science studies', this has more usually been the preserve of historians, philosophers, psychologists or sociologists. Similarly, when the nature of science was not an explicit aspect of school curricula, then preparation to teach about science (rather than about some science) was not seen as a necessary component of courses to prepare science teachers.

Although the importance of teaching about the nature of science was officially recognised and sanctioned in the introduction of the English NC, policy does not of itself enable effective teaching. As is well recognised, the curriculum as implemented in classrooms may be very different from the intended curriculum set out in official documentation (Reid, 1990). Curriculum processes needed to be more iterative and cyclical if policy is to be well represented in practice (Thornton & Wright, 1963)

In the case of teaching about the nature of science in England, a lack of expertise and experience in this area has acted as a barrier to a full implementation of the good intentions behind the curriculum reform. As Figure 3 suggests, the transformation of scholarly disciplinary knowledge into school science knowledge is a process that is mediated by the teacher's understandings of target knowledge (Kind & Taber, 2005). For such a transformation to be effective, teachers need both a good understanding of the scholarly knowledge to be transformed (of aspects of science studies in this instance) and the parallel pedagogic knowledge relating to what students at different levels can be expected to understand, and how such understanding may be initiated and developed. As the Qualifications and Curriculum Authority have recommended, "guidance materials should be developed" (QCA, undated/a, p.3).

As part of the response to such recommendations, in 2003 a government initiative known as the Key Stage 3 Strategy (*i.e.*, aimed at improving the teaching of 11-14 year olds) invited universities involved in initial teacher education to participate in a project to "enrich existing initial teacher education and training about the Ideas and evidence in science aspect of Scientific Enquiry (Sc1)". The present author directed one of the small scale projects set up under this initiative. Five English Universities undertook work as part of the initiative, producing ideas for approaches and activities to support teachers, which were later disseminated, with the support of the Science Enhancement Programme, a charitable foundation (SEP, 2004).

At Cambridge University, trainee teachers (science graduates taking a one-year teacher training programme) who volunteered to be involved in the project undertook visits to schools to explore student understanding of the nature of science for themselves, as part of their preparation for teaching placements (Taber, 2006c). Some of the trainees then developed teaching materials and ideas specifically focusing on some aspect of 'Sc1' (Taber *et al.*, 2006). However, preparing the trainees for this work highlighted the problem alluded to previously in this paper. Although the curriculum specifications present an implicit curricular model for the nature of science, teachers – who have often had little formal preparation for teaching this area – are given negligible support in understanding how (pedagogic) decisions were made about why this particular image of science is considered the appropriate target knowledge. Without such a rationale, it is difficult to plan effective teacher education in this area.

From what has been argued in this paper, preparing to teach about an aspect of science (a science concept, or an aspect of the nature of science) has to start from some kind of curricular model, which presents target knowledge that has been designed to be an intellectually honest simplification of current scholarship suitable for the learners. In the absence of a sufficiently explicit and rationalised curricular model to inform teaching, a short document was drafted to represent a suggested level of target knowledge for secondary science teaching. (This document is reproduced for information as Appendix 1.) Whilst offering the trainee teachers some basis to start their planning, this document reflects one individual's views, based on personal reading and previous experience of teaching 'science studies' to adult learners in a college context. It is suggested here that a more systematic approach is needed, and that there is a sufficient and growing knowledge base available to support such an approach.

Working towards a curricular model

A major recent report on the state and future of science education in the UK comments that:

> "Science educators have realised that major trends in 20th century scholarship on science itself…are important for science education. But much science teaching seems not to have absorbed this lesson."
>
> (TLRP, 2006, p.9).

Developing curricular models of scientific concepts draws upon the scientific models themselves, and research into the teaching and learning of those concepts (see Figure 4). Similarly, developing curricular models of the nature of science will draw upon scholarship exploring science from various disciplinary perspectives (e.g., history, philosophy, psychology, sociology, communication studies), complemented by research into the teaching and learning of science (see Figure 5).

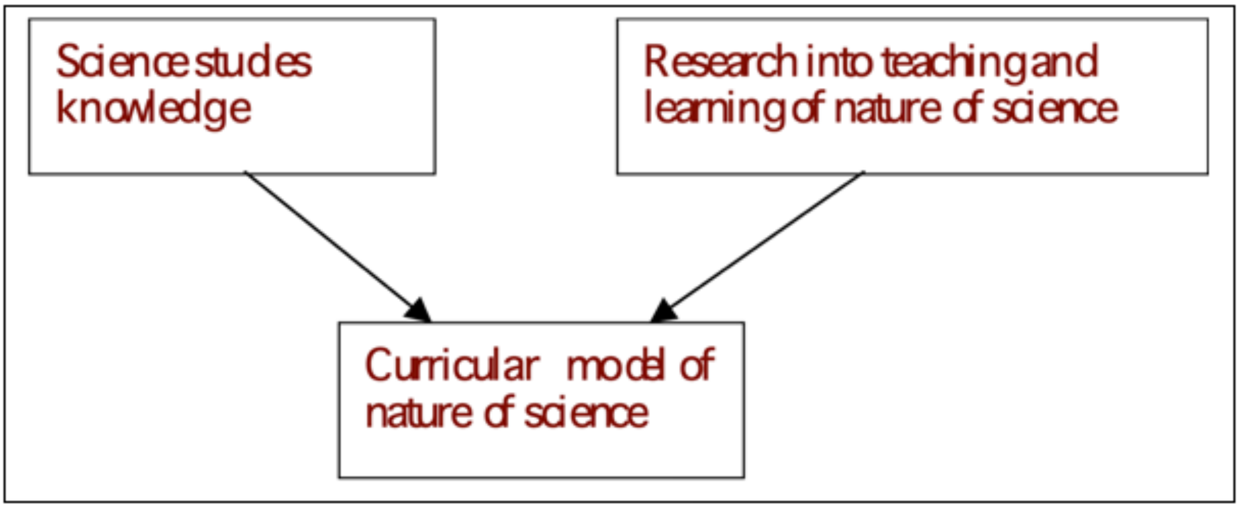

Figure 5: Informing curricular models of the nature of science

The science education literature demonstrates that identifying appropriate target knowledge for teaching science concepts is far from simple. Over a period of decades we have begun to understand how students at different levels of development, coming to science with various 'intuitive ideas' or 'preconceptions' based on folk science and so forth, interact with teaching based on various types of teaching approaches, aimed at teaching particular content in various sequences. Often the research has produced findings that can be seen as indicating various kinds of 'mismatch' between the teaching and the readiness of the learner (Taber, 2001a).

This suggests that effective teaching of the nature of science will be easier to achieve if:

1. an explicit curricular model (or series of such models for different ages/levels) is (are) developed, informed by existing scholarship;
2. a programme of research is undertaken to explore the effectiveness of teaching which uses such a curricular model as target knowledge;
3. the curricular model is revised in the light of such focused research.

Clearly these activities make up a cycle that should be ongoing.

The qualities of a good curricular model are that:

- it is an authentic representation of the nature of science, *i.e.*, in Bruner's (1960, p.33) terms it is 'intellectually honest';
- it is a simplification which matches the 'readiness' of the learners (to allow meaningful learning, *cf.* Ausubel, 2000);

There is little point effectively teaching models which are not intellectually honest – such as the model of ionic bonding discussed above which students can readily learn, but which does not reflect scientific understanding, and so is not capable of being used to explain the properties of ionic substances. An intellectually honest model will be a simplification but not an oversimplification, and will support progression in learning. A model of chemical bonding based upon atoms 'wanting' to achieve octet structures (Taber, 1998) does not support progression in learning, and leads to a discontinuity when (for example) learners meet hydrogen bonding at the next stage of their studies (Taber, 2001b).

Similarly, there is little point in a curricular model that retains intellectual validity by remaining so abstract and complex that students can make little sense of it (*cf.* Shayer & Adey, 1981). Learners need to be able to understand new ideas in terms of existing learning (using analogies and metaphors *etc*., as teaching models where necessary) and so an appropriate curricular model is informed by an appreciation of the intellectual capacities of the learners, their prior learning about the topic, and any relevant 'alternative conceptions' they may bring to class. As suggested above, there is already a body of relevant research in science education to inform decisions about the levels of simplification needed.

The knowledge base for developing the curricular model

When teaching science concepts, the academic scholarship that will inform the development of intellectually honest curricular models derives from science disciplines themselves. When teaching about the nature of science, curriculum planners needs to draw upon scholarship from such diverse areas as philosophy, history, psychology and sociology. Popper's prescription of conjecture and refutations (1959); Ziman's (1991) work on how science comes to knowledge; the models of how science progresses put forward by Kuhn (1996) and Lakatos (1970) (and Feyerabend, 1988); and the model of the structure of argumentation proposed by Toulmin (2003) are among many other possible sources may be drawn upon. There are a number of popular introductions to the philosophy of science (*e.g.*, Harré, 1972; Brown, Fauvel & Finnegan, 1981/1989; Losee, 1993). Some approaches are informed by cognitive perspectives (*e.g.*, Thagard, 1992), such as Nerssesian's (1995) focus on the role of modeling. There is a wide range of material available on many aspects of science studies (*e.g.*, Biagioli, 1999), including material providing historical perspectives (*e.g.*, Chant & Fauvel, 1980), sociological perspectives (Bloor, 1991), feminist perspectives (Reed, 1978), multi-cultural perspective (Harding, 1993), the role of creativity and imagination in science (Miller, 1986) *etc.*

There is then no shortage of useful source material which can, in principle, inform appropriate simplifications (*i.e.*, curricular models) developed as part of the target knowledge set out for learners. To some extent this process is happening piecemeal, so as one example Toulmin's model for explanation in science has already been drawn upon (Erduran, Simon & Osborne, 2004). The various strands of 'science studies' offer many potentially relevant perspectives, and a single discipline such as philosophy of science may offer a range of different models designed to illuminate the same aspects of science. This makes the development of appropriate and effective curricular models of the nature of science more complicated and nuanced than is the case with science concepts - where in most cases there is reasonable consensus on the current scientific models.

The second source of guidance on developing a curricular model derives from research into teaching and learning about the nature of science. There is already a considerable literature in this area offering insights into student understanding (Grosslight, Unger, Jay & Smith, 1991; Arnold & Millar, 1993; Duveen, Scott & Solomon, 1993; Solomon, Duveen & Scott, 1994; Driver, Leach, Millar & Scott, 1996; Chinn & Samarapungavan, 2005), teacher understandings (*e.g.*, Abd-El-Khalick & BouJaoude, 1997; Newton & Newton, 1997; Justi & Gilbert, 2002b, c; Lunn, 2002; van Driel & Verloop, 2002), teacher classroom behaviours (*e.g.*, Brickhouse, 1989; Ryder and Leach, 2005;

Waters-Adams, 2006), and so forth. The literature includes a range of recommendations on incorporating nature of science teaching into science instruction (*e.g.*, Campbell, 1998; Collins, Osborne, Ratcliffe, Millar & Duschl, 2001; Clough, 2005, 2006; Grandy & Duschl, 2005) including advice on supporting students in specific aspects such as argumentation (Simon, Erduran & Osborne, 2006) or modelling (Justi & van Driel, 2005; Sins, Savelsbergh & van Joolingen, 2005).

Some of this science education research focuses on current limitations in teaching and learning, or makes proposals that are not yet fully tested in the classroom. None-the-less, there certainly exists a sufficient knowledge base to support the design of explicit curricular models that can be piloted and further developed.

Coda: 'How science works'

The statutory curriculum for 14-16 year olds (but not yet for lower grade levels) in England and Wales has been revised for Autumn 2006, specifying the programme to be taught to students taking school-leaving examinations in Summer 2008. The new programme of study intends that "pupils learn about the way science and scientists work within society" (QCA, 2005, p.37). According to the commentary, pupils will "consider the relationships between data, evidence, theories and explanations, and develop their practical, problem-solving and enquiry skills, working individually and in groups". To this end, it is specified that:

> "Pupils should be taught:
>
> "a) how scientific data can be collected and analysed;
>
> b) how interpretation of data, using creative thought, provides evidence to test ideas and develop theories;
>
> c) how explanations of many phenomena can be developed using scientific theories, models and ideas;
>
> d) that there are some questions that science cannot currently answer, and some that science cannot address."
>
> (QCA, 2005, p.37)

The new curriculum, has a balanced focus on 'how science works' and a 'breadth of study' (*i.e.*, content topics), which is laudable. However, the evolution of the teaching of the nature of science as part of a NC in England during the past one and half decades offers something of a cautionary tale, suggesting that a more explicit curricular model is needed. The QCA monitoring exercises demonstrate that the level of information provided in this level of specification (*cf.* Table 2) does not provide the support that enables teachers to deliver. Teachers need to have a rationale for these bare specifications of what students are expected to learn; a clear idea of the extent and level(s) of understanding expected; and sufficient foundation for developing appropriate teaching models and activities.

The development of this new curriculum has been directly influenced by the work of science educators, and especially an influential report ('Beyond 2000') recommending the centrality of scientific literacy in school science (Millar & Obsorne, 1998). Indeed, in the period leading up to the implementation of the new curriculum, a new course for 14-16 years-olds has been developed from the principles advocated in 'Beyond 2000', in partnership between science education specialists (coordinated at the University of York), the Nuffield Foundation (a charity supporting curriculum development), and one of the Examination Boards (OCR). This '21st Century Science' (21CS) course sets out to ensure scientific literacy for all pupils in the age range, through teaching ideas about science alongside scientific explanations – the type of integration that the 1989 NC intended - but was not able to deliver.

The course has also been influenced by the influential 'assessment for learning' movement, which has campaigned for a shift to more emphasis on formative (compared with summative) assessment in teaching (*e.g.*, Black & Wiliam, 1998; TLRP, 2006). 21CS has been designed in a holistic manner, recognising that 'content', teaching approach and assessment need to be considered as strongly interacting parts of a course of study (see http://21stcenturyscience.org). From September 2006 this course becomes generally available for all schools preparing students for the revised KS4 science curriculum. Only time will tell how successful 21CS will be in helping students learn about the nature of science as well as about some of the more important scientific explanations. Its well-considered basis, carefully designed integrated structure, and the research evidence collected through a carefully evaluated pilot could provide teachers with the basis of a curricular model for the nature of science suitable for planning and supporting effective teaching.

However 21CS is just one syllabus option available, and many teachers will be working with one of the other new courses being introduced to meet the revised NC specifications. It is likely that many teachers will continue to feel unsupported as they plan to teach their students 'how science works' without guidance from a carefully designed curricular model of the nature of science. What is needed to support these teachers, and their colleagues working in other educational systems (for example, those facing similar challenges in the New Zealand context) is a programme of work in science education developing an 'intellectually honest simplification' of this very complex area of knowledge that can inform teaching, providing the curricular model(s) needed to enable teachers help learners come to a better understanding of 'how science works'.

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Appendix

The Draft Cambridge Curricular model of the Nature of Science

Science is about understanding (making sense of) the world (*i.e.*, the universe in which we exist, not just the earth).

We try to understand the world for three main reasons:

- curiosity (people like to make sense of the world) [there is an 'explanatory imperative', we get intellectual satisfaction, also we can feel unease when something doesn't make sense to us; some people like to feel at one with nature, or may even see this as a spiritual quest/practice]
- prediction (to help us plan, to take advantage of opportunities, to avoid problems *etc*.)
- control (to help us make our lives healthy, comfortable *etc*.) [note, according to some scholars this aspect may typically appeal more to boys, and less to girls, so perhaps be sensitive about examples used, *e.g*., avoid electric chairs and atom bombs?]

We try to understand the world by developing theories that enable us to explain what happens, and what might happen in the future (under various conditions).

An explanation is an answer to a 'why' question. A scientific explanation uses scientific ideas (such as theories) to answer questions.

A theory is a way of explaining the relationship between different things. ['things': There is an issue here of theoretical entities, and how they come into being.]

Theories are developed by scientists in response to observations. There are many different types of scientific work, involving different sort of observations. Sometimes these are of natural phenomena (just watching, measuring what is there), and sometimes scientists set up the conditions for an observation – we call this an experiment.

Information collected during observations and experiments is called data.

When we observe a regular pattern in our data, we sometimes call this a 'law of nature'.

Before scientists can carry out an experiment, they must already have an idea of what the relationship might be. An idea about a relationship that has not yet been tested is called a hypothesis. [The hypothesis is tentative – should we call this a guess, an intelligent guess, an informed guess?] Scientists use imagination to form hypotheses [– this is a creative process]. To test a hypothesis a scientists must design an experiment and predict the outcomes if the hypothesis is correct. There are always many possible hypotheses that could explain any observation, so an experiment can never prove a hypothesis is the correct one.

Experiments are subject to errors, because our measurements are not exact, sometimes equipment is not working perfectly, and sometimes we do not fully understand how our equipment will work. (Scientists also make mistakes sometimes when doing experiments!)

Nature is wonderful (literally) and so very complicated. Scientists often try to simplify what they are studying by making models. Models are things [ugh!] that represent part of what we are interested in. Models may be physical (scale models), mathematical (equations), graphical (drawings, graphs, schematics, flow-charts…), or even an analogy (saying how something is like something else). A model is simpler that the real thing [should we use the word phenomena?], but reflects some part of it. The scientist knows the model is not the real thing [phenomenon], but because it is simpler it can help her think about the real thing [phenomenon]. Because the model is simpler than, and different to, the real thing we have to remember that what we learn from the model may not always tell us about the real thing. However, sometimes models can lead to hypotheses that we can test in experiments with the real thing [phenomenon].

It is a matter of judgement when an idea can be called a theory. A theory needs to be able to explain observational evidence, using accepted scientific ideas [concepts?]. Usually a theory explains the results of many observations and/or experiments. To be useful a theory has to make (testable) predictions rather than just explain what is already known (*cf.* Popper, Lakatos). Usually we are not happy [?satisfied] when experimental results don't fit the predictions of theories, and we look for better theories (different, or just developed).

When there are several theories that explain the same observations, scientists usually try to design experiments to help find which seems to explain the phenomena best. Scientific theories are expected to be consistent (not to contradict themselves), and to be as simple as possible. [A theory that is inconsistent is known to need some development; the requirement for simplification less rigorous – who is to say how simple or complex the world actually is! Occam's razor is an epistemological preference, but nature may actually be quite hairy!] No matter how much evidence supports a theory, scientists always accept that other experiments/observations may later show the theory needs to be developed or replaced. For a theory to be useful it must be specific enough to provide useful predictions – predictions that could then be tested. [This is a major demarcation criterion for science *cf.* non-science. (*cf.* Popper)]

Scientists use logic to relate ideas – to make predictions, to design experiments, to interpret observations. A good scientific explanation will be logical, and will use ideas (concepts and theories) that are well-accepted in science.

What is science – the business of understanding the world/nature by making observations, forming hypothesis, designing and doing experiments, building models and developing theories.

Science is a social process. Some scientists work alone, but most work in research groups or teams, and often different groups share ideas and data to help each other (often in several countries). Even scientists who work alone (*e.g.*, Lovelock?) use the ideas of other scientists in their work, and communicate their ideas to other scientists. Scientists can only build theories using the evidence available to them, and rely upon the science that they have learnt (the concepts and theories that they have been taught about and understand). Sometimes well accepted, but flawed ideas, can prevent scientific progress. No scientists can know the whole of science (which is massive), and even great scientists had have areas of ignorance (and made/make mistakes). Sometimes scientists become strongly attached to certain ideas, and find it hard to be fair in deciding whether the evidence supports their favourite theories. Sometimes scientists let friendship, rivalry, ego (big-headedness?) and even prejudice (*e.g.*, against women - *e.g.*, R. Franklin, L. Meitner) influence their judgement: they are human like the rest of us. Luckily, other scientists will check their work and ideas.

Scientific theories develop over time as more scientists develop new models and experiments. Scientific ideas are taken seriously once they are written-up and published in special publications (magazines?) called research journals. When lots of scientists publish work supporting particular theories, and other scientists are unable to develop experiments that contradict the theories, the theories may become so well accepted that they are almost treated as facts or truth. However, there are many examples of widely accepted theories that were later found to be inadequate when new evidence was found (*e.g.,* phlogiston). Overall, though, science seems to be developing more effective theories and models of the world, and these have been used to produce a great many technological advancements (antibiotics, central heating, dyes for clothing, CD players…)