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Teaching about the nature of scientific knowledge and investigation on AS/A level science courses

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**Teaching about
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Abstract

This document describes a small-scale project which designed teaching resources for use by teachers in developing students' understandings about aspects of the nature of science in post 16 AS/A level science courses. The impact of the resources and associated teaching strategies on student learning was evaluated through written diagnostic questions and interviews with students. The project also identified areas of knowledge and expertise that act as barriers and affordances to teachers in using the materials to promote student learning about the nature of science.

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Contents

1 Introduction

The nature of science in the science curriculum

The science curriculum has traditionally focused upon the *technical contents* of science, that is, the theories, generalisations, laws and models that can be found in science textbooks. However, professional organisations and policy makers have long advocated that students should also learn something about the *nature of science itself* through their science education (Nuffield 1998, AAAS 1990, Millar 1996, Royal Society 1985). This policy goal is increasingly reflected in science curricula. In England and Wales, for example, there is an explicit focus upon certain facets of the nature of science in AS/A-level science syllabuses which includes epistemological aspects about how knowledge is warranted as reliable, and sociological aspects about the place of scientific activity in society. This can be seen in the NEAB A/AS[1] Physics syllabus for examination in 1999, which requires that students learn about evaluating the reliability of conclusions drawn from experimental data, and recognising the social, political and ethical implications of science.

There is, however, a considerable gap between the intentions of curriculum policy makers and the teaching that actually takes place on AS/A level science courses in England and Wales. This may, in part, reflect the fact that teachers have only recently been required to teach AS/A level students about the nature of science. Furthermore, although syllabuses refer to the nature of science, course examinations do not include assessment on nature of science issues. In addition, although there are some curriculum materials which address the social implications of science and technology (e.g. SATIS 16-19), few teaching resources exist which address epistemological issues. We therefore decided to focus our attention on developing materials that aim to address epistemological aspects of AS/A level syllabuses.

Students' thinking about epistemological issues in science

There is now a significant body of research which addresses students' thinking about epistemological issues in science, and the implications of this for teaching and learning science (for a recent review, see Désautels and Larochelle 1998). Common themes in students' thinking about epistemological issues in science can be identified within this literature. In this project, we identified three tendencies in students' thinking about epistemological issues in science as the focus of our curriculum development work. These tendencies were chosen because they are well supported in the literature, and because they have significant implications for students' learning in science.

> *Tendency 1: Students' views about the purposes of scientific investigations.*
> Scientific enquiry is often seen as making generalisations following from a series of observations, or making an object, rather than as often involving the testing of ideas (e.g. Driver *et al.*, 1996; Aikenhead *et al.*, 1987). For example, Driver *et al.* (1996) presented a sample of sixty-six 16 year olds with brief descriptions of three experiments which involved the evaluation

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[1] The NEAB syllabus referred to is one of a number of AS/A level courses that was offered in English and Welsh schools to post 16 students during the period of the study. AS/A level qualifications are the most popular route of entry into undergraduate study in England and Wales.

of a theory or generalisation. In each case only 20% to 50% of the student sample described the experiment as an attempt to test an idea or a theory.

Tendency 2: Students' views about the nature of theoretical explanations in science. Theoretical explanations are often viewed as emerging unproblematically from data (e.g. Driver *et al.*, 1996; Aikenhead *et al.*, 1987; Larochelle and Désautels, 1991). For example, Driver *et al.* (1996) presented students with two short stories about theories. In discussing these short stories less than 15% of the sample recognised the conjectural and tentative nature of scientific explanations. In a discussion of students' conceptions of scientific laws and theories, Désautels and Larochelle (1998) describe studies which point to a lack of understanding of the nature of theories and models in science; a lack of understanding that persists amongst students through their university studies, (Désautels, Larochelle and Pepin, 1994). This over-simplification of the relationship between data and theory in science is further supported by a study of university and upper secondary school students (Ryder and Leach 2000) which found that students had difficulty either recognising or articulating the role of theoretical models in interpreting data.

Tendency 3: Students' views about assessing the quality of scientific data. The process of scientific measurement is often seen as unproblematic: data leads to certain knowledge. For example, in a written survey of 422 science students aged 17-18 years from five European countries, students answered questions about the relationship between sets of measurements and the 'true' value of a physical quantity (Leach *et al.*, 1998). In their responses, around 50% of the sample did not show an explicit understanding of the ways in which data spread can be used to assess the quality of a data set. A study by Séré *et al.* (1993) looked at the concepts university students had about measuring data. They found that students recognise that more measurements are better without understanding why. There was a tendency amongst students to ascribe a hierarchy to measurements, attaching more importance to some measurements than to others, rather than recognising the need to treat measurements as sets of data. For example some students attached more importance to the first measurement or the most frequent value. Furthermore, the students in the study did not distinguish between random and systematic errors or between precision and accuracy.

Taken together, these tendencies in student thinking have important implications for student learning in science. For example, Ryder and Leach (1999) show that in undertaking laboratory tasks many students place undue emphasis on description of the phenomenon under study. In doing so they neglect the role of theoretical ideas both in the design of the study and in the interpretation of the resulting measurements.

Teachers' practices when teaching about the nature of science

Science teachers' understandings about epistemological issues in science are largely tacit; teachers have a working understanding of the issues involved but are rarely required to make these understandings explicit (Samarapungavan, 1992). Furthermore, research has shown that teachers' understandings about science often reflect the kinds of naïve views held by many science students (Lederman, 1992). This is significant since teachers' understandings about science is likely to influence the image of science portrayed to students during science teaching (Brickhouse, 1990). Barriers that prevent teachers from promoting student learning about epistemological issues in science have also been identified (Abd-El-Khalik *et al.*, 1998; Smith and Scharmann, 1999).

The teaching approaches often advocated for teaching about the nature of science (e.g. extended project work, group discussion work) are unfamiliar to many science teachers. Given the evidence about science teachers' likely epistemological knowledge, and the unfamiliarity of some science teachers with key teaching approaches, the teacher's role is particularly critical in determining the success or failure of curriculum materials in promoting students' understanding of epistemological issues in science. In this study we therefore decided to examine aspects of the teaching that appeared to act as barriers and affordances to the use of materials in promoting student understanding about epistemological issues in science.

Theoretical underpinnings for the development and evaluation of the teaching activities

The teaching activities developed in this project were designed to address specific learning demands (Leach and Scott, 1995; 1999; 2000). By 'learning demand' we mean the intellectual challenges facing the learner as they address a particular aspect of the science curriculum, that arise due to differences between the social language of school science and the social language which the learner brings to the classroom (Leach and Scott, 2000; p.9). In the context of this study, features of the social language that learners bring to the classroom are summarised in the three tendencies in students' thinking about epistemological issues. The social language of school science is the way in which the purposes of scientific investigations, the nature of theoretical explanations, and assessing the quality of scientific data are normally talked about, or acted out, in science lessons.

We describe the learning demands for students that are addressed by each teaching activity later in this report. There are, however, some general issues that we have taken into account in the design of all the teaching activities. The first of these relates to how teaching about epistemological ideas in science is located and contextualised within science courses. Various approaches have been suggested in the literature, and some of the key differences can be seen in the approaches of Matthews (1994) and Roth (1995). Setting to one side the philosophical differences between the two authors, there is a clear difference in the location and contextualisation advocated for teaching about epistemological ideas in science. Matthews advocates teaching philosophical content through clearly defined programmes of study, which address the nature of scientific knowledge. Such a course could be exemplified by the course 'Understanding Scientific Reasoning' (Giere, 1991) which presents a sequence of focused exercises on the nature of science. By contrast, Roth (1995) introduced students to epistemological ideas in specific contexts, so that their learning about the nature of science was embedded in their learning of science content. Due to the structure of AS/A level syllabuses, it was not possible for us to develop extended units of study on the nature of science. In any case, we imagine that students would encounter considerable difficulty in deploying philosophical knowledge learnt with minimal contextualisation in actual learning situations. We therefore developed six short teaching activities, which relate to the subject matter content of specific AS/A level courses. We did not imagine that short teaching activities such as these would result in radical changes to students' epistemological ideas in science. Rather, we viewed the teaching as providing teachers with opportunities to begin talking with their students about epistemological ideas in science, in the hope that these conversations would continue throughout the course.

The second general issue taken into account in the design of the teaching activities concerns the knowledge about the nature of science to be introduced through the curriculum. There is no portrayal of the epistemology of science that commands universal support in the science studies literature. Furthermore, there is some agreement within the science studies literature, at a very fundamental level, that the scientific enterprise is diverse with the result that it is not possible to generate an unique portrayal of *the* nature of science. Rather than presenting a view of epistemology in science, as is often found in the introductory chapters of textbooks, we therefore decided to address fundamental epistemological ideas in specific contexts. We suspect that most experts in science studies would agree, at a fundamental level, about the epistemological underpinnings of the contexts that are addressed in the teaching materials.

The third issue relates to the nature of students' knowledge about epistemological issues in science. There is some evidence that individual science learners talk about epistemological issues in science in different ways, according to the context (e.g. Ryder *et al.*, 1999; Brickhouse *et al.*, 2000; Leach *et al.*, 2000). Rather than thinking of individual students as having a single view of epistemological issues in science, we therefore conceptualise their knowledge in terms of a profile. Furthermore, although a student might articulate a naïve view about the epistemology of science in one context, responses in other contexts can demonstrate that his/her 'profile' of representations of epistemology in science includes a view that would have been appropriate in the original context. We therefore conceptualise the task of teaching about epistemology in science in terms of enabling students to deploy their profile of epistemological knowledge more appropriately in different contexts (Leach *et al.*, 2000), and becoming better able to articulate epistemological ideas. The approach used to evaluate student learning about epistemology science involved identifying the range of ideas used by students in response to questions, and the way in which those ideas were articulated.

The structure of this report

Six teaching activities were produced during the project. This report has the following aims.

1. To describe the design of these teaching activities.
2. To present an evaluation of the extent to which the teaching activities promoted students' understanding of specific epistemological issues in science.
3. To identify features that acted as barriers and affordances to teachers' use of the activities.

The report has six sections. The next section describes the methodology that underpinned the design and evaluation of the teaching activities. The third section presents the results of the evaluation of student learning, and teachers' experiences of the lessons. In the fourth section key findings of the study are identified and discussed. This is followed by a summary of conclusions and implications of the study for future development and research.

2. Methodology

This section addresses:

- the methodology used to design teaching activities that address the three tendencies in students' thinking outlined in section 1;
- the methodology used to evaluate these teaching activities in terms of students' learning and teachers' responses.

2.1 Designing the teaching activities

Underpinning the design of the teaching tasks is our view of what learning about epistemological aspects of science involves. We are not expecting students to deconstruct their existing views about the nature of science, rather to add to a profile of existing ideas by highlighting in the teaching an aspect of the nature of science which students often fail to draw upon. Each of the teaching interventions has the explicit aim of having students recognise the significance of a particular aspect of the nature of science and to show how this relates to a particular context. The aim of the interventions is to extend the students existing profile of epistemological views. So in addressing, for example, the role of theoretical models we would hope to see evidence that students were able to include ideas about the significance of theoretical models in generating new knowledge when presented with a context outside the teaching intervention. Given the constraints of such short interventions, what we hope to demonstrate in this study is that explicit and contextualised teaching about aspects of the nature of science can help students to develop more sophisticated epistemological profiles. When presented with a context other than that used in the teaching we might expect students to be able to draw upon ideas that were highlighted by the teaching in talking about the new context.

Six tasks were designed for this study, one addressing tendency 1, three tendency 2 and two tendency 3. The activities draw on a range of contexts. Some are specific to biology, chemistry and physics, whereas others are relevant to AS/A level courses in general. In designing the activities we considered a number of key design criteria:

1. the activities present students with appropriate epistemological ideas relevant to a specific scientific context, and equip them to use those ideas in related contexts;
2. the learning aims of the activities are made explicit to the students;
3. the activities use historical and contemporary scientific contexts;
4. the activities involve substantial interactions between students;
5. the teacher is provided with purposeful guidance about managing the activity and achieving closure.

We began by identifying a range of possible activities and contexts that might address the tendencies outlined earlier. Initial versions of the six tasks were developed in consultation with a group of local teachers. These were then piloted with at least one class. Each lesson was observed and audio recorded in order to give feedback about the extent to which teachers and students understood the lesson materials. The students involved in the pilot lessons completed a questionnaire to elicit their reactions to each lesson and teachers were asked for their reactions. The evaluation instruments used in the study to assess the extent of student's learning were also piloted during this phase. The findings from the pilot lessons were fed back to the teacher group and, along with the comments of the teacher group, were reflected in the subsequent revisions to the teaching tasks. The revised teaching tasks were then implemented by a second group of teachers including the teachers in the development group. At the implementation stage the evaluation instruments were administered before and after the teaching.

The teacher group was central to the development of the teaching tasks. The ten teachers, representative of the three school science disciplines, met at twilight sessions at which they were consulted about the development of the materials. This ensured that at each stage of development the activities designed were realistic and appropriate for teachers and students. These teachers also took a lead in implementing the tasks and giving feedback on the challenges they identified in using the materials. A further group of local teachers were involved in either the initial piloting of the tasks or in the implementation phase.

The following table shows how the six tasks map on to the three tendencies. Details of each activity are given below. All activities can be downloaded from http://www.nuffieldfoundation.org/aboutscience.

Activity	Tendency 1 Purposes of scientific investigations[2]	Tendency 2 The nature of theoretical explanations	Tendency 3 Assessing the quality of data
Purposes of science	✔		
Electromagnetism		✔	
Cell membranes		✔	
Continental drift		✔	
Chemical data			✔
Mobile phones			✔

2.1.1 Activity addressing tendency 1: The purposes of scientific investigations

Purposes of science

The aim of this activity is to broaden AS/A level students' understanding of the various purposes for investigations[2] in science, and the variety of methods by which

[2] in this report the word 'investigation' is used as an umbrella term for all empirical work in science. It should not be confused with the more narrow meaning used in the UK national curriculum for science

professional scientists carry out their investigations. As we saw in section 1, there is evidence that A level science students tend to think about scientific investigation as a process of *careful description*, failing to recognise that investigations sometimes involve the testing of *ideas*. For example, students will often fail to make links between the data that they collect during practical work, and the ideas that form the basis of the practical work. For such students, collecting a 'good' set of data is an end in itself. The need to *explain* the data in terms of scientific ideas is not recognised.

To address these issues, students are presented with short descriptions of several research studies. Each description includes an account of the *purpose* of the research. The examples of research were chosen to reflect a range of purposes for scientific investigations:

- ***describing what happens*** – *finding out about a phenomenon or event because scientists think it might be interesting and might start significant new areas of research;*
- ***testing ideas*** – *testing predictions generated from scientific ideas;*
- ***developing methods*** – *advancing scientists' abilities to perform scientific techniques more effectively (e.g. improving yields, cost effectiveness or minimising environmental impact);*
- ***focussing on problems (rather than methods and ideas)*** – *using well-established methods and techniques to investigate new questions. The questions might come from scientific, commercial or social concerns (e.g. developing ways to deal with new strains of bacteria harmful to human health).*

For each description the students are asked to identify the key purpose of the research. Students then draw upon all of the examples to generate a range of purposes for scientific investigation. The teaching aim of this lesson is to show students that scientific investigations have a variety of purposes.

2.1.2 Activities addressing tendency 2: The nature of theoretical explanations in science

Many students do not tend to recognise the difference between theoretical knowledge in science, and objects and events in the material world. For example, they may not recognise the difference between the Newtonian concept of *force*, which is formally defined in terms of related concepts, and phenomena such as pushing or pulling. For this reason they often fail to appreciate the role of theoretical knowledge in modelling the natural world (Ryder and Leach 2000). For many students, theories in science arise directly from data gathered through observations and measurements of natural systems. The three lessons developed to address this tendency present historical analyses of the development of a specific theoretical model. These analyses illustrate the creativity and intuition that are part of gaining new insights into the natural world. By choosing these contexts we have been able to that show how the development of theoretical models involves more than the careful collection of data.

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[2] In this report the word 'investigation' is used as an umbrella term for all empirical work in science. It should not be confused with the more narrow meaning used in the UK national curriculum for science.

In drawing on a range of appropriate contexts for these activities we have used a variety of different kinds of model. For example, Maxwell's model of electromagnetism as a fluid is highly abstract, and emphasises the use of analogies in science. By contrast models of membrane structure represent the phenomenon under study much more directly.

Electromagnetism

This lesson is based on the development of James Clerk Maxwell's model of electromagnetism. The activities in this lesson focus on the use of abstract ideas and analogies in developing theoretical models. The first activity given to students introduces the distinction between observable or measurable phenomena and theoretical ideas that are created in order to explain them. The students are then presented with the story of how Maxwell developed a mathematical model of electromagnetism by drawing an analogy between electromagnetic effects and fluids. Several elements are stressed in this presentation: the abstract nature of the model, the role of analogy, the fruitfulness of the model in unifying theoretical ideas, and the predictive success of the model. In the final activity students work with the more accessible kinetic model of gases to highlight the usefulness of models in making testable predictions that generate further research. There are two reasons for the choice of a new context: it gives students the opportunity to transfer the ideas they have learnt in the first part of the activity and offers a more accessible example of how theoretical models can generate predictions.

Cell membranes

The second lesson presents a history of the development of models of cell membrane structure. These models are less abstract than Maxwell's fluid model of electromagnetism, in that they describe the relationship between entities that exist in cells (e.g. lipids, proteins, organelles). Nonetheless, this analysis of the development of models of cell membrane structure provides a clear illustration of the fruitfulness of going beyond the available data to establish possible models of a natural system that then lead to further research. The distinction between the membrane model and Maxwell's model is not intended to be taught, but is a helpful distinction to make in developing the teaching goals in both contexts.

The story is presented in three stages. At each point students are given evidence that was available at the time, and descriptions of the models of membrane structure that were suggested. The first piece of data is presented without any underlying model: the aim of this is to start students interacting with the presented evidence in a critical way. The first two models are then presented, both of which are equally well supported by the available data and both involve conjecture about the arrangement of proteins for which no evidence was available. The key point at this stage is that the models went beyond available data and involved "informed conjecture" by the scientists concerned. In the final activity students are presented with new evidence and a new model that led to the currently accepted understanding of membrane structure. In the final pieces of evidence contain information about the arrangement of molecules in the membrane that can be explained by only one of the models. By using this sequence of historical snapshots we aimed to communicate the conjectural nature of theoretical models.

Continental drift

This activity sets up a role play in which students are asked to participate in a mock scientific conference on continental drift set at the end of the 1960s. This context differs from those used in the other activities in that the subject matter is not part of biology, chemistry or physics AS/A level specifications. However, this analysis of continental drift does provide a powerful context in which to communicate ideas about the development of theoretical models.

At the beginning of the activity students are presented with a history of the idea of drifting continents. Emphasis is placed on the lack of consensus in the scientific community. Each pair of students is then given a single piece of evidence relating to continental drift, and asked to give an opinion to the class on whether the evidence supports the model of drifting continents. Students are encouraged to ask questions at the end of the presentation of each piece of evidence. This activity demonstrates that there was no single piece of evidence that could be used to prove the validity of the continental drift model. Rather, the scientists involved had to make critical judgements about how each of the available theoretical models could account for the evidence as a whole.

2.1.3 Activities addressing tendency 3: Assessing the quality of scientific data

Students often see the process of scientific measurement as unproblematic: data leads to certain knowledge. Two lessons were developed which address how different kinds of data are handled in science. The first of these uses contexts from AS/A level chemistry to introduce students to sources of uncertainty in making measurements and to present ways in which scientists deal with this uncertainty. The second uses the recent concerns over health risks from mobile phone use to show how the validity, repeatability and reliability of experimental data can be used to judge its quality.

Chemical data

This activity begins by asking students to identify different sources of uncertainty that arise in a series of experimental measurements described on cards. The aim is to highlight the inevitability of uncertainty in any measurement. Sources of uncertainty include random errors, systematic errors, errors arising from the modelling process and human errors. The teacher then makes a presentation outlining ways in which scientists assess and communicate uncertainty in measurements. An issue that arose in the piloting of this activity was students' use of the term 'error'. It was clear that for many students an 'error' was simply a human mistake. In an effort to clarify this issue the activity uses the term 'uncertainty', rather than error, to encapsulate all potential sources of measurement error, including human error. Students are then introduced to the idea of spread as a measurement of random error in a set of data. A teacher presentation deals with handling measured values by looking at the likely range of values. This range could come from either an estimate of experimental error or statistical analysis of the spread of a set of data. The techniques for arriving at these estimated ranges are not dealt with. Subsequent activities engage students with a variety of contexts from professional and school science that require them to draw on the ideas introduced in the presentation. We felt it particularly important to use professional science contexts to reinforce the message that error in science does not simply arise due to 'mistakes' being made by novice students working with poor equipment. To this end an extract from a recent thermodynamics paper is included which presents professional science in the way it is communicated among scientists.

Mobile phones

This lesson addresses issues associated with the determination of risk. Working in groups students are asked to select pieces of scientific evidence to support a case either for or against mobile phones as a cause of health problems. In reviewing the evidence students are directed to assess whether the evidence suggests a causal mechanism for possible physiological effects, or a correlation between symptoms and mobile phone use. Students are also asked to make a judgement about the quality of each piece of evidence by considering issues of validity, repeatability and reliability. Each group of students is then asked to make a case either for or against mobile phones as a cause of health problems, and also to raise criticisms of the evidence presented by the other group. As well as introducing ideas about validity, repeatability and reliability as ways to assess scientific evidence the lesson also highlights the distinction between causal *proof* and an assessment of potential *risk*. Students are encouraged, through reflecting on the material in the lesson, to think not in terms of whether mobile phones are proven to be dangerous, but whether there is sufficient evidence of a possible health effect to modify people's use of the technology.

2.1.4 Constraints on the design of the activities

We aimed to make the teaching part of existing AS/A level courses. The contexts of the tasks are, therefore, drawn from AS/A level course requirements wherever possible. However, given the need to find examples that are accessible to students and effective in communicating the relevant learning aims, and also the desire to include some contemporary science contexts, this was not always possible. With one exception, we designed the tasks to be completed in a sixty-minute lesson with follow up homework in some cases. This reflects a recognition of the time pressure teachers are under to cover current AS/A level course content. Indeed, one of the activities requires more than one lesson and this was found to be an issue for teachers in piloting.

2.2 Design of the evaluation of the teaching activities

The activities developed in the study are evaluated from two perspectives:

1. the extent to which students showed development in their understanding of the nature of science i.e. evidence of student learning;
2. the reactions of teachers and students to the lessons.

2.2.1 Evaluation of student learning

In order to probe the learning that took place as a result of the six lessons we must be clear what development we might expect in the students' understanding. In the evaluation of the teaching we looked for evidence that the students:

a) used more appropriate ways of thinking about a scientific issue as a result of the teaching;
b) became more articulate in communicating their ideas about the nature of scientific knowledge and investigation;
c) drew on the contexts presented in the teaching to illustrate their responses to the different context used in the research probe.

The evaluation instruments (referred to as 'probes') were designed to probe students' understanding within the tendency addressed by the teaching, but using a context different from that presented in the teaching. This approach enabled us to identify students' ability to transfer new ways of thinking developed in the lesson to a different context from that used in the teaching. With one exception, the probes used were based on ones previously developed by the authors. These probes included closed response items. Previous studies using these probes with only closed response questions identified problems in eliciting students' understandings from their responses to closed statements (Leach *et al.* 2000). It was not possible to be sure that students ascribed the intended meaning to each of the closed statements. In this study these earlier probes were adapted wherever possible to include open response questions. By introducing open response questions students were given the opportunity to demonstrate their understanding in their own words. In many cases students were asked to complete closed response items after they had given an open response. This gave students the chance to indicate responses that they felt were appropriate but had not volunteered in their open response, and avoided students being prompted to refer in their open response to closed response items provided previously. All of the probes were piloted in the initial phase of the project and modified as appropriate.

All of the students were asked to complete the probes before and after the teaching. In most cases the post-tests were completed within a week of the teaching. The students' written responses in the post-tests were validated through interviews with a sub sample of students for each task. The post-test interviews with students were also used to probe their responses to the written probes in more depth (see appendix 2). The interviews had the following aims.

- To allow students to elaborate on their responses.
- To probe students' use of terminology (e.g. theories, models). In particular, students were asked to explain what they meant by terms they used in their written responses.
- To assess students' abilities to articulate their understanding after the teaching activity.
- To identify any inconsistencies in students' understanding and probe how strongly held any new ways of thinking were.

The written diagnostic probes

Full versions of the four probes used in the study are provided in appendix 1. Table 2.1 shows the probes that were used to evaluate each of the activities.

Teaching activity	**Poster probe**	**Interpreting data probe**	**Oils probe**	**Leukaemia probe**
Purposes of science.	✔			
The role of theoretical models: **Electromagnetism**.		✔		
The role of theoretical models: **Cell membranes.**		✔		
The role of theoretical models: **Continental drift.**		✔		
Assessing the quality of data: **Chemical data.**			✔	
Assessing the quality of data: **Mobile phones.**				✔

Table 2.1 Probes used to evaluate each lesson.

Poster probe (appendix 1.1)

This probe assessed the range of purposes for professional scientific investigation identified by students. This probe is not set within a specific context. It was hoped instead that in response to an open question students would draw on contexts of their own to illustrate their answer. We were mainly interested in the extent to which students gave suggestions that go beyond the gathering of data or developing new technologies. We were also interested in whether students would draw on the examples presented in the teaching to illustrate their responses in the post-test.

Students were asked to work in pairs. They were given a large piece of paper and the following instructions:

Most people would say that 'doing experiments' is an important aspect of what scientists do. But why do scientists do experiments, and how do they decide what to investigate? Produce a poster/diagram/chart to explain as fully as you can why you think scientists do experiments and how they decide what to investigate. To help us understand your poster, try to give as many examples as you can to illustrate your points.

Teachers were asked to allow 15-20 minutes for this activity. They were told to make students aware that the purpose of the poster is to communicate ideas rather than to be displayed and hence that there was no need to be concerned with presentational issues. The teachers were also asked to encourage students to articulate their viewpoints as fully as possible by posing questions such as: 'that's interesting, what did you mean by that?'; 'can you write that extra detail on to your poster!'. Teachers were asked not to prompt students about issues that they might have missed. The extent to which teachers were able to encourage students to give full responses to the probe without prompting their answers was varied. This probe was piloted with a group as part of an introduction to the teaching sequence it addressed.

For this probe a sub-sample of students was involved in paired interviews. Their pre-test and post-test posters were used to identify a response that belonged to each of three themes identified from piloting. These themes were: epistemological, (including references to testing theories or searching for new phenomena); utilitarian, (including making artefacts or improving people's quality of life); and social, (including any notion of personal gain for the scientist). The analysis of the probe is described in detail in section 3.1.1. Using examples from the posters the interviewer probed the students' understanding of how scientists would use experiments for this purpose. The students were also asked whether they could remember any of the contexts presented in the lesson.

Interpreting data probe (appendix 1.2)

This question was used to probe changes in students' understanding of the role of theoretical models around all three of the lessons that addressed this tendency. The question draws heavily on previously published work (Leach *et al.*, 2000; Ryder and Leach, 2000). The focus of this probe is upon whether students are able to recognise how theoretical models are used to understand phenomena in science. The question is designed to find out on what basis students think that competing models can be evaluated. We were interested in whether their suggested strategies for determining between two models were entirely data focused, or whether they included an examination of internal features of the models. The context is based on models of superconductivity, drawing upon contemporary work in solid state physics. However, theoretical models underpinning the proposed relationships between temperature and resistance are highly technical, and were not presented.

In the first instance, students were presented with two diagrams that showed the relationship between temperature and conductivity of the superconductor predicted by each of the differing models. It was stated in the text that the line on the diagram represented predictions made by each of the models. Students were then shown a diagram that presented measurements of the resistance of the material at various temperatures. All data points had associated error bars. It was stated that although a third research group had collected this data set, it was recognised as good quality data by all research groups at a conference. However, the groups at the conference did not agree about the model underlying the relationship between resistance and temperature. Two different theoretical models were being drawn upon. Both the lines from the theoretical models were shown in relation to the measured data; both lines lay within the error bars for the measurements.

Students were asked in pairs to discuss their answers to the following question: 'What courses of action do you think that the scientists now need to follow in order to decide which theoretical model provides the best interpretation of the data?'. Following a short paired discussion each student was asked to write down his or her individual response to the question.

Students were then presented with eight statements about what the scientists could do next. Students were asked to indicate whether they understood clearly, understood partly or did not understand the statements, and to indicate whether they felt that each statement was an appropriate or inappropriate course of action, or that they were not sure. The statements referred to various strategies involving gathering more data or data sets with fewer errors, examining the assumptions and approximations used by the models, considering the underlying models, looking for other underlying models, and leaving the choice of models up to individual scientists as there is no way of finding out which interpretation is the correct one. Finally, students were asked to choose one or two courses of action as the best ones for the scientists to follow, and to explain their choice.

Previous studies suggest that students who have underdeveloped ideas about the role of theoretical models would give responses focused on collecting more or better data, whereas those that see the importance of theoretical models would also suggest looking at the details of these models. We were also interested in the distinction between suggesting model focused actions in response to an open question and accepting that looking at the details of the models is appropriate in response to prompting within a closed response question.

We recognise a number of limitations in this probe. During the study it became clear from some students' responses that the way the models were presented in the probe caused confusion. For many students the distinction between the predicted lines from the model and the pattern of the data points was unclear. The context of the probe is also challenging and for a lot of students discussion of the assumptions and approximation appeared problematic in this context. However it was felt that the context achieved a balance between being accessible to students and also being a contemporary context in which the students were not aware of any accepted scientific consensus.

Oils probe (appendix 1.3)

This probe is set in the context of nutritionists trying to measure the mass of 100cm^3 of several kinds of oil by making measurements of aliquots taken from a larger sample. Of course, we recognise that there are better methods of determining the mass of 100cm^3 of oil, and professional nutritionists would no doubt use them. In the first instance, students were presented with two sets of 9 measurements of the mass of 100cm^3 of nut oil, arranged in ascending order, and with a mean value. The two sets of measurements were presented as having been made by two different groups from the same original sample of oil. The spread of measurements from one group was wider than from the other group, though both data sets had the same average. The average value corresponded to a measured value on one list. A measured value was repeated in one list. All values and averages were given to three significant figures. Students are asked to write down what the nutritionists should conclude to be the mass of 100cm^3 of oil. Students were then asked to choose one of six possible statements relating to the confidence that could be attributed to findings from the two sets of measurements. The six statements were derived from previous research and piloting. The responses refer to the existence of repeat measurements, and the relative spread of the data sets.

The next part of the question had a similar format. Students were presented with two sets of 9 measurements of the mass of 100cm^3 of soya oil. The design of these data sets was rather different, in that the average values were different and neither average corresponded to any measured value. The difference in averages was small compared to the spread of the data. One value was measured by both groups. The spread of one data set was wider than that of the other. Again, students were asked to write down what the nutritionists should conclude to be the mass of 100cm^3 of oil, followed by a closed response question.

In the last part of the question, students were presented with 2 further data sets. The first consisted of 9 measurements of the mass of 100cm^3 of sunflower oil, the second consisted of 9 measurements for olive oil. The mean values were different. Students were asked whether the mass of 100cm^3 of the two oils was different, and to select from five closed-response answers derived from previous research and piloting. These closed-response statements referred to the spread of the data sets, the existence of repeated measurements and the size of the difference between the averages compared to the spread of the data set.

This question was used in previously published work (Leach *et al.*, 1998) and draws heavily on the work of Séré *et al.* (1993) and Millar *et al.* (1998). The probe addressed a subset of the teaching aims of the lesson. No suitable probe was available to test students' ideas about the sources of uncertainty in science.

Leukaemia probe (appendix 1.4)

This probe was set in the context of a cluster of leukaemia cases around a chemical plant. Several groups of scientists had been asked to investigate the number of cases of leukaemia around this and other similar plants. The outcomes of each of these investigations were contradictory: some found higher number of cases around the plant, and other groups did not. Other groups found higher than expected numbers of cases in areas with no chemical plant. The probe was designed to identify whether students recognised the distinction between identifying a mechanism and identifying a correlation, and whether they were able to suggest how further data might be judged. This question draws heavily on previously published work (Leach *et al.*, 1998).

Following presentation of the leukaemia context, pairs of students were asked to discuss what courses of action they thought that the scientists needed to follow in order to decide what recommendations to make. Following a short paired discussion each student was asked to give his or her individual responses to the question.

Students were then presented with seven statements about what the scientists could do next. Students were asked to indicate whether they clearly understood, partly understood or did not understand the statements, and to indicate whether they felt that each statement was an appropriate or inappropriate course of action, or that they were not sure. The statements referred to various courses of action including gathering more data or bigger data sets, making a decision about the chemical plant based on the existing evidence, looking for other factors that may cause leukaemia, and trying to find an explanation of how emissions from the plant might cause leukaemia. Finally, students were asked to choose one or two courses of action as the best ones for the scientists to follow, and to explain their choice.

2.2.2 Evaluating the reactions of teachers and students to the lessons

In addition to evaluating students' learning resulting from the teaching we also investigated teachers' and students' reactions to the activities. We were interested in identifying the obstacles, for teachers and for students, to developing students' understanding of the nature of scientific knowledge. Full interview schedules are provided in appendix 2.

Teachers' responses
For each of the activities one teacher from the development group was interviewed in detail about their response to the teaching. These interviews focused on the feelings the teachers had about the effectiveness of the lesson and the challenges they perceived in teaching the tasks for the first time. Teachers were asked what they thought were the benefits to students in undertaking these activities. All implementations of the teaching activities were observed and audio recorded. These observations informed the formulation of specific interview questions about aspects of teaching the activities that teachers saw as problematic.

Students' responses
These lessons presented both students and teachers with activities that are not typical of AS/A level science courses. Furthermore, we were conscious that students might not view the material as of direct relevance to the AS/A level courses. For this reason, the students were asked about their reactions to the lessons in a written questionnaire and a sub-sample of students was interviewed. These data provide evidence of the level of motivation they had in the lessons, their perception of the difficulty of the tasks and the clarity with which the aim of the teaching was communicated.

2.3 Implementation and evaluation of the teaching activities

Wherever possible the teaching tasks were evaluated with at least two classes. With one exception these classes were from different schools. The teachers involved in the implementation phase included those in the teacher development group, together with a group of teachers who had not been involved in the development of the teaching activities. All of the lessons were observed and audio recorded. The sizes of the groups used in the implementation are given in Table 2.2.

	A-level classes of teachers from the development group										**A-level classes from additional teachers**				**Number of students**
	B	B	B	C	C	C	P	P	P	P	B	C	C	P	
Purposes of science				9								15 + 15			39
Electro-magnetism							12	11	12						35
Cell membrane	12	11	12												35
Continent-al drift										8					8
Chemistry data					9	11									20
Mobile phones											9		17	11	37

Table 2.2 The number of students involved in the implementation of each activity

Unfortunately we were unable to arrange implementation of the continental drift probe with more than one class. This activity received mixed reactions from teachers, largely because continental drift does not feature in AS/A level science curricula.

Table 2.3 gives the number of students involved in the study and the number of complete sets of pre and post evaluation data for each teaching activity.

	Total number of students involved	Number of complete sets
Purposes of science	39	28
Electromagnetism	35	27
Cell membrane	35	18
Continental drift	8	1
Chemistry data	20	14
Mobile phones	37	7

Table 2.3 The number of complete sets of pre and post evaluation data for each teaching activity

For several of the activities a considerable number of students were absent for either the pre or post test or the lesson, or returned incomplete probes. In part this was due to the timing of the study near the end of the school year close to examination schedules.

The students were also asked to complete a written probe associated with a teaching activity they had not been involved in. The intention was to use these responses as a control data set. However, in many cases this proved too time consuming for teachers to implement. As a result of poor returns this control data is not presented.

For each task a sub-sample of four to six students was interviewed. This sub-sample was selected on the basis of responses to the post-test probe. For each task one of the teachers involved in the implementation was interviewed. All the interviews were audio recorded and fully transcribed. Table 2.4 shows the sample size for the student interviews.

	Number of students in the interview sub-sample.
Purposes of science	8 (4 pairs)
Electromagnetism	6
Cell membrane	4
Continental drift	3
Chemistry data	6
Mobile phones	4

Table 2.4 The number of students involved in interviews.

The open responses in the written probes were coded. Given the small size of the sample this coding was done separately by two researchers and then agreement reached on any discrepancies in the coding. Written responses were validated by comparing them with responses given to these questions during interviews with the same student. Details of the coding schemes used are given in section 3.

2.4 Methodological limitations of the study

This exploratory study was undertaken within a short time scale: the materials were developed, piloted and implemented in a period of six months. Many of the limitations identified here are a result of this short time scale.

The teaching tasks

The design of the teaching tasks was constrained by our decision to limit the tasks to a sixty-minute lesson with homework time (with the exception of the Chemistry Data task). It was our perception that teachers felt under considerable time pressure in teaching AS/A level course and would be reluctant to use a more extended sequence of activities. This view was confirmed by the teachers involved in piloting the activities. The limitation of single lessons is that it meant, in some cases, we were not able to include a new context in which students could demonstrate transfer of new ideas to another context.

Sample size

The relatively small size of many AS/A level classes, and the limited number of teachers involved in the study, mean that the number of students with whom the materials were evaluated is small. Coupled with poor levels of returns for some of the data this results in a small sample size for the evaluation studies. As a result, data from written responses is presented and discussed only when the number of complete responses is sufficient to give a significant effect.

The diagnostic probes

There are limitations with some of the probes. Given the short time scale of the study it was not possible to develop and pilot completely new probes for all the tasks. As a result we used probes developed from previous studies. The extent to which the focus of these probes matched the potential learning gains we might expect from each lesson varies. In particular the 'differences in values from measurement' (oils) probe only addresses one of the learning aims of the lesson it was used to evaluate.

The implementation of the probes

We evaluated the students' learning by using written probes before and after the lesson. This allows us to identify changes in students' thinking and improvements in their ability to articulate their ideas. However in some instances the repeated testing had a negative effect on students' returns. Because the pre and post tests often followed each other within a week, some of the responses reflected a reluctance to complete the probe a second time. In some cases students gave less detailed answers in the post-test, or omitted views that they still held. The short duration of the project also precluded any delayed post testing.

3. Results

3.1 Evaluation of student learning

This section presents findings concerning student learning for each of the three tendencies in turn. For each tendency findings are presented separately for each of the relevant teaching activities. Evidence is drawn from two sources: the written responses to the probes and the interviews with the students. In each instance the probe responses were analysed by two researchers who agreed a coding scheme based on the responses. All the responses were coded individually by each researcher and the resulting codings compared. Where there was a difference between each researcher's coding, agreement was reached on the final code given.

3.1.1 Tendency 1: Purposes of science

Only one teaching activity addressed this tendency. The associated evaluation probe asked students to draw a poster to answer the question 'why do scientists do experiments?' Students worked in pairs, and the coding of the responses was for pairs of students. The coding scheme for this probe separated the responses into two themes, as set out below.

- ***Uses and applications.*** Responses in this category refer to: making artefacts, medicines etc.; improving the quality of people's lives; and improving techniques to make them safer or more economical. Below are some examples from students' written responses.

  "To find cures in order to improve standard of living"

  "Commercial interest, provide drugs for third world countries"

  This category included purposes introduced in the teaching activity as 'describing what happens' and 'testing ideas'.

- ***Ideas.*** Responses in this category refer to the testing of ideas/theories or exploratory research. For example:

  "To prove or disprove a hypothesis"

  This category included purposes introduced in the teaching activity as 'developing methods' and 'focussing on problems'.

Within each of these themes the coding scheme identified the level of sophistication with which the students described these purposes. We identified a hierarchy of response in terms of whether the students emphasised the process rather than the outcome. These codes are detailed below. In both themes uncodable responses were coded as N.

Uses and applications.

O Students give no response in this category.

C Students give one or more responses in this category but in a simplistic form that focuses on the product rather than the research itself *e.g. Make things, improve peoples lives, find cures.*

B Students give one or more responses in this category that relate to the research process instead of just the outcome or product *e.g. improving a technique, addressing a socially or economically relevant question.*

Ideas

O Students give no response in this category.

C Students give one or more responses in this category but in a simplistic form that focuses on a clearly defined outcome rather than the research process itself *e.g. prove a theory, discover something.*

B Students give one or more responses in this category that relates to the research process without an explicit outcome *e.g. test a theory, find out more about something, open up new areas of research.*

The coded responses are shown in Table 3.1. We also identified the changes in the coded responses between the pre and post tests. These changes are summarised in figure 3.2

			Uses/applications theme			Ideas theme	
Group	Student pair		Pre test	Post test		Pre test	Post test
1	A&B		C	B		O	O
1	C&D		C	B		C	B
1	E&F		O	B		C	C
1	G&H		C	B		B	B
2	I&J		O	B		C	B
2	K&L		C	B		C	C
2	M&N		C	C		C	C
2	P&Q		O	B		C	C
2	R&S		C	C		C	B
3	T&U		C	C		C	B
3	V&W		C	C		B	B
3	X&Y		C	C		B	B
3	Z&AA		N	N		N	N
3	BB&CC		N	N		N	N

Table 3.1 Coded responses for the 'Purposes of Science' probe.

Pre and post test responses of students for the purposes of science activity - uses and applications theme.

Pre and post test responses of students for the purposes of science activity - ideas theme.

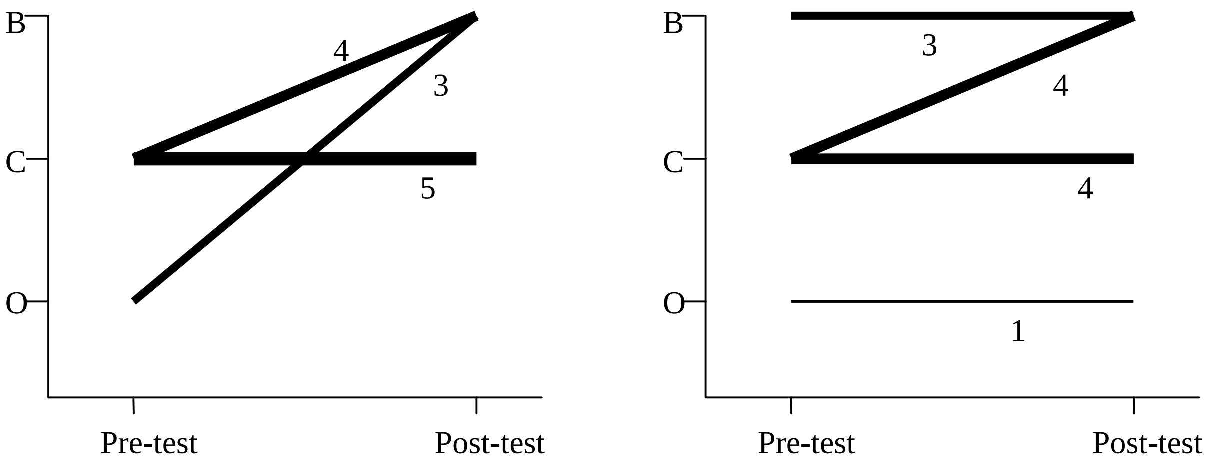

Figure 3.2 Changes in responses for the 'Purposes of Science' task.

Discussion of findings for uses and applications theme

Of the students who gave codable responses to the probe, 58% showed a more sophisticated understanding of the role of scientific research in developing techniques and economically viable products following the purposes of science activity. The majority of developed responses referred to the development of techniques rather than artefacts. With one of the three sample groups in particular the post test responses reflected recall of the list of purposes used in the teaching sequence. All those students, who gave no response that was coded in the uses and applications theme, did so after teaching, suggesting that students who had a limited range of ideas about the purposes of science had broadened their ideas following teaching.

Discussion of findings for ideas theme

Of the students who gave responses which were coded O or C (i.e. provided the possibility of showing improvement within our coding scheme) 44% of students showed improvement in understanding the role of research in testing theoretical ideas. Development for most students was in describing a process of testing a theory rather than statements that reflected a view that experiments would unproblematically prove or disprove a theory.

Issues arising from the interview data for tendency 1 'purposes of science'

All the interviews took place after the teaching and the post-test probe. These interviews highlighted several issues which cause problems for the students despite the teaching. The poster probe responses showed that all the students recognised the role of experiments in testing theories after the teaching. However we need to be cautious in seeing this as indicative of any detailed understanding of the relationship between theory and data. None of the students interviewed were able to give a clear account of how experimental data informs theoretical knowledge without generating such knowledge directly. When questioned about how experimental data relates to theory the students were unable to go beyond describing the use of experiments to test or prove theories:

Student G *I suppose it's looking at everyday life and where the things are coming from and effects that things have on the world, and so we have a look at that and have a look at chemistry behind it.*
Purposes_G_18

The lack of clarity about the relationship between theory and data was part of a more general lack of awareness of how scientists decide what experiments to perform. Some students were unclear about how scientists decide what to investigate:

Interviewer *Do you have any sense of how they [scientists working at a laboratory visited by the student] decided what experiments they were going to do?*

Student A *No actually.*

Interviewer *You couldn't tell that just from going around [the laboratory]?*

Student A *No. I actually have no idea how they scientifically look at something. I don't [know] if it's something, if they did experiment before and they found something different that they want to look at. I don't know.*
Purposes_A_18

Other students saw scientists as autonomous in their work. Scientists decide what to investigate on the basis of what interests them:

Student E *Maybe what they find interesting themselves, or if they've been testing something and they find a different avenue that they could explore maybe brings up something new that they've not thought of before or something.*
Purposes_E_10

In one case the students were trying to reconcile their idea that scientists research what interests them with their own experience of a visit to a laboratory:

Student B *We went to Glaxo Wellcome and they just seemed to have to, we were looking at spectroscopy and they just seemed to have to do what they were told.*

Interviewer *Right. So do you think this was relevant to them because they were interested in it?*

Student B *Well maybe when they first started the job but probably not in the actual individual experiments they were doing.*

Interviewer *So they're not actually saying I'm going to do this experiment because I'm interested, they're just told which experiment to do.*

Student B *But then I expect you go into the field you want to go into because you're interested in it.*
Purposes_B_20

We were interested in probing students' abilities to use contexts presented to them in the teaching sequence when they communicated their ideas about the purposes of science. The interviews suggested that students recalled the purposes of scientific research presented in the lesson more easily than the contexts used to illustrate them. Here is an example of a student struggling to recall the contexts used in the Purposes of Science lesson.

Student E *There was the vaccination one and there was one about, something about the environment, what was it? I can't remember. Oh there was the water testing on the, or was it, no something testing on another planet and testing the rocks or the water or something.*
Purposes_E_16

Key findings
The lesson enabled around half of the sample to exhibit a more sophisticated written response about the purposes of scientific research, at least in the short term. Students were less successful at being able to draw on contexts met in science lessons to exemplify their ideas about the purposes of science. More sophisticated ideas shown by students showed a recognition of science as developing techniques, methodologies and theoretical knowledge as well as useable end products.

3.1.2 Tendency 2: The role of theoretical models in science

The ‘Interpreting Data' probe was used to evaluate all three teaching activities that addressed the role of theoretical models. Students were presented with a context in which there were two different models that both fit an agreed set of data. In an open response students were asked to suggest possible courses of action that the scientists could take. They were then presented with a range of possible actions and were asked to react to these.

The coding scheme identified the extent to which the students recognised the importance of looking at the models as well as collecting more data.

O *Students who do not give an open response which refers to the theory, model, assumptions or approximations made by the two groups AND said either of the following statements were inappropriate courses of action or were unsure of their response.*

- Examine the assumptions and approximations used by each of the groups in developing their theoretical model.
- Examine the extent to which each theoretical model has successfully explained the electrical resistance of other superconducting materials.

C *The statements above were accepted as appropriate courses of action but there is no response to the first part of the probe which refers to the theory, model, assumptions or approximations made by the two groups. This category also includes any responses that suggest the student does not recognise the theoretical models used in this context, for example, referring to a model that is a line of best fit or data set e.g. “Average the two models”.*

B *The statements above were accepted as appropriate courses of action AND there is response to the first part of the probe that states simply that the theory, models, assumptions or approximations should be looked at. There is no elaboration of what might be involved in ‘looking at the models’, OR any elaboration is simplistic and relates to the terms presented in the introduction to the probe such as approximations and assumptions. This category would NOT include responses that suggest the student does not recognise the theoretical models used in this context.*

A *As for category B but the response to the first part of the probe also includes some degree of elaboration of what might be involved in ‘looking at the models’. The elaboration should make clear the role of ideas in the models and not simply reiterate the terms used in the probe. For example "compare theories, see where they differ and consider the arguments” or “look at assumptions or approximations for both models to see if any are invalid making the model invalid”.*

N *Students with uninterpretable, contradictory or incomplete responses to either the open or closed questions.*

Within this hierarchy the key issue is whether the student sees examining the models as inappropriate (coded O), does not suggest examining the models in the open part of the probe but accepts this as an appropriate action when presented with it (coded C), or suggests examining the models as a course of action in the open part of the probe (coded B or A). The distinction between responses coded B and A is one of elaboration. We have tried to give a sense of the ability of students to communicate what it might mean to examine the models in distinguishing between responses coded B and A.

Electromagnetism

The coded responses to this probe for the Electromagnetism lesson are given in table 3.3. The changes in students' responses between the pre and post test are summarised in figure 3.4

		Question1	
Group	Student	Pre test coding	Post test coding
1	A	A	A
1	B	O	B
1	C	A	A
1	D	A	A
1	E	A	A
1	F	C	C
1	G	C	C
1	H	O	O
2	I	C	B
2	J	B	B
2	K	O	O
2	L	O	O
2	M	N	N
2	N	O	B
2	O	C	O
2	P	O	C
2	Q	O	N
2	R	C	A
2	S	N	N
3	T	C	B
3	U	C	B
3	V	B	B
3	W	O	A
3	X	C	A
3	Y	O	B
3	Z	O	O
3	AA	O	O

Table 3.3 Coded responses from the Interpreting Data probe for the Electromagnetism lesson.

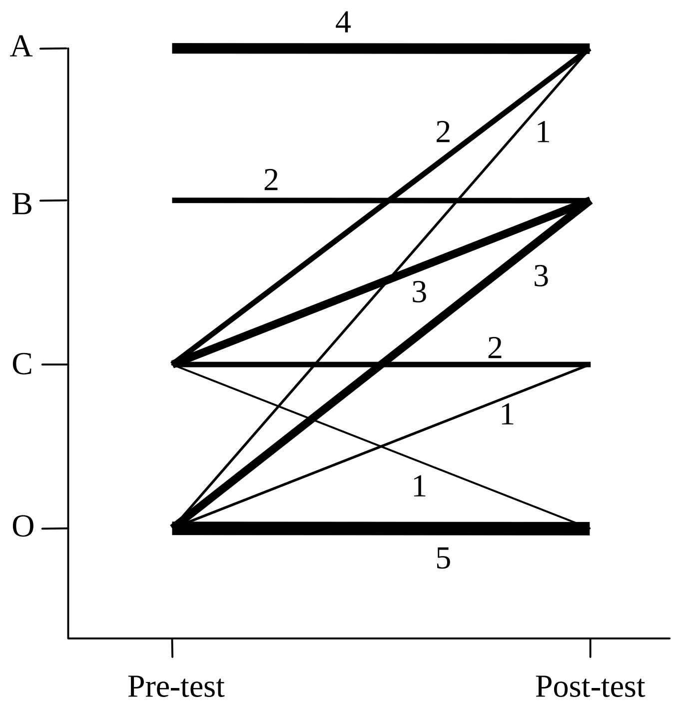

Figure 3.4 Changes in response from the Interpreting Data probe for the Electromagnetism lesson.

Of the students who were coded O or C in the pre test, 56% showed an improvement in their understanding of the role of theoretical models. These students were the ones who gave more explicit recognition of the importance of the models in the probe after teaching. Those students coded B or A we saw as already recognising the importance of models prior to the teaching. The distinction between B and A was one of elaboration rather than a change in understanding of the role of models. No students moved from B to A as a result of the teaching. A significant number (50%) of students coded O in the pre-test showed no progression and a smaller but still notable number of students coded C in the pre-test showed no progression.

Cell membranes

The extent of students' learning as a result of this activity was also evaluated using the interpreting data probe. The coded responses to this probe for the Cell Membrane lesson are given in Table 3.5. The changes in students' responses between the pre and post test are summarised in Figure 3.6.

50% of the students coded O to B in the pre-test showed an improvement according to the coding scheme used. Of the students who were coded O or C in the pre test, 38% showed an improvement in their understanding of the role of theoretical models. These students were the ones who gave more explicit recognition of the importance of the models in the context of this probe after teaching. We saw those students coded B or A as already recognising the importance of models prior to the teaching. Of the 4 students coded as B in the pre-test, 3 were coded A after the teaching. The distinction between B and A was one of elaboration rather than a change in understanding of the role of models. A significant number (50%) of students coded O in the pre-test showed no progression.

		Question1	
Group	Student	Pre test	Post test
1	A	B	A
1	B	N	O
1	C	C	C
1	D	O	B
1	E	B	A
2	F	O	O
2	G	O	O
2	H	O	O
2	I	C	B
2	J	O	O
2	K	O	A
2	L	O	C
2	M	B	B
3	N	O	C
3	O	O	N
3	P	B	A
3	Q	O	O
3	R	C	C

Table 3.5 Coded response from the Interpreting Data probe for the Cell membranes lesson.

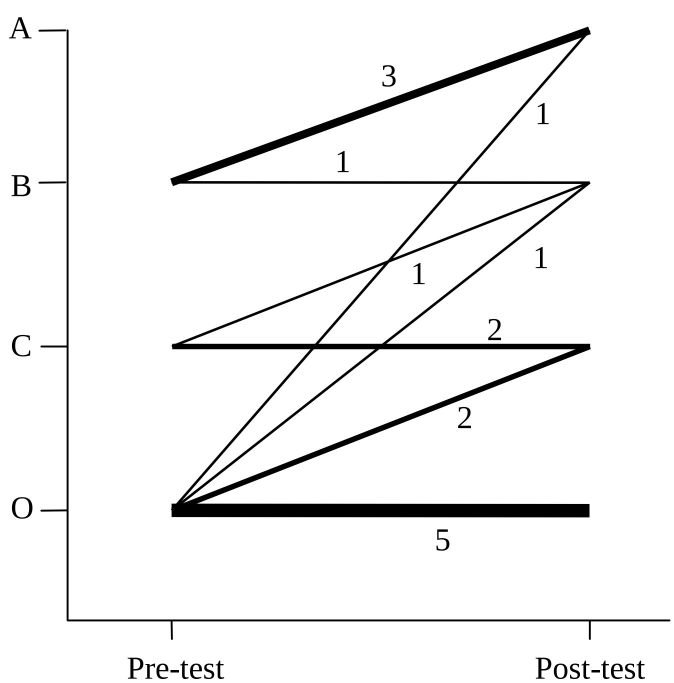

Figure 3.6 Changes in response for the Cell membranes lesson.

Continental Drift
Unfortunately we were only able to arrange to implement this activity with one group. The number of complete sets of probes for this group is very small. As a result we do not have similar findings to present as for Electromagnetism and Cell Membranes.

Issues arising from the interview data for tendency 2 'role of theoretical models'

The interviews with students that followed the post-test probes provide some insights into the development that took place in their understanding of the role of theoretical models. Interviews for all three tasks evaluated using the Interpreting Data probe raised similar issues. The interviewer began by asking the students to describe what action the scientists should take next in the context of two theoretical models that both fit an agreed set of data. In the remainder of the interview students were asked to justify their choice and elaborate on their understandings of key terms (see interview schedule, appendix 2).

- *Students who showed gains as a result of teaching*

A significant number of students across the two activities for which we have data showed a development in their understanding of theoretical models. These students were able to articulate views in the interview that showed recognition of the importance of generating models. The following students all gave responses in the open part of the pre-test probe that involved collecting more data with no reference to examining the models. Following the teaching they all mentioned the usefulness of examining the models.

Student T in response to the Electromagnetism lesson:

Interviewer	*I wonder if you could just perhaps talk me through again some of the ideas you had about what should happen next.*
Student T	*Oh erm ... I think it was go back and look their main like theory of it all, see if they've all done it correctly. If they haven't then re-look at another like an outside source which can give you an individual view of the theory that they have so, or even if you reduce the errors on the error bars, see which is more potentially closer to each [model].*
Interviewer	*Right, yes, okay. One of the first things that you said just then was about going back and looking at whether they'd done it correctly. Tell me a bit more about what you mean by that.*
Student T	*Whether they've got the main theory points and they've taken in consideration with them and done, worked everything out to plan as they set out to do.* Electromagnetism_T_2

Student X in response to the Electromagnetism lesson:

Interviewer *I just want to ask you what possible courses of action do you think the scientists now need to follow in order to decide which theoretical model provides the best interpretation of the data?*

Student X *There's all sorts of stuff (…)they could look at the theoretical models a lot more because they might find that they've assumed certain things that the other group hasn't so that will explain differences in the models.*
[…]

Interviewer *Okay. Let's go onto another one of the things that you mentioned. That is this idea about assumptions. Tell me a bit more about what's involved there. This is when you were talking about theoretical models.*

Student X *Yes. If the two groups have formed a theoretical model on things they already know about, models they already know about, they might have, like if one group has assumed something to be like a certain model, the scientists already know it's proven and the other group haven't. If the second group introduced that into their model then they might get two models that were a lot more similar, if you see what I mean.*
Electromagnetism_X_1

Student V in response to the Electromagnetism lesson:

Interviewer *I just want to ask you (…) what possible courses of action do you think the scientists now need to follow in order to decide which theoretical model provides the best interpretation of the data?*

Student V *I think they should go and have a look at what assumptions and things they've made because if they've made different ones, you see, it'll just throw them both totally in different directions won't it?*
Electromagnetism_V_5

In all these cases the students suggested that the scientists should examine the models. This response was only given in the post-test probe and interview after teaching. However the extent to which they were able to communicate what it might mean to examine the models was more variable. Only one student in the interview sample was able to describe what the approximations and assumptions in this context might involve:

Interviewer *Right. It would help if you could give me an idea of what the assumptions involved.*

Student X *Well like they've made assumptions on what the superconductor is like on a microscopic scale using existing models that they've got of known*

materials and I thought if one group's used one microscopic model and another one hasn't used that particular one, if they got together and decided which one to use and use the same one it might give them too much similar models.
Electromagnetism_X_6

Student T gave a more typical response when asked to elaborate on their written response in the probe:

Interviewer *You said here [in the written probe] "I think the researchers need to look at the assumptions they've made and compare them with the approximations used by each group of researchers which in turn should develop both of the researchers theoretical ideas."*

Student T *Yes. With that they need to look at ... the assumptions like with a, the changing in temperature is changing resistance and their outcomes are slightly above the error-bars, or below them, which are their approximations. And so if they look back at the theory that it started with, compare them both together, make sure they've done everything correctly, if not they might have had like ... they might have been out a little bit with the theory (…) and it might change their view which would change the assumptions and get a different outlook on the graph.*
Electromagnetism_T_6

In some cases students who said it would be appropriate to examine the model then gave a confused account of what this might mean. When model-focused views of the context presented in the probe were probed during interviews many students fell back on more secure views about the value of getting better data to determine which was the better model. Indeed for a number of students their understanding of the distinction between the data, models and predicted values from the models showed ambiguities. As a result, we need to be cautious in interpreting the responses given to the interpreting data probe as indicating secure developments in students' understandings.

- *Students who appeared to show no gains as a result of teaching*

There was a significant group of students who appeared to show no development in their understanding in response to the teaching. In particular about half the students who stated it was inappropriate to examine either the theoretical model itself or the approximations and assumptions used in developing the model, held this view after the teaching. We have identified a number of issues which appeared to create problems for this group of students in developing more appropriate ideas about theoretical models.

i) These students failed to grasp the central aims of the lesson

In the interviews there was a feeling that those students who had gained the most from the teaching had recognised the aim of the lesson as whole. For them the explicit message about theoretical models in the teaching was apparent. Student X, who gave a very thoughtful account of the role of models in the interview, illustrates this in describing the aim of the lesson as teaching about models:

Interviewer *What do you think the teacher (…) wanted you to learn in the lesson?*

Student X *Erm ... well I think one of the things I think to get the feeling of (…) that a model, it's not, it will never be able to explain actually what is happening. That sounds a bit strange but what it is, it's giving you example of something that like represents it happening. Like you can't visualize like a magnetic field or something but you can make models which, of something that we can see and understand, that simulates that effect. That's not actually what happens but that's how we can represent it, does that make sense to you?*
Electromagnetism_X_14

In contrast Student Z, who showed no gains as a result of the teaching, clearly did not understand the aim of the lesson.

Interviewer *(…) what do you think [the teacher] wanted you to learn during the lesson?*

Student Z *I don't really know to be honest.*
Electromagnetism_Z_18

However, from observations of the lessons and interviews, there is evidence that these students engaged with the activities. It appeared that each activity in isolation made some sense to students in terms of the task they were asked to complete. However, these students failed to grasp the overall teaching aim of the lesson.

ii) Some students had a very weak understanding of what a theoretical model is
In the context of the 'interpreting data' probe this group of students seemed unable to understand the distinction between the models, any predicted values and the data. In the interview these students talked about the data and the model interchangeably. It is possible that this confusion was enhanced by the context used in the probe.

iii) 'Average the models'
This was a common response in the probe and was followed up in the interview. Students who gave this response typified the confusion between model, predicted values and data. Student Z gave a typical response when questioned about averaging the models:

Student Z *Erm ... I think they should draw up another model and then they should take an average of all of the models from all the different groups and then that'll give them a more accurate model to go by and then they should use that model as the final one.*

Interviewer *Yes, okay. The other model that they would draw up, where would you see that as coming from?*

Student Z *From using all these different models.*

Interviewer *Right. So the other model is coming from these two models.*

Student Z *Yes. And averages.*

Interviewer *From the averages of ...*

Student Z *Both models. Both the different ones from different groups.*

Interviewer *Yes. So the average of the models rather than the results, or would you think ...*

Student Z *Probably the results I'd say.*

Interviewer *So the averages of the results?*

Student Z *Yes.*
Electromagnetism_Z_3

iv) Resolving the conflict.
In the absence of a clear understanding of the role of theoretical models in science, students drew on ideas for resolving conflict from outside science. Responses relating to the scientists 'getting together' to 'share ideas or resources' were common. For example, in the following extract Student U looks for a majority viewpoint from other scientists to resolve which model is the better one.

Interviewer *Any other things that the scientists might need to do next?*

Student U *They could look at other models from other groups to see if some agree with one more than other.*

Interviewer *Right. So why would they do that?*

Student U *To get more opinions, different viewpoints. See if one agrees more with one of the models.*

Interviewer *Right, okay.*

Student U *See [if] it is of the majority really.*
Electromagnetism_U_6

Furthermore, student V sees discussion between the two groups as offering a resolution to the conflict:

Student V *So if they go back and compare, come to sensible conclusions on what they think should be there after discussion, then they should get the same thing and it should be better, more accurate.*
Electromagnetism_V_6

Taking into account potential problems with the probe there seems to be a significant group of students who are not able to differentiate clearly between models based on theoretical ideas and data collected through experimental measurements. For these students a single lesson is not sufficient to give them an understanding of the role of theoretical models. We are not surprised by this finding. Furthermore, it seems that some students are so unclear about the distinction between the models presented to them and experimental data that they are not able to grasp the teaching points of the kind of activities developed by this study.

Key findings

There was a general trend of development following the lessons for many students. Development was either in terms of increased elaboration about the role of models, or a recognition that an examination of the models was relevant to resolving the conflict. However, there was a significant number of students for whom the lessons had little impact on their ideas about theoretical models. Students for whom the lesson had little impact either failed to recognise the theoretical nature of the models presented, or drew on social experiences of resolving conflict to address the conflict between the models.

3.1.3 Tendency 3: Assessing the quality of data

Two teaching activities addressed this tendency: Mobile Phones and Chemistry Data. The ‘leukaemia' probe was used to evaluate learning for the Mobile Phones activity. The 'oils' probe was used to evaluate learning for the Chemistry Data activity.

Mobile Phones

The ‘leukaemia' probe used to evaluate learning for this activity presented students with a context in which scientists had obtained conflicting evidence of the possible link between a leukaemia cluster and a nearby chemical plant. Students were asked to suggest possible courses of action the scientists should take. They were then presented with a number of courses of action and asked to indicate whether each of these was considered appropriate or inappropriate.

The coding scheme identified students' responses according to one of three categories of action: gathering more data or looking at other factors, establishing correlation, and looking for a possible mechanism. Within the second and third of these categories the sophistication of the response is identified by codes 1 and 2. There is no clear hierarchy of response in this probe although responses coded C and M could be seen as a development on those coded O.

Coding scheme for ’leukaemia’ probe

O ***More data / other factors.***
1 *Do more studies or collect more data of the same type.*
2 *Look for, or analyse, other factors which might be the cause without any reference to correlation or mechanism.*
3 *Putting the problem down to bias, e.g. ’get other scientists to do the same thing again’.*

C ***Correlation***
1 *Students mention looking for a statistical link between the chemical plant and leukaemia. No mention is made of looking for a mechanism.*
2 *Students mention factors that would strengthen a correlation, e.g. replicability, increasing sample size, appropriate sampling.*

M ***Mechanism***
1 *Evidence that the student thinks that identifying a plausible mechanism for a substance from the plant causing leukaemia is important.*
2 *Evidence that the student recognises the question of validity in relating findings about physiological effects in animals to leukaemia in humans.*

The coded responses for this probe are given in Table 3.7. Of the three groups who were taught the mobile phones lesson, only one group completed the pre and post test probe. The number of completed returns for this group was very low and as a result we only have data for a very small number of students.

School	Student		Pre test	Post test
1	A		M1	C2
1	B		M1	O1
1	C		C1	O2
1	D		C1	C2
1	E		O2	C1
1	F		O1	C2
1	G		O2	O2

Table 3.7 Coded responses from the 'Leukaemia' probe for the 'Mobile Phones' lesson.

From this small number of students there appears to be no clear development identified by the probe. Students switch their responses between looking for other factors, correlation and a mechanism. This probe was adapted from one used in a previous study. When we look at the teaching aims of the Mobile Phones activity there is a clear gap between the teaching aims and the probe. The teaching activity emphasised validity, reliability and repeatability of data as tools for assessing the quality of data. The probe did not address any improvement in student learning specific to this aim.

Chemistry Data

The 'oils' probe associated with this teaching activity presented several sets of data for the mass of a quantity of oil (see section 2.2.1 and appendix 1.3). These data sets had different amounts of spread, included repeated values and were presented with the average of the data set. The first two questions used open responses in which students were asked to select a value from the two sets of data and explain the reason for their choice. The coding scheme identified whether they gave an appropriate value and whether they were able to give a reasonable explanation of why they chose that value.

Coding scheme for the 'oils' probe

Data set 1

O Students state a result for the mass of oil that is other than the average of the two sets of data.

Cw Students state the average of the two sets of data as their result but give a reason that incorporates an incorrect idea about what averages represent e.g. *"because it is equidistant from both ends."*

C Students state the average as their result and their reason does not refer to the average as being representative of a set of data e.g. *"the average gives an overall answer, it is going to be the best estimate"*.

B Students state the average as their result and their reason refers to the average as representing a set of data e.g. *"because the average takes into account all other measurements", "an average eliminates the possibility of choosing an anomalous result"*.

Data set 2

O Students state a result for the mass of oils that is neither the average of both sets of data or the average of the set with the least spread.

C1w Students state a result for the mass of oils that is the average of both sets of data but give an incorrect reason.

C2w Students state a result for the mass of oils that is the average of the set of data with the least spread but give an incorrect reason.

C1 Students state a result for the mass of oils that is the average of both sets of data but do not give a reason that refers to the benefit of a larger sample size.

C2 Students state a result for the mass of oils that is the average of the set of data with the least spread but give a reason that does not refer to the smaller spread of data set A.

B1 Students state a result for the mass of oils that is the average of both sets of data and give a reason that refers to the benefit of a larger sample size e.g. *"the greater the number of samples the more accurate the mean is likely to be."*

B2 Students state a result for the mass of oils that is the average of the set of data with the least spread and give a reason that refers to the smaller spread of data set A e.g. *"group A's work seems to be more accurate because they have a smaller range of measurements"*.

Data Set 3

This question provided students with a set of closed response options. The statements offered were:

A. The mass is greater for olive oil than for sunflower oil, because the average is larger.
B. There is no difference in the masses, because the range of measurements in each set is much bigger than the difference between the averages.
C. There is no difference in the masses, because the value 94.1 is in both sets of measurements.
D. We cannot be sure that there is a difference in the masses, because the range of measurements in each set is much bigger than the difference between the averages.
E. We cannot be sure that there is a difference in the masses, because the value 94.1 is in both sets of measurements.

The coded responses for this probe are given in table 3.8. The changes in students' responses between the pre and post test are summarised in figure 3.9.

			Data Set 1			Data Set 2			Data Set 3	
School	Student		Pre test	Post test		Pre test	Post test		Pre test	Post test
1	A		B	B		C1w	C2		D	D
1	B		B	B		C1	C1		D	D
1	C		B	B		C1w	B2		D	D
1	D		B	B		B1	C1		D	D
1	E		C	C		C1	C1		D	D
1	F		B	B		B1	B1		D	D
1	G		Cw	B		B1	B1		D	D
2	H		B	B		B1	B1		A	A
2	I		Cw	B		C1w	C1		A	A
2	J		B	B		B1	B1		A	D
2	K		C	C		B2	C1		A	D
2	L		C	C		O	N		D	D
2	M		B	B		B1	B1		D	D
2	N		C	C		B1	B1		A	D

Table 3.8 Coded responses from the 'Oils' probe for the 'Assessing the Quality of Data: Chemistry Data' lesson

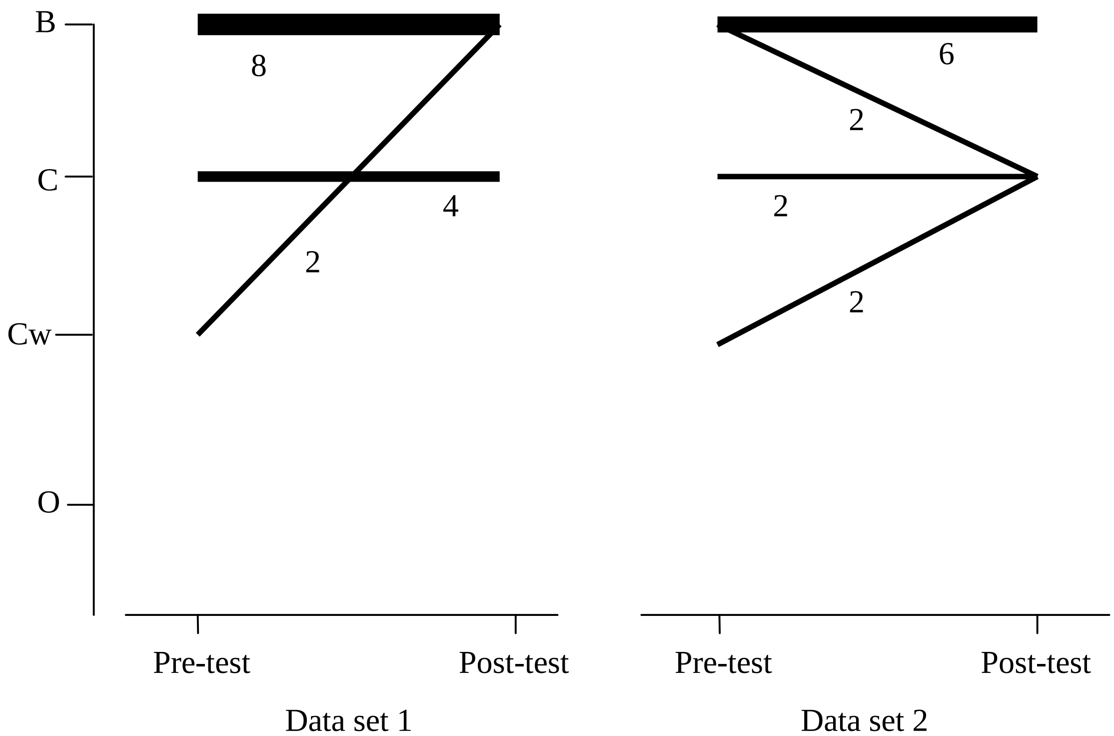

Figure 3.9 Changes in response for the 'Chemistry data' lesson.

For the first data set, all of the students in the sample selected the average as representative of the set of data. This contrasts with findings from previous work (Leach *et al.*, 1998). Of these 57% were able to give a reasonable explanation, most commonly that the average takes account of all the measured values. Two students initially gave reasons for choosing the average that showed a misunderstanding of what the mean value represents, e.g. *"because it is equidistant from both ends"*. Both these students were coded B after teaching. Using the average of a set of data seems to be straightforward for students. However, giving an explanation is more problematic. Similarly, all but one student was able to select an appropriate value for the two sets of measurements in data set 2. Of the students in the sample 64% were able to evaluate data set 3 on the basis of the spread of the data before teaching. Of the 5 students who focused on the difference between the averages, 3 recognised the spread of the data as important after teaching.

This probe did not assess all of the learning aims associated with the Chemistry Data teaching activity. Whilst the teaching activities did deal with issues of spread in data this was built around the broader idea of dealing with experimental error. For the students interviewed the main aim of the lesson was identifying sources of error in experimental work. The 'oils' probe did not address this aspect of students' understanding.

3.2 Teachers' reactions to the materials

In addition to evaluating student learning we also examined teachers' experiences of teaching about the nature of science on AS/A level courses. A number of issues were identified through observations of the lessons and informal discussions with teachers in the pilot phase of the project. The issues were followed up in interviews with teachers in the development group after they had taught the lessons.

3.2.1 Teachers' lack of confidence

It was clear from conversations and interviews with the teachers involved in this study that they found the teaching challenging and unfamiliar. Several of the teachers described the difficulties in teaching issues that they did not feel fully confident about. Some teachers felt their lack of confidence in their own knowledge about the nature of science was a problem during the teaching. They considered it important to teach the ideas presented in the lesson but found it difficult to focus the teaching on the aims of the lesson. This seemed to be because the ideas presented were ones the teacher had not thought through prior to seeing the notes on the lessons.

Teacher A *It's not something I was particularly happy with teaching again. You come to it and it's something that you're fine with in your own head and you look through and you think 'fine', but then when it comes to standing up and having to deal with things, comments that pupils and students have made and how to tie that into the work. You think yes, but, that's fine but it just need tightening up a little bit and how do we do that?*

Interviewer *It sounds to me that you're feeling that you, yourself, were not that confident about the issues that you were teaching. Is that fair?*

Teacher A *Yes. That's fair, God yes.*
Chemistry data_TA_19

In other cases teachers found the lessons challenging but felt reasonably confident once they had spent time working through the supporting teachers' notes in preparing for the activity.

Interviewer *What were your general reactions to the lesson?*

Teacher B *I think initially I was a little bit concerned about having to teach something that I hadn't really any knowledge, or little knowledge of myself and clearly you do that in school and have no problem with it, but having to teach it to an A Level audience where you know that they were going to be more probing and you really need that personal background to answer those, I was initially concerned. I think when I sat down and spent a bit of time preparing it and using the materials you sent along, it seemed fine.*

Interviewer *So initially challenging, thinking about both sciences and the scientists but the materials helped us to get inside it and you felt in the lesson reasonably confident about that. Do you think that's fair comment?*

Teacher B *Yes*.
Continental drift_TB_1

These two different points of view were borne out in observations of the lessons. Where teachers were able to make clear sense of the guidance provided the lesson aims came over more clearly in the teaching.

On the advice of teachers in the development group we attempted to design the materials in a way that recognised that most teachers have little experience of teaching about the nature of science. The following quote reflects the feeling that guidance was important when the lesson was being taught for the first time.

Interviewer *Would it have been problematic to have done the lesson first time without that [the teachers' guidance notes], or would you have been okay just to sort of pick up the material?*

Teacher C *No I think for the first time I needed that. I needed that because I needed to know what I was doing but then I suppose with anything once you've done it once, when you do it the next time you add a bit of yourself into it because you're a bit more confident with it*.
Cell membranes_TC_36

The inclusion of teaching aims relating to the nature of science in exam syllabuses and initial teacher training curricula is relatively recent. As a result many teachers have no experience of teaching the issues identified in this project. Nor have they had any training, either about the issues themselves (often given little mention on undergraduate science courses) or how to teach them. Hence, we are not surprised by the lack of confidence expressed by teachers. The lessons and the guidance given to teachers were designed as a starting point in a move toward increased exposure of the nature of science issues on AS/A level courses. We are encouraged that all the teachers interviewed said they would use the lesson they implemented again in their courses, usually in an adapted form to suit their needs.

3.2.2 Teachers saw the type of activities developed in the lessons as novel

In order to encourage students to engage with the ideas presented to them there was an emphasis on student-student interactions in the activities. The teaching activities tended to involve students responding to a context through paired discussion, followed by a clearly focussed pulling together of their ideas by the teacher. The aim of the paired discussion was to prime students for a focussed intervention from the teacher by getting them to think about the issues. For example in the Electromagnetism lesson the students are asked to place a number of statements on a scale from 'real phenomena' to 'abstract ideas'. The purpose of this is to stimulate students to think about abstract ideas before the teacher makes a clear teaching point about the role of abstract ideas and analogies in science. Observations of the lessons showed that this aspect of the lessons was more effective when the teacher kept the paired discussion short. In this case the students were able to engage with the issue and develop their own ideas sufficiently to enable them to recognise the points made by the teacher in the lesson. For some teachers there was a conflict between the short time suggested for the discussion and a sense that they did not want to interrupt discussion before students exhausted all their ideas.

A further issue arising from observations of the lessons was the problem of dealing with 'wrong answers'. The lessons have very clear teaching objectives, yet in many cases teachers were reluctant to tackle explicitly ideas offered by the students that contradicted the teaching aims of the lesson. In interviews teachers were hesitant in putting forward the idea that there could be wrong answers in the context of lessons about the nature of science. Some of the teachers in the study also expressed the need to handle students' suggestions sensitively, which in some cases may have led to an ambiguous response from the teacher. The (inappropriate) message that there are 'no right answers in science' was presented on more than one occasion.

3.2.3 Teachers often felt that the teaching aims of the lessons need to be reinforced in subsequent teaching.

Several of the teachers interviewed were clear that one of the potential benefits of these lessons was in providing a reference point to draw upon later in the course. They saw themselves referring to the ideas raised in the lessons during their teaching of subsequent topics, for example by drawing on the experiences of the Electromagnetism lesson when teaching other theoretical models on the physics curriculum.

Teacher D *So what I'd say is it has provided an opportunity for me to, if you like, revisit some of those ideas through the work that I'm doing. I'm not saying that I wouldn't have used that method anyway but it's allowed me to refer back to their experiences that they had.*
Electromagnetism_TD_11

3.2.4 Teachers generally seemed motivated by the lessons

The overall feeling of the teachers interviewed was that the lessons were effective. They saw the ideas taught in the lessons as worthwhile. The only caveat to this was a sense that teachers felt under a great deal of pressure to get through the content of the AS/A level course. Often the lessons were well received in part because they are short teaching sequences of an hour or less. However, all the teachers interviewed said they felt the lesson was worthwhile and would use it again in some form. In some cases teachers valued the novelty of the activities; they appreciated the kind of thinking and discussion that was a part of the lessons.

Teacher C *I liked the structure of it [the Cell Membranes lesson]. I liked the resources. I think I need to (…) talk about the outcomes of it because*

that's what impressed me most with the kids really. (…) I thought it was a useful tool for them to be able to realise the progression, the progression that's made in scientific discoveries, if you like. Because I don't think that in general they're aware of it. You tell them something in a lesson and they just kind of believe it. Yes, that was discovered one day and that's it. They don't actually think that there's anything before that. (…) I thought that the lesson was a good way of getting it across that things aren't just discovered one day into the complex way that we know them today.
Electromagnetism_TC_2

3.2.5 A summary of teachers' experiences

There is no agreed, single view of the nature of science. However students often held views that were clearly wrong. Teachers did not seem confident enough about what counts as right and wrong answers to give students clear feedback on their performance as they would on a conceptual topic. Nature of science lessons were often seen as 'woolly' with no clear answers to give students. Teachers either felt their own understanding of the nature of science was insufficient to enable them to handle students discussion, or else they were unsure about correcting inappropriate views in the classroom. In one instance a teacher closed a debate between students about the reality of magnetic lines of forces by suggesting there were no wrong answers in science.

However, these issues are set against a generally positive reaction from teachers. All of the teachers involved felt that the issues tackled in the lessons were important and relevant to AS/A level students. Most of the lessons were seen as effective and with sufficient guidance for teachers to use them without too many problems.

4. Discussion

4.1 The process of designing the teaching activities

It was clear from the inception of this study that both theoretical and pragmatic concerns would influence the design of the teaching materials. The rationale for the design of the tasks was to develop materials to support teachers in teaching explicitly the issues identified in tendencies 1 to 3 (see section 1) within existing AS/A level courses. These materials would use contexts from contemporary and historical science that were part of the AS/A level specifications. This rationale had to be reconciled with a number of practical issues that needed to be addressed if the materials were to be effective in the classroom. These issues have an impact on the extent of development in students' understanding that we might expect to see as a result of the teaching.

The length of the intervention
We proposed to develop short sequences of activities that teachers could use with guidance as part of an AS/A level course. It was clear that teachers felt under considerable pressure to cover the subject matter content of AS/A level courses and were reluctant to pilot teaching sequences longer than a single lesson. The activity on assessing the quality of data in chemistry in particular proved problematic due to its length. As a result 5 of the 6 activities are designed as single lessons. We cannot therefore expect radical developments in students' understanding of the nature of scientific knowledge, on the basis of such short interventions by the teacher. However, by focussing on a particular aspect of the nature of scientific knowledge, and making the aim of the teaching explicit, we would expect students to be able to draw upon a wider range of ideas about the nature of science than they were able to prior to the teaching. Also, teachers can pick up the key issues in subsequent teaching, having opened it up in these lessons.

The contexts used
Our aim was to use historical and contemporary contexts from science to teach students about particular features of the nature of science rather than attempt to convey a general, philosophical viewpoint to students. It was also our intention to use contexts that involved subject matter that is part of the AS/A level specifications. We had some difficulties in identifying contexts that were accessible to AS/A level students, relevant to the AS/A level specifications and illustrative of the issues we wanted to teach. As a result, more of the contexts used are historical than we intended. The advantage of using historical examples is that an account can be presented which reaches closure. In the case of contemporary examples, lessons may quickly become out of date as new knowledge is developed. We also decided to use the story of the theory of plate tectonics, which is not linked to the AS/A level specifications, because it provides such a clear illustration that the relationship between theory and data is not straightforward. The use of plate tectonics as a context proved to be an issue for some teachers. This was either because it was seen as a problem spending time studying subject matter outside the specifications, or because teachers did not feel confident in their own knowledge of the context.

4.2 The features of teaching that acted as barriers and affordances to student learning

In order to evaluate the teaching in this study, we were looking for evidence that the interventions resulted in students using a wider range of ideas about the nature of science or in becoming more articulate in their expression of such ideas.

The findings of the evaluation of students' learning are summarised below.

1. Many of the students' responses to questions addressing their understanding of the tendency addressed drew upon a wider range of ideas about the nature of science. These students' responses included ideas about the nature of science that were not exhibited before the teaching.

2. There were improvements in some of the students' ability to articulate their ideas. These students used a similar range of ideas about the nature of science before and after teaching but were more confident in articulating their views after the teaching.

3. There were a number of students for whom, on the basis of evidence from our probes, the teaching seemed to have no impact.

There were notable limitations in the success of the evaluation instruments at identifying changes in students' thinking. These are discussed in section 2.5.

For those students for whom the teaching seemed to have no impact we feel that a single intervention is simply not sufficient to have any impact on their views of the nature of scientific knowledge. These students held the most naïve views of those surveyed. In interviews, some of these students were unable to describe the teaching aims of the lesson; aims that were clear to other students.

We are not suggesting that students will develop a sophisticated view of the nature of science on the basis of the kind of intervention developed by this study. However, these materials appear to be effective in that they are able to introduce new ideas about how science works to students and to raise the validity of particular views for students. Whilst no single intervention is ever likely to have a radical impact on students epistemological profile, lessons such as these could form the basis of a more co-ordinated strand running through AS/A level courses that would have the potential to broaden the range of ideas that students are able to draw upon in different scientific contexts.

4.3 The features of teaching that promoted learning about the nature of science

From observations of the lessons a number of features emerged that were common to those lessons that were described by teacher in interview as having been effective.

Conversely there were a number of approaches taken by teachers that detracted from the apparent success of the teaching.

In those lessons seen as effective, the teacher referred explicitly to the aims of the lesson. In these instances students were therefore clear in the interviews about what they had learnt from the lesson. In other lessons where the aims were emphasised to a lesser extent, the students were unclear about the learning aims as distinct from the subject matter of the context used in the lesson. This was especially evident in the closure of the lesson. Where this was effective the teaching aims of the lesson were reinforced strongly in the teachers summing up. From observations of the lessons it seemed that presenting the teaching aims with clarity was problematic for those teachers whose own understanding of the issue in question was naïve. Teachers who appeared more confident about their understanding of the key issues of the lesson were more effective in making the aims of the lesson explicit.

The teaching materials made peer discussion a central part of the teaching, particularly in raising the issue in the early part of the lesson. In some of the lessons observed the handling of the class discussion that followed paired work was problematic. It was clear that some of the teachers in the study were reluctant to tackle input from the students that indicated an inappropriate view of the issues. In these instances the common response from the teacher was to suggest that there are 'no right answers'. This clearly detracted from the explicit teaching aim of the lesson by suggesting that any opinion is equally valid. The teaching materials were explicit focussed on appropriate ideas about science that research indicates are often not recognised by students. It would be our view that whilst it is hard to say any answer is complete in that is universal across different contexts, some answers are wrong and some answers are more sophisticated than others.

4.4 Teachers’ reactions to the materials

Overall teachers' responses to the materials were very positive. The majority of the teachers who were asked to pilot the materials felt that it was worthwhile teaching students about the nature of scientific knowledge. Moreover, they were clear that materials that supported them in addressing students' understanding of the nature of scientific knowledge would be essential if they were to tackle this effectively. On the few occasions when teachers were reluctant to implement the materials the reason given was the lack of time.

However, there was a marked lack of confidence on the part of most of the teachers in implementing the materials. This was for a variety of reasons.

- A lack of confidence in their personal understanding of the issue in question. For some of the teachers the teaching aims and the issues addressed by the materials were ones to which they had given little previous thought. The level of confidence among the teachers in their own understanding of the nature of science issues addressed by the materials was varied. We are not surprised by this and indeed attempted to address this in the guidance notes produced with the materials. The success of these notes depended on the teacher's own personal knowledge of the issues. We did not seek to explicitly test teachers understanding of the nature of science in this study.

- A lack of clarity about how to deal with students' ideas in the classroom. Some teachers found the students' ideas about the nature of science difficult to deal with in the classroom. There was a feeling amongst some of the teachers that they were not confident to tackle ideas from the students that were clearly wrong or inappropriate. Instead there was a sense that the teacher felt the discussion of individual ideas was more important than explicit handling of the teaching aims.
- The lesson was different to their normal teaching. Most of the teachers involved in the sample were experienced. Several of them said that it was demanding teaching something with unfamiliar aims and unfamiliar activities. For experienced teachers, being asked to implement something as unfamiliar as these lessons and being observed doing so undermined their confidence.

4.5 The knowledge and expertise teachers needed in order to implement the tasks in their teaching

Most of the teachers we observed in the implementation of these tasks described the experience of teaching this material as challenging but interviews and observations showed this to be for different reasons as outlined above. The question this raises is what expertise teachers need to use the teaching materials effectively. We feel from our observations that this depends, unsurprisingly, on the teacher's background and their own understanding of the nature of science. The teachers who implemented the lessons showed a varied level of confidence in talking about the issues addressed by the lessons. There were however a number of more general points that came out of discussion and interviews with the teachers relating to the teachers knowledge and to the teachers expertise in staging the lessons.

Teacher knowledge

The clarity of the teaching aims of some of the lessons was hampered by the teachers' lack of understanding of the issues presented. An example of this was in the 'Assessing the Quality of Data: Mobile Phones' lesson. The key point that should come across to students at the end of the lesson is that evidence often leads to probabilities rather than proof. This distinction is not recognised by many students. It was common for students to express the view in lessons that there is either a proven risk or there is no risk at all. In one lesson we observed this view was reinforced for students in the plenary discussion because the teacher also held the same view. In these instances the teachers own lack of knowledge about the range of views about the nature of science that were appropriate in that context prevented the activities from being staged with clear and explicit teaching aims. Where the lessons were staged with more explicit aims the teacher's own range of views about science were more appropriate to the context of the activities.

Teacher expertise

A detailed commentary of the materials was provided in a format that could be used by teachers during the lesson. Teachers used the commentary to good effect in making clear the teaching objective of each activity. In several of the observed lessons the teachers used the commentary in the classroom. This was particularly important in the way they handled the discussions that provide closure to the activities. Several of the teachers felt that the commentary and guidance notes enabled them to be effective in making the aims of the teaching clear to students and helped them to stage an unfamiliar lesson.

As a result of teaching these lessons some teachers were able to gain insights into how they might teach similar aspects of the nature of science in other parts of the course. However, the impact of this should not be overstated. The kind of possible further interventions described by some of the teachers were very low key. For example; teachers suggested using the lessons as reference point in discussions about theories and models later in the course.

The supporting notes seem to provide an effective aid for teachers to be able to use the material successfully the first time. It is also likely that they would become more skilled at using them with practice. This is not just because the lessons are novel, but because the teachers were thinking through the issues addressed in the materials. We would expect that using the resources would develop teachers' own understanding of the nature of science or at least their awareness of some of the issues.

5. Conclusion

In section 1 we conceptualise learning about the nature of science as developing an increasingly sophisticated range of ideas about how science works and being able to deploy this wider range of views about science appropriately in new contexts. From this standpoint we set out to develop a series of single interventions that could be integrated into existing AS/A2 courses and to evaluate the success of these interventions at giving students a wider range of views about science that they could draw upon in talking about science in unfamiliar contexts. It would not be expected that single interventions of this length could be effective in showing lasting change in students' epistemological profiles. However we wanted to explore the potential of single lessons to add to the range of ideas about science that were drawn upon by students in a particular context. We identified progression as students either:

- Using an idea about the nature of science not drawn upon before the teaching;
- Becoming more articulate at expressing an idea about the nature of science.

Given the limited nature of these interventions we did not expect to see dramatic changes in the epistemological profiles exhibited by students. What we did expect was to see students using the ideas addressed in the teaching that previous research shows are often not included in student's reasoning about the nature of science.

In tendency 1, the purposes of science, around half of the pupils gave a wider, more sophisticated range of purposes of scientific research following the teaching.

In tendency 2, the role of theoretical models in science, for those lessons where there is data, between 40 and 55% of pupils drew upon ideas about the nature of science that they did not use before the teaching intervention. A small number of students gave more articulate responses using the ideas addressed in the teaching.

In tendency 3, assessing the quality of data, poor returns hampered the evaluation of the teaching. What data there is suggests that issues about assessing data are complicated by naïve views about the nature of proof in empirical science research and a lack of recognition by students, and in some cases teachers, of the importance of understanding the role probability in scientific research outcomes.

Across all three tendencies there was a significant group of students whose responses to the evaluation probes was unaffected by the teaching intervention.

Teachers were enthusiastic about the aims of the lessons and felt that the lessons were effective. However, most showed a lack of confidence about implementing the lessons. There were some teachers whose own lack of understanding of the nature of scientific knowledge was an obstacle to achieving the teaching goals of the lessons.

So in summing up, these interventions were successful in broadening the profile of views about the nature of science which some of the students in the sample drew upon in response to a specific context. However, there were also a number of students for whom these single interventions had little effect judging by the evidence of our evaluative probes. Furthermore, observations and interviews with teachers highlighted the difficulties for teachers in teaching about the nature of science, something that for many teachers is unfamiliar. We would suggest that the design of the lessons developed by this study is effective and he lessons have the potential to provide the beginning of a more coherent strand of teaching about the nature of science that could be threaded into existing AS/A level courses.

6. Implications for future development and research

A number of the outcomes of this study raise implications for future development of teaching about the nature of science. These implications may also extend beyond teaching AS/A level students to more widespread issues about developing the teaching in this area.

Extended teaching sequences

The evaluation of learning outcomes in this study was based on single lesson interventions by the teachers. It is clear that little lasting effect on students' understanding of the issues taught is likely to result from such short interventions. What is needed is a more extended sequence of teaching threaded through the AS/A level course. Several of the lessons designed in this study have complementary aims and could form the basis of a more extended teaching sequence. The teachers involved in the study were clear that one of the benefits of interventions such as these is in drawing on the teaching in future lessons by referring back to the teaching goals of the lesson. Where students have engaged with the issues presented in the lessons this could provide an effective point of reference for further teaching.

Recognition of the different expertise of teachers

It was clear from observations of the lessons that the teachers' own level of expertise about the nature of science has a significant impact on the effectiveness and clarity of the teaching about science. If research is to go further in assessing the potential of teaching in this area and its limitations it must take account of teachers' expertise and motivation. This project saw the teacher's role in both the development and implementation of the materials. If a similar model is adopted in developing further teaching resources in this area we would advise that curriculum developers and researchers identify teachers whose own understanding of the nature of science is sophisticated.

The need for teacher development

The impact of teachers' expertise on the teaching that was observed suggests that more widespread and effective teaching about science will demand effective development of teacher's knowledge and expertise in this area. The teachers in the study were clear that teaching about science was unfamiliar to them. We would suggest that research is needed to identify the issues that might underpin effective professional development for teachers in this area. Possible areas of research might include identifying the aspects of the nature of science in which teachers are least confident and identifying possible models of teacher development that could address these areas.

Uptake of the material by teachers

Interviews and conversations with teachers raised a number of factors that might effect the uptake of the teaching materials by teachers.

Teachers are more likely to use the materials if the aim and context of the teaching motivate them. The context of the teaching seems to be important in teacher's reaction to the materials. The materials were received more enthusiastically where the context was either:

- closely related to the content of the existing course;
- topical (such as the debate on mobile phones);
- familiar to the teacher.

For some teachers the enthusiasm to trial the materials came from a recognition of the importance of the teaching aims of the lesson. For these teachers the context was less important.

There were a small number of teachers whose motivation to be involved in trailing the material faded. This was commonly put down to pressures of time on AS/A level courses. At present none of the teaching goals of these materials are assessed as part of the courses taught. As a result teaching about science for some teachers is an extra, which they cannot afford the time to implement. This perception would no doubt change were the nature of science to become an assessed part of the course.

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Appendix 1: The four probes used to evaluate student learning

Appendix 1.1: Poster probe evaluating tendency 1 (purposes of scientific investigation)

Aims of the probe

- To see the range of purpose(s) for investigative work identified in response to decontextualised questions.
- To see whether, after teaching, the cardsort contexts are drawn upon, and the points that those contexts are used to make.

Administration of the probe

Students work in pairs. Each pair is given the following instructions:

> Most people would say that 'doing experiments' is an important aspect of what scientists do. But *why* do scientists do experiments, and how do they decide what to investigate? Produce a poster/diagram/chart to explain as fully as you can why you think scientists do experiments, and how they decide what to investigate. To help us understand your poster, try to give as many examples as you can to illustrate your points.

Notes for teachers

Students work in pairs. Each pair will need a large piece of paper (A1 flipchart paper is ideal) and a couple of marker pens. Alternatively, you may prefer the pair of students to work with ordinary pens on a piece of A3. The activity should take about 15-20 minutes.

Experience suggests that when students are asked to draw a poster, they often spend time producing pieces of work appropriate for display. Students should be made aware that the purpose of the poster is to communicate ideas, rather than to be displayed. Students should therefore be discouraged from spending time on presentational issues.

We have found that the teacher has a critical role during this kind of work in ensuring that students articulate their viewpoints as fully as possible. Once students start working on their posters, when you look at their work ask questions such as 'That's interesting, what did you mean by that? OK, can you write that extra detail on to your poster!'. Please resist the temptation to coach students during these exchanges. We want them to record and articulate their own viewpoints as fully as possible, without prompting about areas of content that they might have missed.

Appendix 1.2: Interpreting data probe evaluating tendency 2 (the nature of theoretical explanations in science)

Background

This probe aims to assess the extent to which students recognise the role of models in the interpretation of data. It is being used in order to evaluate the effectiveness of the teaching task Electromagnetism. This teaching task aims to develop students' ability to:

- understand the role of models in developing scientific understanding;
- recognise that models often involve abstract concepts and analogies;
- understand that a model need not be intended as a mechanical explanation of a phenomenon but can be used as an aid to understanding the phenomena and generating predictions about it.

Notes for teachers

This research probe needs to be implemented with a whole class of students.

The role of the teacher is to organise the completion of the two questions. Teachers are requested not to provide students with guidance concerning possible responses to the questions.

Begin by giving a copy of the research probe to each student.

Explain the reason for entering a date of birth. This helps us to match the scripts later whilst still preserving a level of anonymity.

Read the introduction section (pages 2 to 4) to the class.

Ask students to break into pairs (and a triple, if necessary) and discuss in their group responses to the discussion issues on page 5.

After 5-10 minutes tell students to stop their discussion.

Now tell the students to write their own individual response to question 1 in the space provided.

When all of the students have completed their response to question 1 collect their response sheets. We would suggest this should take no more than 10-15 minutes, Students could be asked to move to the last part of this question shortly before this.

Now give each student a copy of question 2.

Ask students to write their response to question 2 individually. There should be no discussion at this point.

Please enter you date of birth [. .]
(This is to help us identify your script)

Interpreting Data

This question is about a real issue being worked on by scientists at the moment. In order to answer this question, you *do not* need to understand the technical details of the scientists work: the main focus of the question is upon the ways in which scientific data is analysed and interpreted.

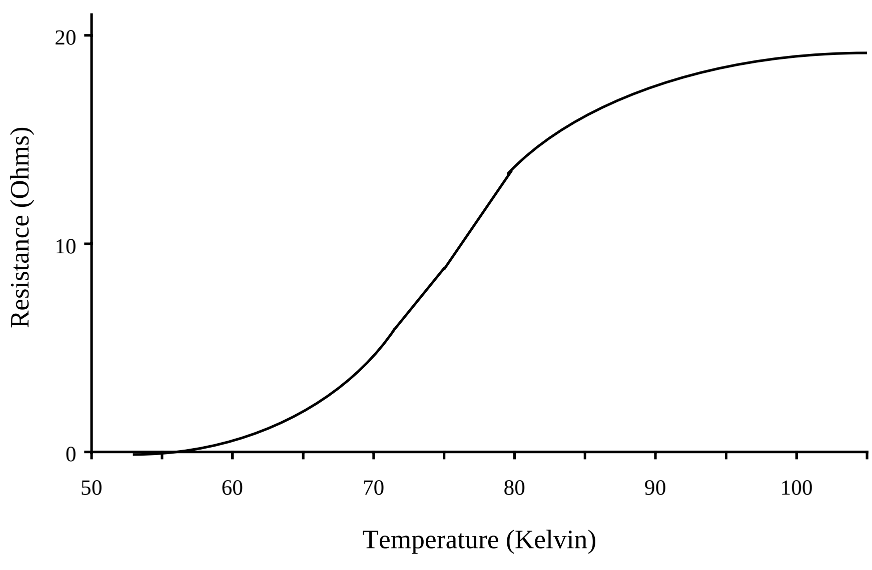
Superconductors are very special materials. Using superconductors to transfer electricity around the country could lead to a significant reduction in energy consumption. This is because these materials have zero resistance to electricity at low temperatures.

Several groups of scientists around the world are investigating the properties of a new superconductor. Some of these groups are trying to give a **theoretical explanation** of how the electrical resistance of this material falls as the temperature is lowered. These theoretical explanations involve the development of a **theoretical model** of how the superconductor carries electrical current, and how this behaviour changes as the temperature is lowered.

These **theoretical models** are developed using insights into the **microscopic structure** of the material. In developing these theoretical models scientists need to make **approximations** and **assumptions** about the behaviour of the material. They also need to be **creative** in the way that they think about the material. Scientists often draw analogies with other materials with which they are familiar in developing theoretical models for new materials.

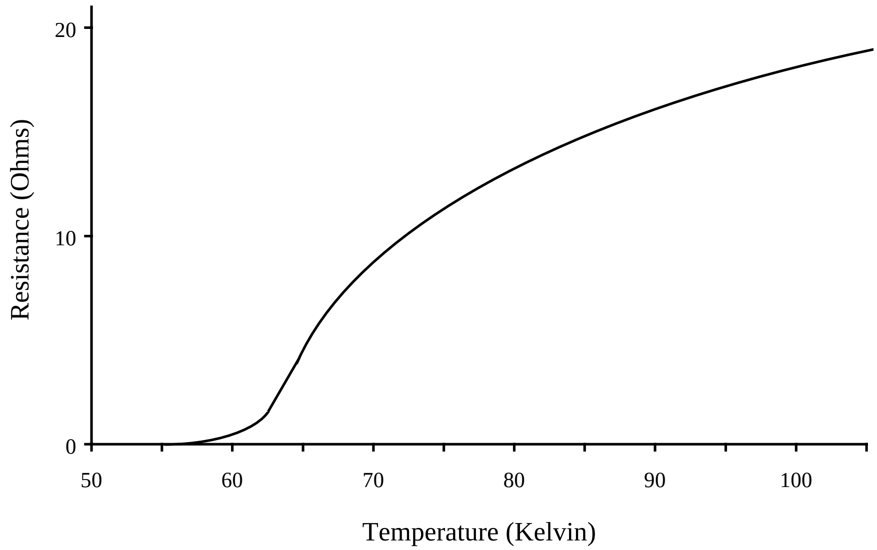
The LIS group have developed their own **theoretical model** to explain the fall in electrical resistance of this new material. The LIS model predicts that the fall in electrical resistance of the material as the temperature is lowered will follow the trend shown by the line on the diagram below:

THEORETICAL MODEL DEVELOPED BY THE LIS GROUP

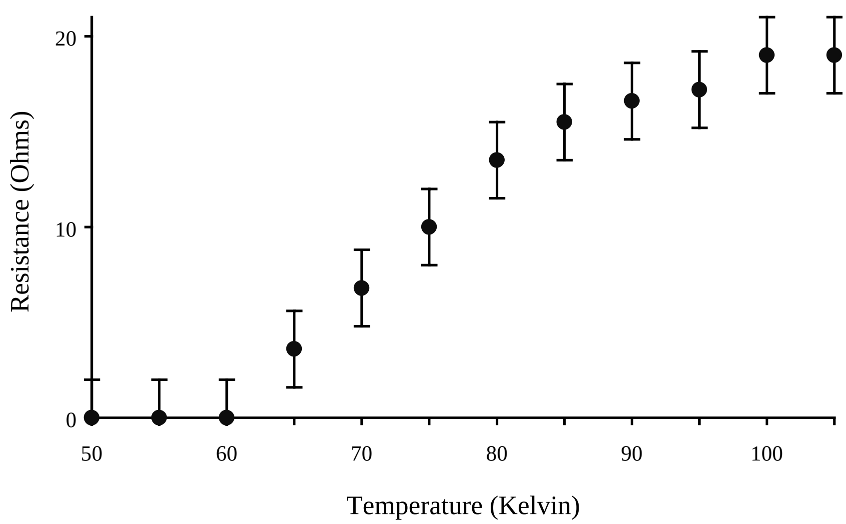


The COAST group have developed a *different* **theoretical model** to explain the fall in electrical resistance of this new material. The COAST model predicts that the fall in electrical resistance of the material as the temperature is lowered will follow the trend shown by the line on the diagram below:

THEORETICAL MODEL DEVELOPED BY THE COAST GROUP

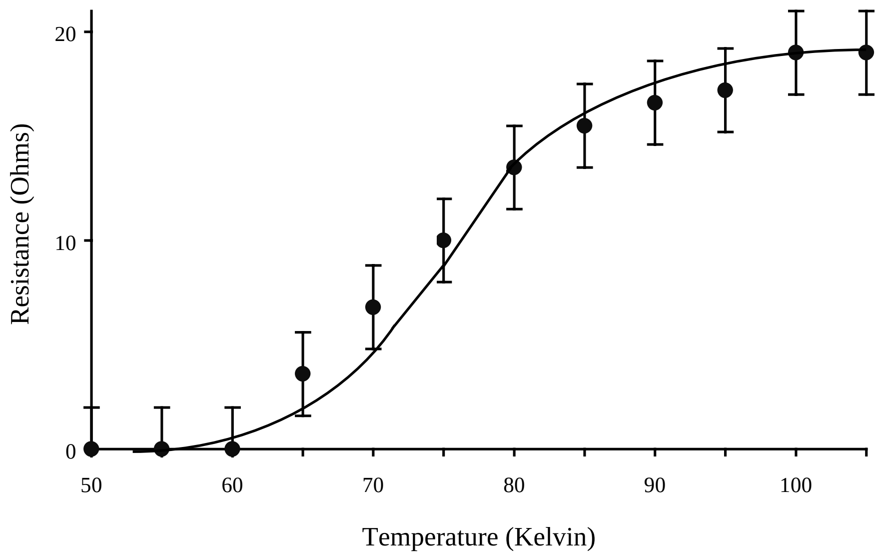


Another group of scientists has measured the electrical resistance of this superconductor as the temperature is changed. The investigation was performed under carefully controlled conditions, and other scientists have been able to repeat the measurements in their own laboratories and get virtually identical results. The results, with error bars, are given below:



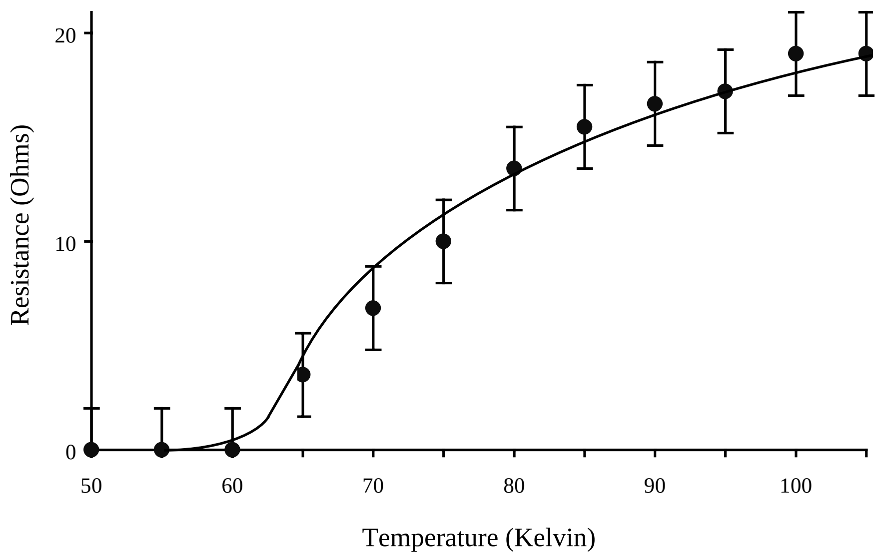
The theoretical model developed by the LIS group generates a line which passes through all of these error bars:

LIS GROUP INTERPRETATION



Similarly, the theoretical model developed by the COAST group generates a line which passes through all of these error bars:

COAST GROUP INTERPRETATION



Scientists from the LIS and COAST groups, and also scientists from other groups, have come together at a conference meeting in order to decide what to do next.

Paired student discussion

You have 5-10 minutes to discuss the following question with your partner:

⇒ What courses of action do you think that the scientists now need to follow in order to decide which theoretical model provides the best interpretation of the data?

Your teacher will ask you to stop your discussion after 5-10 minutes.

You will then be asked to write your <u>own</u> answer to the following question.

Question 1

⇒ Using the space provided describe possible courses of action that you think the scientists now need to follow in order to decide which theoretical model provides the best interpretation of the data?

⇒ **In each case explain why you think this is an appropriate course of action.**

⇒ Give as many courses of action as you can think of. Continue on the reverse side of this paper if necessary.

When you have done this decide which ONE of the above courses of action you think would be the most important thing to do next?

Please circle the response you have given that you think is most important.

[space was provided here for extended answers by students]

Question 2

Answer this question without discussing your answer with anyone else.
Listed below are a number possible courses of action for what the scientists could do next. For each statement indicate whether,

i) You understand what the scientists are suggesting.
ii) Whether you think their suggestion is useful or not.

	I clearly understand this statement.	I partly understand this statement.	I do not understand this statement.		I think this would be an appropriate course of action.	I do not think this would be an appropriate course of action.	I am not sure whether this would be an appropriate course of action.
A Fill in the gaps between the available data points by measuring the resistance of the superconductor at additional temperatures.							
B Reduce the error bars for the existing data points.							
C Examine the assumptions and approximations used by each of the groups in developing their theoretical model.							
D Examine the extent to which each theoretical model has successfully explained the electrical resistance of other superconducting materials.							
E Examine how well respected the scientists in the LIS and COAST groups are within the scientific community.							
F Look for additional theoretical models which might explain the data.							
G The scientists need to recognise that each of these theoretical models might give equally good explanations of this data set.							
H The scientists need to accept that there is no way of finding out which theoretical model gives the best explanation of this data set.							

In the box below give the letter(s) of **one or two** statements which you feel are the **<u>most important things</u>** to do next.

Explain below why you think that this choice (or choices) is the most important thing to do next.

[space was provided here for extended answers by students]

Appendix 1.3: ’Oils’ probe evaluating tendency 3 (assessing the quality of data)

Please enter you date of birth [. .]
(This is to help us identify your script)

Differences in Values from Measurement

Two groups of nutritionists have been asked to measure the mass of 100 cm^3 of nut oil. Each group takes nine samples of 100 cm^3 of the oil from a large container and weighs each sample. These are their results, after having sorted them into ascending order:

Measurements in grams:

Group A	81.9	83.5	86.5	87.1	87.3	87.5	87.5	90.5	92.1	(average 87.1)
Group B	84.9	85.7	86.6	86.9	87.0	87.3	88.2	88.5	88.8	(average 87.1)

What should Group A state as their result for the mass of 100 cm^3 of nut oil? *Please fill in your answer in the box below:*

Please explain your reasoning:

With which of the following statements do you most closely agree?

A	We can be more confident in Group A’s result, because the range between the largest and the smallest measurement is greater.	
B	We can be more confident in Group A’s result, because two of their measurements agree.	
C	We can be more confident in Group A’s result, because one of their measurements is the same as their average.	
D	We can be more confident in Group B’s result, because the range between the largest and the smallest measurement is less.	
E	We can be equally confident in either Group’s result, because both sets of measurements have the same average.	
F	We cannot decide which Group’s result we can use with greater confidence.	

Another two groups of nutritionists have been asked to measure the mass of 100 cm^3 of soya oil. Each group takes nine samples of 100 cm^3 of the oil from a large container and weighs each sample. These are their results:

Measurements in grams:

Group A	82.3	82.6	83.0	83.2	83.3	83.8	83.9	84.2	84.3	(average 83.4)
Group B	81.5	82.2	83.1	83.8	84.5	84.6	84.7	85.9	86.6	(average 84.1)

Looking at both these sets of results, what would you state as the mass of 100 cm^3 of soya oil? *Please fill in your answer in the box below:*

Please explain your reasoning:

With which of the following statements do you most closely agree?

A	We can be more confident in Group A's result, because the range between the largest and the smallest measurement is less.	
B	We can be more confident in Group B's result, because the range between the largest and the smallest measurement is greater.	
C	We can be equally confident in either Group's result, because the value 83.8 is in both sets of measurements.	
D	We can be equally confident in either Group's result, because there is not much difference between the averages.	
E	We cannot decide which Group's result we can use with greater confidence.	

A group of nutritionists wants to compare the masses of sunflower oil and olive oil. They make nine measurements on 100 cm^3 samples of each sort of oil. These are their results:

Measurements in grams:

Sunflower oil	92.1	92.4	92.6	92.7	93.1	94.0	94.1	94.3	94.4	(average 93.3)
Olive oil	92.5	92.9	93.0	93.2	93.4	93.7	94.1	94.2	94.5	(average 93.5)

With which of the following statements do you most closely agree?

A	The mass is greater for olive oil than for sunflower oil, because the average is larger.	
B	There is no difference in the masses, because the range of measurements in each set is much bigger than the difference between the averages.	
C	There is no difference in the masses, because the value 94.1 is in both sets of measurements.	
D	We cannot be sure that there is a difference in the masses, because the range of measurements in each set is much bigger than the difference between the averages.	
E	We cannot be sure that there is a difference in the masses, because the value 94.1 is in both sets of measurements.	

Appendix 1.4: ’Leukaemia’ probe evaluating tendency 3 (assessing the quality of data)

Guidelines for using this probe

This research probe needs to be implemented with a whole class of students.

The role of the teacher is to organise the completion of the two questions. Teachers are requested not to provide students with guidance concerning possible responses to the questions.

Begin by giving a copy of the research probe to each student.

Explain the reason for entering a date of birth. This helps us to match the scripts later whilst still preserving a level of anonymity.

Read the introduction section (page 1) to the class.

Ask students to break into pairs (and a triple, if necessary) and discuss in their group responses to the discussion issues on page 1.

After 5-10 minutes tell students to stop their discussion.

Now tell the students to write their own individual response to question 1 in the spaces provided.

When all of the students have completed their response to question 1 collect their response sheets.

Now give each student a copy of question 2.

Ask students to write their response to question 2 individually. There should be no discussion at this point.

Please enter you date of birth | . .

(This is to help us identify your script)

Assessing the quality of data.

A small number of children living in one area of the country are found to be suffering from leukaemia. The number of cases is small, but more than you would normally expect in a population of that size. It is suggested that a particular substance, which is emitted in small quantities from a chemical plant in the area, may be the cause. The chemical plant, however, is a major source of employment and its closure would put many people out of work.

Several groups of scientists were commissioned to investigate the number of cases of leukaemia in the areas around the chemical plant. For comparison, other groups of scientists were commissioned to look at the incidence of leukaemia in similar communities that are far away from any chemical plant.

Some groups report finding more cases of leukaemia than expected in the region near a chemical plant. Some other groups report that the number of cases of leukaemia is no higher than you would expect in the general population. Some groups report that there are other areas of the country with a slightly higher than expected incidence of leukaemia, but with no chemical plant nearby.

Paired student discussion

You have 5-10 minutes to discuss the following question with your partner:

⇒ What courses of action do you think that the scientists now need to follow in order to decide what recommendations should be made about the case.

Your teacher will ask you to stop your discussion after 5-10 minutes.

You will then be asked to write your <u>own</u> answers to the following question.

Question 1

⇒ Using the space provided describe possible courses of action that you think the scientists could now to follow in order to decide whether there is a link between the chemical plant and the cases of leukaemia.

⇒ In each case explain why you think this is an appropriate course of action.

⇒ Give as many courses of action as you can think of. Continue on the reverse side of this paper if necessary.

When you have done this decide which ONE of the above courses of action you think would be the most important thing to do next?

Please circle the response you have given that you think is most important.

[space was provided here for extended answers by students]

Question 2 Please enter you date of birth [. .]

Answer this question without discussing your answer with anyone else.
Listed below are a number of further research projects or actions that have been suggested by different groups of scientists. For each statement indicate whether,

iii) You understand what the scientists are suggesting.
iv) Whether you think their suggestion is useful or not.

	I clearly understand the aim.	I partly understand the aim.	I do not understand the aim.		I think it is a useful course of action.	I do not think it is a useful course of action.	I am not sure whether it would be useful or not.
A Each of the groups should repeat their studies, in order to check their results and reach a firm conclusion.							
B A new research group should check the results and analysis of the original researchers, in order to reach a firm conclusion.							
C A further study of the same kind should be made with much larger sample groups: if enough data are collected, an answer should become clear.							
D There is already enough evidence to decide that people's safety is at risk, it should be recommended that the plant be closed.							
E There is already enough evidence to decide that the risk to people around the chemical plant is very small, recommend that the plant be allowed to continue operating.							
F Further scientific work should begin, aiming to identify factors *other* than the chemical plant that might be responsible for causing leukaemia.							
G Scientific work, of a more theoretical kind should be started, to try to find an explanation of *how* particular emissions might cause leukaemia.							

In any scientific research funding is an issue. Imagine you are responsible for allocating a limited budget to the different projects or actions suggested.
In the box below give the letter(s) of **one or two** statements which you feel are the **<u>most important things</u>** to do next.

Explain below why you think that this choice (or choices) is/are the most important things to do next.

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Appendix 2: Interview schedules used to evaluate and validate student learning and to probe teachers' reactions.

Appendix 2.1 Poster interview schedule

Epistemological theme

1. Identify an example from their poster that has an epistemological focus.
Tell us more about this idea <insert example>

2. How do scientists discover/prove <insert context from example above>?
[if they mention experiment] *Why did these scientists do experiments?*
[if they mention theory/ideas] *Where did these scientists' ideas come from?*

3. How do scientists decide which questions/theories etc. to find out about?

4. Why do you think that some scientists' work stands the test of time, while other scientists' work is forgotten?

Utilitarian theme

1. Identify example from the poster with a utilitarian focus (e.g. To make medicines):
How do scientists know where to begin in <insert chosen example>?

Social theme

1. Identify an example from the poster with a social focus:
How do scientists know how to make <example> more efficient/profitable?

General

1. Overall, what do you think are the most important reasons why scientists do experiments? [refer to poster and examples that came up in the interview].

2. Which of the examples of why scientists do experiments can you remember from the lesson?

3. Are there any of these examples which have similar reasons to the ones on your poster?

Appendix 2.2 Interpreting data probe interview schedule.

Present the probe context to the student again.

1. **What possible course of action do you think the scientists now need to follow in order to decide which theoretical model provides the best interpretation of the data?**

   Which course of action do you think would be most important?

   (Probe any key words which are used by the student – see below)

   Follow up any written responses from the student of interest.

2. Present the options given in question 2 of the probe.

   Which one or two statements do you feel are the most important thing to do next?

3. *Why did you chose these course of action?*

Key words and ideas to follow up if raised: Theory / model / theoretical model Assumptions / approximations Mechanism Averaging the models Collect more data / taken more readings

Appendix 2.3 Chemistry data task interview schedule

1. Present data set 1 to the student.

You chose the value <insert value given on written probe>; **can you tell me why?**

Present 1st set of statements to the student.

You agreed most closely with statement <insert response>, **can you tell me why?**

2. Present data set 2 to the student.

You chose the value <insert value given on written probe>; **can you tell us why?**

Present 2nd set of statements to the student.

You agreed most closely with statement <insert response>, **can you tell me why?**

3. Present data set 2 and the 3rd set of statements to the student.

You agreed most closely with statement <insert response>, **can you tell me why?**

Appendix 2.4 Leukaemia probe interview schedule

The key issue in this interview is to probe the reasons behind making or not making decisions.

Present the probe context to the student again.

1. **What possible course of action do you think the scientists now need to follow in order to decide whether there is a link between the chemical plant and leukaemia?**

   Which course of action do you think would be most important?

   Follow up any written responses from the student of interest:

2. **Present the options given in question 2 of the probe.**

   Why did you think <insert course of action> is appropriate/ inappropriate/ undecided?

   Repeat for each relevant option.
   Probe any inconsistencies (e.g. D and E both seen as appropriate).

3. **The decision you have selected as most appropriate is <insert answer most important action>.**

   Can you tell us your reasons for this choice?

Appendix 2.5 Generic interview schedule (used in all student interviews)

1. **What do you think the teacher wanted you to learn in the lesson?**

   Do you think you learnt something about <insert aim stated by student>?

   Is there anything else you think you learnt about in the lesson?

2. **How do you feel generally about the lesson?**

   What parts of the lesson did you enjoy / not enjoy?
   Why was that?

3. *Follow up any specific questions to students related to each task.*

Appendix 2.6 Teacher interview schedule.

1. **What were your general reactions to this lesson?**

2. **What aspects of the teaching, if any, did you find challenging?**

   What do you feel was gained from this lesson by the students?

3. **Questions specific to the task.**

4. **Would you use this lesson again?**

   Why would you use/not use the lesson again?

   In what way would you do things differently next time?

5. **Can you think of any ways that the teaching could be reinforced in other parts of the course?**