Undergraduate Learning in Science Project

Working Paper 5

Undergraduate science research projects and students' images of the nature of science

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Abstract

The Undergraduate Learning In Science Project (ULISP) started at the University of Leeds in September 1994. Project members include educational researchers, lecturing staff within various science departments and others with interests in teaching and learning at the undergraduate level. The aim of the Project is to inform understanding of science teaching and learning at the undergraduate level, through a variety of research activities.

The Research Project Study was a two year ULISP research investigation into final year undergraduates experiences during project work. The results of this research study are reported in ULISP working papers 2 to 8 listed in Appendix C.

This paper addresses the students' images of the nature of science. Reference is made to interviews held with students at the beginning and end of project work, in which students explicitly discussed their developing images of the nature of science. In this paper we give a description of these images of science. We also investigate the extent to which these images are changed through project work, the relationship between students' espoused images and their chosen scientific discipline, and the broader significance of students' images of science and their learning during their undergraduate science course.

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Prof. Steve Scott	Department of Chemistry
Dr. Ed Wood	Department of Biochemistry & Molecular Biology

Contents

Labelling of transcript selections:

Quotes from interviews with students are presented in italics. Each quote is given a reference. For example:

1 A 10

The first digit refers to the number of the interview. First (1) given at the beginning of the student's project, third (3) given at the end.

The letter identifies a particular student

The last digits refer to the statement number in the interview transcript

1 Introduction

A useful distinction can be made between two types of knowledge in science. Knowledge *of* science includes the key theoretical concepts and laws of particular disciplines. It is this subject matter knowledge which characterises most science curricula in schools and universities. On the other hand, knowledge *about* science focuses on the nature of science itself: how subject matter knowledge is agreed upon by scientists, how scientists decide which questions to investigate, how scientists work together, what scientists do when they disagree, and how scientists communicate their findings to other scientists. These issues tend to be less prominent in science curricula, though students nonetheless develop knowledge about science as a result of their science education. In this paper we consider the importance of students' knowledge about science for undergraduate science education.

Discussion of the nature of science centres around *epistemological* issues and *sociological* issues. Epistemology is concerned with the grounds for believing that knowledge is true, whereas sociology is concerned with the operation of communities. In the case of science, sociological and epistemological questions are closely related. For example, scientific institutions and communities have a critical role in the validation of public scientific knowledge.

The epistemological and sociological basis of the scientific enterprise has received attention in the 'Science Studies' disciplines of history, philosophy and sociology of science - though this attention has not resulted in a consensus view. At one extreme, science is portrayed as a wholly rational activity which uncovers true knowledge about the world. At the other extreme, scientific knowledge is viewed as historically, socially and politically contingent. Newton-Smith (1981) and Driver et al. (1996) both give an accessible review of these various positions.

Our focus in this paper is upon students' images of science. By 'images of science' we mean knowledge about the epistemology and sociology of science. This knowledge may be implicit or explicit. In practice, individuals do not have a unique image of science which is used in all contexts. For example, they may well draw upon different images of science when planning a particular scientific investigation, and when answering a decontextualised question such as 'How do scientists do investigations?'. We will therefore refer to individuals' *profiles* of images of science.

People's images of the nature of science are important from at least two perspectives. Science impacts on many everyday questions of lifestyle, economics and politics: 'is British beef safe to eat?', 'do VDU screens damage your health?', or 'should we fund further exploration of space?'. Although particular individuals are unlikely to have specialist knowledge about all of these topics, a realistic understanding of what science can and cannot do, together with an insight into the motivations of scientists, may help them to make informed decisions about these issues. Knowledge *about* science acquired during undergraduate courses is of more use to students understanding of these scientific issues, than is specific content knowledge from within disciplines.

Images of the nature of science are also important for students learning the subject matter knowledge of science. Students who see science as a collection of facts rather than an integrated scheme of explanatory models are more likely to adopt a rote learning strategy and less likely to achieve deep, conceptual understanding of scientific knowledge. This argument is presented in detail in Leach, Ryder and Driver (1996a) and Driver et al. (1996).

If knowledge *about* science is to be addressed at the undergraduate level, it is important that those involved in designing and teaching science curricula have an insight into the nature of science within particular disciplines, and an awareness of the profiles of images of science typically drawn upon by students in various contexts. A considerable research effort has addressed students' images of science: this is reviewed in the next section.

1.1 Existing work on students' images of science

The literature on the images of science that underpin the teaching and learning of science has been reviewed by Lederman (1992) and Arnold and Millar (1993). Empirical work in this area includes the investigation of students' images of science and the evaluation of curriculum attempts to develop images of science. Participants in these studies have included students in primary and secondary schools, university students (studying both science and non-science subjects), teachers in primary and secondary schools, pre-service teachers (teacher trainees), university lecturers, practising research scientists and the general public.

Coverage across these sample populations has been far from uniform. In particular there have been very few investigations into undergraduate students' images of science. Below we give details of the methodological approach used in some of these studies, and consider their uses and limitations. We also provide brief details of research findings reported in some these papers. In section 7 these findings are evaluated in the light of data from our own study.

An important methodological issue for studies of undergraduates' images of science is the extent to which the study probes students' views in a specific context or in an open context. Empirical investigations focusing on a single context can tease out the complexities of students' views of a single aspect of their image of science. Séré et al (1993) on students' ideas about the reliability and validity of physical measurements, Hammer (1994) on physics students' images of 'conceptual knowledge' and Friedler et al (1993) on students' abilities to distinguish between anthropomorphic explanations and teleological explanations are all examples of such context-specific studies. Séré et al (1993) reported that few of the 20 first year undergraduate science students in their study understood why it is necessary to make several measurements of a physical quantity. In addition, few of these students distinguished between random errors and systematic errors.

By contrast, Perry (1970) investigated students' images of science using decontextualised questions. Using interviews with students Perry conceptualised the intellectual and ethical development of students in terms of a 9-point scale ranging from 'dualism' to 'commitment to relativism'. One application of this scale is to a student's certainty about knowledge, with dualism as right-wrong, truth is absolute, and relativism as knowledge being subject to uncertainty and debate. The Perry scheme (or something similar to it) has been used by researchers to investigate undergraduate student's images of the certainty of scientific knowledge. Reviewing this literature, Finster (1991) reports that undergraduate chemists operate as dualists on the Perry scale, seeing chemical knowledge as either right or wrong. In our view, however, such investigations pay insufficient account to the context-dependence of students' images of scientific knowledge. For example, many students view some knowledge as certain whilst other knowledge is viewed as being open to change and development.

A further characteristic of studies is whether a nomothetic or ideographic approach is taken. A nomothetic study elicits students' views of the nature of science against a particular view of the nature of science. Rowell and Cawthron (1982) report such a study. A questionnaire was generated based on 45 statements about the nature of science taken from the works of Popper and Kuhn. This questionnaire was given to 254 undergraduate students and 52 lecturing staff from both science and non-science departments. Broadly speaking students tended to agree with Popperian statements which advance a rational, hypothetico-deductive view of scientific knowledge generation, but reacted negatively to statements based on Kuhnian ideas, where science is subject to occasional revolutions in what is accepted as scientific knowledge. Such a finding led the authors to conclude: "It is not difficult to make a case that science can, and arguably should, be presented in a manner taking account of its distinctly human nature, and that such an approach would be more meaningful than the objective image currently advocated."

The major disadvantage of a nomothetic approach is that data collection and subsequent analysis must be characterised in terms of the norms chosen, rather than around the students' own images of science. A study based on an ideographic approach is described by Fleming (1988). This study uses the Views on Science, Technology and Society (VOSTS) closed response questions, developed for use with Canadian high school students. These students were given statements about science and asked to explain why they agreed or disagreed with each statement. The written responses were then used to generate a series of closed response categories for use with a larger high school sample. Fleming (1988) administered a selection of these closed response questions to 200 chemistry undergraduates. Follow up interviews were held with a random sample of 30 students, to explore their views in greater detail. Fleming reports that the VOSTS results are remarkably similar to those obtained from students nearing the end of their high school education. This indicates that there is little (if any) longitudinal change in individual student's images of science during their university career - at least as evidenced through written responses to the VOSTS probes.

A further characteristic of empirical studies is the extent to which students' own descriptions of their images of science (espoused knowledge) are related to their implicit views about science that inform their actions during a science course (implicit knowledge). The work of Rowell and Cawthron (1982) cited earlier is an example of a study focusing entirely on students' espoused views of science. By contrast the work of Séré et al (1993) makes inferences about students' images of science based on their responses and actions during a course about physical measurement. Edmundson (1989) describes a study which gives some insights into the relationship between students' espoused views and their approach to their undergraduate science course. Edmundson administered a questionnaire to 559 biology students. This was followed by detailed interviewing of 19 students considered as representative of the whole population. Interviewees were asked questions such as 'where does scientific knowledge come from?', 'how much does it take to disprove a theory?' and 'how do scientific theories change?'. The key feature of the study was the attempt, through interviews, to draw out the complexities in individual student's images of scientific knowledge and relate these to the student's experiences on the course and their approach to learning. Edmundson concludes that '[students'] conceptions of scientific knowledge are intimately linked to their approaches to learning science'. Sheppard and Gilbert (1991) report similar findings though less detail is given concerning the intricacies of undergraduate students' images of scientific knowledge.

Other studies which relate to undergraduate students images of science are those undertaken with pre-service teachers (see Lakin and Wellington (1994), Abell and Smith (1994) and the review in Lederman (1992)). Since many of these will have recently graduated from an undergraduate science degree (or indeed be participating in a joint science and education degree course) the target population for these studies is close to that of undergraduate science students. However, the major focus of these studies is on the influence of teachers' images of science on their approaches to teaching in the classroom, rather than the relationship between images of science and science content learning.

1.2 Methodological focus of the study

Our primary interest was to investigate the range of images of science that underpin students' learning of science during undergraduate courses. In order to do this, data collection focused upon undergraduate research projects. Students on final year research projects are working with professional scientists often on an original research question - they are experiencing scientific knowledge in the making. At the same time projects aim to help students learn about science - particularly the use of experimental/computational techniques and the personal demands of real research (Ryder, Leach and Driver; 1996a). In this way projects provide a curriculum context where knowledge about the nature of science is very important. They are also contexts through which a richer understanding of the nature of science can develop.

Brief details about study design are given in section 2 of this paper (further details are given in Leach, Ryder and Driver 1996b). Students were asked questions about epistemological and sociological aspects of their research projects (e.g. 'How will you ensure that your project follows good scientific practice?'). In addition, decontextualised questions were asked (e.g. 'What is the purpose of experimentation in science?'). In the ensuing discussion it was possible to probe specific incidents from students' projects. Such an approach allowed us to comment on the extent to which students' views about the nature of science, described either in the context of their project or otherwise, related to their actions and learning on their project.

This study is longitudinal in design in that it followed the same students over an eight month period while they undertook their research project. This allowed us to describe any changes in students' images of science during their research projects, and to comment upon possible causes of change. It is recognised, however, that other areas of the undergraduate curriculum (lectures, tutorials, laboratory work) will also influence students' images of science.

Section 2 of this paper describes the design of this study. Multiple approaches to data analysis were used, in order to address a variety of different questions: the methodology and findings from various approaches to analysis are described in sections 3, 4, 5 and 6. Section 3 presents a question by question analysis of students' responses to questions about the nature of science in general. In section 4, a framework for characterising undergraduate students' images of science is developed. Our analysis involved reviewing data across a number of related interview questions. This framework was then used to characterise individual students' profiles of images of science, in order to comment upon longitudinal changes and the relationship between images of science and learning. Analysis of this area is presented in sections 5 and 6. In section 7 of the paper, we discuss the status and significance of our findings to undergraduate science education.

2 Outline of the study

Full details of the design of the Research Project Study are presented in Leach, Ryder and Driver (1996b). The study focuses on the experiences of both students and their supervisors during final year undergraduate research projects. These projects contribute up to one third of the marks available in the final year. Twelve students from four departments (Biochemistry & Molecular Biology, Chemistry, Earth Sciences and Genetics) were followed over the entire period of their projects. Students were interviewed on three occasions - at the start of their project, when their project was well underway, and at the end of their project[1]. In addition, students were asked to keep a diary detailing their day-to-day experiences during the project, and occasional visits were made whilst students were working on their project. The supervisors of these students were interviewed once - when the students had completed their project work. Full interview schedules are given in Leach, Ryder and Driver (1996b). .

In order to investigate students' images of science a series of questions were used:

1) How do scientists decide which questions to investigate?

2) Why do scientists do experiments?

3) How can good scientific work be distinguished from bad scientific work?

4) Why do you think that some scientific work stands the test of time whilst other scientific work is forgotten?

5) How are conflicts of ideas resolved in the scientific community?

6) [Final interview only]
In what ways have your experiences on the project influenced your understanding of what scientists do? (*What are the key things that you have learnt about being a scientist through doing this project?)*

Students were asked questions 1-5 during their first interview and again during their final interview. In addition the final interview included a question asking the student whether they felt that their images of science had been changed by their experiences of project work. The interviews were conducted in a conversational style and students were encouraged to draw on their project work to illustrate their comments.

Questions 1-5 were designed to allow a broad range of epistemological and sociological issues to be raised. Each question was used as a prompt to begin

[1] Student M did not participate in the round of final interviews

a discussion. Typically this initiated a series of follow up questions from the interviewer probing the issues raised by the students. In many cases the students' responses to a single question led on naturally into other of questions 1-5. In this way coverage could often be achieved in a natural, student-led exploration of their images of science. The five questions were piloted with two of the students in the study and found to be effective in stimulating a discussion in which images of science could be probed.

All of the interviews in this study were transcribed for further analysis: these transcripts comprise the data source for the study. In addition to the questions described above students often discussed their views of the nature of science elsewhere in the interviews when describing activities on their project. Where appropriate these have also been included in our analysis of each student's images of science.

Students' discussions about their images of science were analysed by an iterative procedure involving the team of three researchers. Three approaches to analysing the data set were used, in order to address the following research questions:

i) What are the main images of science held by a selection of final year undergraduate science students?

ii) Are there any changes in these students' images of science during final year projects, and what features of project work (implicit or explicit) may have influenced these changes?

iii) To what extent are these students' images of science dependent on their scientific discipline (i.e. chemistry, genetics...)?

iv) What is the significance of students' images of science to their learning of science and the design of undergraduate science curricula?

Our first method of analysis categorised students' responses to each of the five interview questions presented above. This question-by-question analysis is presented in section 3. Our second method of analysis categorised student responses using a coding scheme developed specifically to focus on particular areas of epistemological and sociological reasoning. This cross-question analysis is described in section 4. These two analyses allow us to address research question (i). In order to address question (ii) it was necessary to apply the characterisation of students' epistemological and sociological reasoning to *individual* students' transcripts. In this way, profiles of epistemological and sociological reasoning were produced for each student at the beginning and end of their projects (see section 5). These profiles also allow us to address question (iii). Our third method of analysis involved three student case studies. These allow us to illustrate the nature of changes in students' epistemological and sociological reasoning, and to comment on the significance of these aspects of their reasoning to the progress of their projects (question (iv) above). This case study analysis is presented in section 6. In addition, we comment on possible influences on changes in epistemological and sociological reasoning in each case (question (ii) above).

The broad implications of findings from the study are addressed in the final section of this paper.

3 Students' epistemological and sociological reasoning: question by question analysis

In this part of the paper, students' responses to five open questions about the nature of science in general are characterised. The same five questions were asked of students at the beginning of their projects in the first interview and at the end of the projects in the third interview. Transcripts were reviewed, and substantive features of students' responses were highlighted. A framework for coding was produced, based on these highlighted features, and was agreed upon by the team of researchers through an iterative process of coding the transcripts.

Longitudinal differences in students' responses are discussed in section 5 of the paper.

3.1 Question 1: How do scientists decide which question to investigate?

This question was asked of most of the students in the initial interview and of all but one of the students in the final interview.

Students' responses varied in their complexity and in the extent to which they were rooted in their personal experience. Four main types of answers to the questions were given. In some cases these were interrelated and several types of answers were given by the same student.

3.1.1 Curiosity led

Students see scientists choosing to investigate questions which interest them personally.

> *... it would be something you are interested in [3.F.109.]*
>
> *a lot depends on that persons' particular interest ... 3.J.48.*
>
> *Professor ------ does that area of work because I think he's basically interested in it, he likes the kind of idea of it and the way it fits together. [1.B.32.]*

3.1.2 Extending knowledge in a field

Gaining knowledge for its own sake was stated as important by some students.

> *Anything just to gain knowledge must be important. 1.A.41-42*

After completing their projects, more of the students gave the following type of response.

> *It has got to be relevant to the field in terms of it has not already been done before......you are pushing back some frontiers 1.C.112.*

It was apparent from their comments that they had a much greater appreciation of how scientific questions emerge as a field of research is being developed.

> *I guess by knowing what's going on in that field and knowing where the problems lie and trying to solve it 3.K.29.*

Students also showed an awareness of phases of interest in specific areas within the research community in a subject.

> *I suppose areas where a lot of research is going on that lend themselves to a lot of questions ... sort of topical areas. .... for example, in Geology, the plate tectonics theory which has come about since the 60s has provided most of the questions that people are trying to answer at the moment. 3.F.48-49.*

3.1.3 Utilitarian

The benefit of knowledge for solving human problems was mentioned quite frequently as a reason for scientists' choice of questions to pursue.

In some cases, students saw their own interest in topics being associated with their ability to help others in a general way.

> *Is the work you are planning on doing necessary? Are there people awaiting the outcomes of this research?... How valuable would it be to other people? And then you can get interested enough to do it. 1.C.109.*

> *A lot depends on what that particular person might perceive will be beneficial to mankind or will be of any use to the human race in general. 1.J.48.*

One student however, recognised that it was problematic deciding what knowledge might be useful in the future:

> *I don't think you can really say ... which are more important because so much may be seen as not so important but may lead on to other very important things. 1.A.40.*

A number of specific areas of potential benefit were cited with emphasis on medical and environmental problems.

> *Obviously medical research is important ... there is so much that still needs to be found out and is being found out - cancer cures. 1.A.41.*

> *you could look at it from the perspective of the more we know about things, the better it is ... it's another enzyme we're going to know all about, which can only be useful ... you can understand the implications and how to cure things. This enzyme's involved in carbohydrate metabolism so if you had a fault and you knew all about the enzyme, you might be able to substitute the enzyme. 3.C.36-37.*

> *In my area it's being clinically related. If you've got a disease symptom you try and find out ... how you can control that and perhaps how you can find a therapeutic target in that area. 3.D.30.*

There was also a recognition that choice of a question to pursue was associated with funding opportunities, which in turn could be related to human need.

> *If there are problems like environmental problems, say what sort of species are in the atmosphere that cause asthma or something, then people maybe because of the funding they get, will develop an interest to do it. 3.B.32.*

Furthermore, the way a line of work was developed was seen to be influenced by whether the work was being undertaken for commercial or scientific reasons - a point which is commented on further below.

3.1.4 Financial benefit

Many of the students recognised that scientists need support to pursue their research and that the availability of funding therefore influences the questions that are addressed.

> *[Questions] which have got commercial interest I suppose, where there is money involved. 3.F.48.*

> *It depends ... whether they research something that's going to be financially beneficial, can be used in industry ... pharmacy or medicine. 1.E.56.*

This student continued with an interesting remark about research councils (the only student to mention research councils as a source of funding):

> *I can't imagine funding councils will go for something on a whim of a scientist, sort of like, 'I want to find out what this is just because I want to know'. I think there has got to be that drive - not public interest but maybe what's going to be the end-product and what's in it for us. 1.E.56.*

Business awareness was apparent among some students:

> *If they (funders) are investing a certain amount of money into a particular project, it has to be beneficial to them. So pharmaceutical companies will fund a project which could be useful to them, say maybe they are designing a new drug or something which could have potential commercial value, so they will fund it. Obviously they aren't going to throw away the money ... everybody has their own interest at heart and that's how it works. 1.J.49.*

> *It has got to do with the funding .... something a company wants done ... like before, you do something that you were interested in but now it's a lot of companies that pay you to research. 1.K.75-76.*

While students mentioned the need for financial support, both before and after doing their projects, their comments after completing their projects indicated that they were more aware of the specific ways in which companies could benefit from specific research findings:

> *I initially thought the work [referring to a project in biochemistry] was done to know more about general enzymes but this enzyme in particular has much larger implications and it really is just financial implications. .... When I was writing it up, I was asking about the general picture and nobody actually said somebody is going to make a lot of money if this works, but because of the way that this particular sector of science works, it is really a money spinner. 3.C.38-39.*

There were also more comments which indicated that students thought that the direction in which a research programme developed would be influenced by whether the research was University based or undertaken by a company.

> *I suppose the people who actually control the work that's being done ... you've got your people who are doing it in not say the university base but more company based, like*

> *Smith-Kline Beecham, where they're looking at therapeutic targets but then they're also looking at ways of carrying out bio-technology procedures where you try and make money by making some kind of new plant. 3.D.30.*

> *It depends on why the research is being done, if it's for medical reasons or commercially based or some sort of pharmaceutical product research then they have certain goals at the end that they are trying to achieve. If it's the development of a drug and they have found, say, there is a group attached to it, then they will obviously see if other drugs affect it, or create this drug again ... but the sort of thing I was doing which is not really applied .... it's just on it's own merit, it is just scientific research and then I suppose scientists could ask any questions really ... there are no constraints, they can literally take it anywhere. 3.E.24.*

3.1.5 Discussion

The four types of responses identified here in students' answers to the question 'How do scientists decide which questions to investigate?' were given both prior to and after completing the project. The frequency of the different types of responses are given in Table 1. As this table shows, the main difference after students completed their projects was an increase in the proportion of students who cited *extending knowledge* as the reason for scientists deciding which question to investigate. Some or all of the reasons were linked together in some students' responses as the following example shows:

> *I think it is moneywise these days, it's what you're going to get funded for I think which is the main controlling factor. Obviously, it's interest as well. If they're not interested they're not going to take it on. And it's, it does seem strange, it seems to be that it goes through phases of areas of research, there seems to be some, this is at the front of research at the moment. It does seem as though, I suppose that it is the interest factor if someone comes up with a new funding then it encourages other geologists and geophysicists. 3.G.42.*

The characterisations of the nature of lines of scientific enquiry used by students at various points in the interviews are described in section 4.2.2. Longitudinal changes in this area are described in section 5.2.2.

TABLE 1: HOW DO SCIENTISTS DECIDE WHICH QUESTIONS TO INVESTIGATE?

		A	*B*	*C*	*D*	*E*	*F*	*G*	*I*	*J*	*K*	*L*	*M*	*pre*	*post*
(a) Curiosity led	*pre*			•	na	na	na	na	na	•	•	•	•	5	
	post		•				•	•		•		•	na		5
(b) Extending knowledge	*pre*	•		•	na	na	na	na	na				•	3	
	post	•		•		•	•	•	•		•	•	na		8
(c) Utilitarian	*pre*	•		•	na	na	na	na	na	•		•	•	5	
	post		•	•	•	•				•		•	na		6
(d) Financial benefit	*pre*			•	na	•	na	na	na	•	•	•	•	6	
	post			•	•		•	•				•	na		6
												TOTALS		**19**	**25**

KEY

na = not asked this question

3.2 Question 2: Why do scientists do experiments?

Students talked about the role of experiments at various points during the interviews. Our analysis includes statements in response to the question 'Why do scientists do experiments?' and also other statements relating to this question found elsewhere in the transcripts. To avoid confusion those statements not given in response to the direct question are marked 'Not Q2'.

Our data are necessarily restricted to each student's brief description of their views. Phrases or terms such as 'what is happening', 'the argument', 'find a mechanism', 'understand', 'have an idea' and 'generate a hypothesis' were all used by students in the interviews. Given the breadth of discussion in each interview it was not possible in all cases to clarify the students' meanings of these terms.

This section starts with a description of the four ways in which the students in our sample used the term 'experiment'. This is followed by the descriptions and illustration of eight categories of response - two related to experiments and 'information', the remaining six related to experiments and scientific theory.

3.2.1 Types of 'experiments'

A) Experiments as deliberately designed and controlled measurements of real world phenomena

This was the dominant view. Even though students were not explicitly asked 'what is a scientific experiment' it is clear that 'deliberately measuring the real world' was the most common conception of a scientific experiment amongst the students.

B) *Experiments as laboratory procedures*

Two students (B, J) used the word 'experiment' to describe a standard laboratory procedure:

> *With lab work everything is set out for you. You get a lab book which has different practical experiments written on it and it gives you the whole protocol and even steps, step number one do this do that and even the volumes and the concentrate. They will give you… everything is set out for you. 1.J.22. (NotQ2)*

This may be the result of the student's experience in school and university practical classes.

C) *Computer modelling as a kind of experiment*

One student whose project involved computer modelling saw this as related to experiments (at least in terms of their relationship to theories) but with more tightly controlled variables:

> *If you did the experiment you could do it but it is very hard to get decent information off it.... But... computer modelling kind of limits your variables so it shows you what goes on without actually doing the experiment which has so many different other things that could happen. So, it is quite sort of... I think it is... well, it is just basically a simplification of what goes on. 1.B.9. (NotQ2)*

D) *Thought experiments*

One student (in Earth Sciences) mentioned these:

> *Mostly physical experiments, yes, but thought-experiments as well where you think through a process and see whether it is a viable solution, a viable solution of that process. 1.G.12. (NotQ2)*

3.2.2 *Why do scientists do experiments?*

1 **Experiments give information (without necessarily being related to theory). This information is gathered in order to:**

1a *Satisfy personal curiosity*

Two students mentioned this view in response to question 2. For example:

Curiosity has a lot to do with it. To find out more. I think its just the way… its human nature you're not satisfied with just knowing this much. You want to know more and more. That's probably it. 1.J.50.

1b *Add to the knowledge bank of science*

Four students gave this kind of response. The direct result of experiments is scientific knowledge. There is no elaboration of how the results of experiments may be evaluated in terms of theoretical knowledge.

To forward the knowledge on a particular subject. So in my case if I choose my aims then I would be forwarding the general knowledge on aldolase genes. So the outcome of any scientific experiment is to increase our knowledge on whatever that particular situation is and which will obviously be relevant to anyone working in that field. 1.C.99.

2 ***Experiments are related to scientific theories***

2a *Experiments are used to test/support a scientific theory*

This was the most common response. Proving and disproving were seen as symmetrical procedures here (cf. 2b).

There's no other way they can prove - not prove in the right sense but prove or disprove their particular theory. Science is very practical, you can't say that something is happening without having substantial evidence. 3.J.29.

Well, to verify whether their theory was correct or to see whether their theory was correct or to see if you know they do produce this compound they were looking for or something like I suppose. To prove or disprove, yes. 3.A.34.

2b *Experiments can disprove a theory but not prove it*

This falsificationist view (after the work of Karl Popper) was stated by one student.

And er… so there are those two theories and only obviously one of them can be right and er… the fact that Isaac Newton's theory about er… gravity and light was sort of proved wrong because there was an experiment which Einstein did when there was a solar eclipse and er… so that kind of… because that is wrong that's just as important to be proved wrong because it shows that…

> *that it can like… you can't really prove anything is right exclusively but you can prove things are wrong. 1.B.37. (Not Q2)*

2c Experiments contribute to a collective effort to test theories

Two students included this view in their responses in the final interview. Both used the analogy of a jigsaw puzzle. The scientific community was trying to solve this puzzle and experiments provided the pieces. This appears to be a collective, co-operative view of the role of scientific experiments.

> *Interviewer: What can the experiment give that helps you decide about a question?*
>
> *Student: In a way it does erm, it might not completely answer your question, it might comes in different bits, you know from your experiment in what other people have done it comes in you know different pieces it's just like a jigsaw puzzle, everything comes together you know to get a clear picture of what's happening actually. 3.I.60.*

2d Experiments enable scientists to choose between rival/competing theories

Two students gave this type of response.

> *Initially, most theories - a theory will be personal and somebody will come up with a theory - somebody will come up with an idea to explain something and other people will go away and test that with experiments, with - put it against other theories that other people come up with, compare them, maybe that initial one will have to be changed to some degree, maybe some bits are wrong and some bits are right, somebody else has come up with an improved version of it, which happens all the time - they're always being improved upon. 1.G.122.*
>
> *A lot of people have two different theories and they do experiments to try and prove those theories and it will be only the one who eventually gets the right experiment at the right time and the theory's proved. 3.D.47. (NotQ2)*

2e Experiments enable scientists to develop theories

These responses were usually referring to the role of experiments in the personal development of a scientist's thinking. They would seem to indicate that there is a distinction between experiments that influence local/personal thinking and those that influence the thinking of the scientific community as a whole. It may be that experiments of the former type are more preliminary and exploratory than those experiments which influence the wider community. Furthermore this type of response is a shift from the views 2a-2d which see experiments being performed in *response* to theoretical developments. Here experiments are seen as leading to the personal development of scientific theories.

> *If you do an experiment you can find evidence, like being a detective, to support certain ideas that you might have thought about or to disprove ideas that you thought about before (...) It's a fine tuning of your thinking. 3.B.36.*
>
> *Interviewer: Why do you think scientists do experiments then?*
>
> *Student: To test hypotheses, to clarify certain assumptions and things that they have made. Just to test out their ideas. 3.F.50.*

2f Experiments and theories are in a cycle of development

One student gave this view in their final interview. The response is distinct from the others only in the content of the section underlined.

> *It's often an experiment, a theory comes up first and the experiment's designed to solve that theory, <u>obviously the experiment then creates more theoretical work afterwards</u> .... but I think it's always to disprove or prove somebody's, it seems to me to disprove or prove somebody's theory because that's the way it goes, you don't get any funding or you don't get erm.. there's no need to do an experiment if there's no sort of theory that needs to be proved or disproved. 3.G.48.*

3.2.3 Discussion

Our major categories 1 (experiments give information) and 2 (experiments are related to scientific theories) indicate whether the student explicitly describes scientific theory as having a role in experimentation. Category 2 statements describe a wide range of possible relationships between theory and experimentation. Experiments can test theories, support theories, prove or disprove theories, decide between competing theories or enable scientists to develop theories. This complexity of response may be a consequence of the wide range of project types being followed by the students in our sample. This possible relationship between the students' experience on their project and their images of science is discussed in sections 6 and 7 of this paper.

Table 2 also shows that individual students during a single interview may describe experiments as having a variety of roles. For instance student D describes the role of experimentation as 'adding to the bank of knowledge' (1b), 'testing a theory' (2a) and 'choosing a rival theory' (2d) during his post-project interview. These varieties of response from single students are not surprising given the many *different* roles that experiments have on the practice of science.

The characterisations of scientific knowledge claims and their warranting used by students at various points in the interviews are described in section 4.2.1. Longitudinal changes in this area are described in section 5.2.1.

TABLE 2: WHY DO SCIENTISTS DO EXPERIMENTS?

		A	*B*	*C*	*D*	*E*	*F*	*G*	*I*	*J*	*K*	*L*	*M*	***pre***	***post***
1 (a) Satisfy curiosity	*pre*									•				1	
	post										•		na		1
1 (b) Add to bank of knowledge	*pre*	•		•								•		3	
	post				•								na		1
2 (a) To test a theory	*pre*				•	•		•				•	•	5	
	post	•	•	•	•					•		•	na		6
2 (b) Disprove not prove a theory	*pre*		•											1	
	post												na		0
2 (c) Collective effort to test theories	*pre*													0	
	post					•			•				na		2
2 (d) Choose between rival theories	*pre*							•						1	
	post				•								na		1
2 (e) Help develop theories	*pre*							•						1	
	post		•				•						na		2
2 (f) Cycle of development	*pre*													0	
	post							•					na		1
								TOTAL						**12**	**14**

KEY
na = not asked this question

3.3 Question 3: How can good scientific work be distinguished from bad scientific work?

This question was discussed with nine of the twelve students in the initial interview and with all but one of the students in the final interview. Students' comments ranged from very brief remarks to extended and complex statements referring to a range of evaluative criteria. Seven main criteria for evaluating the quality of scientific work were identified. These will be described and commented on in turn.

3.3.1 *Procedural criteria*

Good science is done when scientists work diligently and follow standard methods. For some students, good scientific practice was seen primarily to involve being careful and conscientious in the conduct of practical work.

> *Being diligent, being careful - always conscientious - knowing that if you do it right then you are going to have a better chance of getting the end results. 1.D.115.*

Conversely, poor scientific practices were cited as using dirty containers and allowing reagents to become contaminated. In some cases, reference was made to 'good experimental techniques'. Others referred to standard methods or protocols.

> *.... there are standard practices, standard ways of doing things and they should be followed to ensure that something follows a standard. 3.C. 43.*

This student goes on to comment:

> *Having said that, if someone designs a new method of doing something, it doesn't necessarily mean that it's not good science. You'd have to ... see how the work compares and that certain practices have been carried out to make good science. 3.C.43.*

Overall, there was an emphasis on good science producing good data. As one student put it:

> *That's really important, to get good data. 1.A.37.*

The reason for standard methods was explained by one student in terms of the need for reproducibility of results.

3.3.2 *Critical approach to experimentation:*

Good science involves thoughtful, critical approaches to the design and conduct of experiments. A number of critical features were mentioned. The need for careful *controls* was cited by one student.

> *Like doing experiments without proper controls. 3.I.64.*

The importance of *reproducibility* of results was mentioned by many students especially in the final interview. This was often linked to the *need to follow* set procedures.

> *... good scientific work I would just say is when you know for definite that you've got something by reproducing it. 3.A.38.*

> *.... when you write a paper you write the exact method, someone else would have to follow the exact method in the hope that it would generate the same results and prove that it wasn't just a one off. 3.C. 46.*

The use of *quantitative* methods was cited as important in establishing the reproducibility of results.

> *You can't really tell by looking at it, you've got to measure them [referring to amplitudes and periods of oscillations]. Because if you were.....saying the period decreases, and it doesn't all the time, it might decrease then increase, and you might not notice that unless you measure it. 3.A.39-40.*

In the final interview, a couple of students also mentioned the importance of *estimating the size of errors.*

> *If you have considered how accurate your results are, that's important. You have got to be honest about putting error limits on. 3.F.52.*

> *I think description ... of errors and uncertainties as one of the key ... things in good scientific work. Even if it's ... conclusions ... are not proving or disproving anything, as long as you can quote how accurate your work is ... and not ... over estimate it's value ... I think that's the key to the sciences, to know the bounds of your predictions. 3.G.50.*

The need for a *critical questioning approach* when considering the methods of others was commented on. One student described the way his supervisor thinks:

> *He will be questioning, for example, if he read a paper done by some people and he looked at their method and thought 'that looks a bit dubious', how have they done that? Perhaps I can do it this way and find out the actual true result or in his eyes the true result as he sees it. So I mean you are always going to question how other people are doing their work. 1.D.119.*

This same sceptical attitude was seen to be important also in interpreting results as the next section describes.

3.3.3 A sceptical questioning approach to interpretation and explanation

Fewer comments were made about the interpretation of scientific results and the development of explanations. Those that were made reflected the need for a critical approach.

The need for theories or explanations to be supported by evidence was commented on:

> *In scientific work, if you publish a paper, every fact that you write you have to have evidence to back it up. I think that is how you can distinguish between the two, (good and bad science). You have to have scientific or experimental evidence to back up your argument. 3.J.31.*

The need for flexibility of mind was recognised in relating evidence to interpretation.

> *I think you've got to have a really open mind to be a good scientist. Even up to the point where all your life you've believed something and somebody else comes along with another bit of evidence ... be prepared to discuss what you've always believed if this new bit of information seems to be definitely true. 3.B.38.*

> *... people who say don't consider it, 'that can't be true, not because of evidence, just because of their feeling, and dismiss it before even analysing it and thinking about it. I think that's very bad science. 3.B.38.*

This same student continued:

> *They shouldn't instantly jump into it and accept it straight away ... but they shouldn't dismiss it straight away. They should have an open mind just saying 'well fair enough, I'll have a look at that'. B.3.39-40.*

The difficulty scientists may have in changing their ideas in the light of counter evidence was also commented on:

> *...My own personal view of a good scientist is somebody who will have an idea about something - will have like a - think of a concept and then somebody will clearly look on it and won't just say that's rubbish, will actually give a lot of thought and be quite happy to accept a new idea or to be even proved wrong .... I mean there are very few scientists who will .... have a sort of idea and will be prepared to change it. .... There are some organisations that won't change their ideas. If a new idea comes in they*

> *instantly block it out - without even thinking. I don't like that at all - I think it's bad. 1.B.43.*

Although comments made by some of the students indicated that they recognised the problematic nature of relating theory and evidence, none of the students commented on the tentative nature of theories or the extent to which they may be underdetermined by data. On the contrary, the comments that were made, suggested that certain theories are definite and right.

3.3.4 Strategic aspects of a research programme

There was very little comment by students on the strategic aspect of scientific work. One remark from a final interview indicated that the student was aware of the importance of a sense of purpose and direction in scientific work:

> *.... asking questions ;'why has this worked?' 'what can be done next?' at each stage of the research, 'what does this prove?' I suppose bad scientific work in a way would be blindly just going along really ... 3.E.28.*

3.3.5 Relating work to other work in the field

This aspect of good scientific practice was recognised and commented on by a number of students in both the initial and final interview.

> *I would say good scientific work is work that has been well researched and probably used a lot of other people's work as well to help. Bad science ... I'd say was the opposite where someone had an idea, tested it and not looked up any of the other information that's around on that subject. 1.A.36.*

One student commented on the problematic issue of evaluating a scientists' work when it differs from the majority view in the field. The importance of supportive evidence from a number of scientists contributing to whether or not a piece of science is accepted was commented on by one student:

> *... it would involve a new technique that hadn't been substantiated and there wouldn't be lots of evidence to back it up that it's a worthy technique. So it would be a piece of work out on its own without the support that would make it valid. 1.C.126.*

At a superficial level, one student recognised the importance of relating work to other studies in the field in written reports:

> *You could probably tell how good the research was by the amount of references ... because it sometimes, there is lists of references at the bottom of your paper .... 1.A.37.*

In the following example, a student describes the role of the community of scientists in judging the merit of work in particular fields:

> *Student: One example would be this chap who had this theory that was at the time very revolutionary and everyone just went 'Oh that's a load of rubbish' and about 20 years later he was proved to be right and it happened to be the basis of biogenetics in biochemistry ...*
>
> *Interviewer: Was it good science then?*
>
> *Student: Yeah, what he did was very logical.*
> *Interviewer: But the scientist at the time decided it wasn't good science....*
>
> *Student: Yeah, at the time they said 'That just can't be right' and they went about on their experiments, and it just so happened that the majority didn't think it was right. The majority rules. 3.D.37-39.*

3.3.6 *Ethical criteria are involved in distinguishing good and bad science*

Four students answered the question how do you think good scientific work can be distinguished from bad scientific work by referring to ethical criteria. One student referred to the ethics of certain types of research:

> *.. good scientific work in my personal view is when it actually benefits ... people in general. When it's not just exploitation of animals of whatever .... The various things we have learned .... about the work that has been going on in, you know, getting a gene from one animal and putting it in another, I don't find that acceptable. 1.J.51-52.*

Another student's comment referred to scientific fraud:

> *I suppose bad scientific work could be any ethical situations that come up ... if for example, they had pinched somebody's data without saying. 3.E.27.*

3.3.7 *Communication skills of good as opposed to bad scientists*

A number of students responded to the question how can good scientific work be distinguished from bad scientific work in terms of evaluating scientific papers.

> *I think to be a right good scientific worker I think you need to remain clear, not get lost in your own terminology ... for someone to pick up your lab book and be able to follow it 1.E.61.*

...and also referring to scientific papers:

> *.... how well the person gets across to you their thoughts. If they've got a better understanding of it then they're going to be better at getting across to you their thoughts. 3.K.32*

3.3.8 Discussion

A summary of the types of responses given by the students is shown in Table 3. As this table indicates, students' responses emphasise empirical criteria for the conduct of good science, with the critical approach to experimentation, especially the reproducibility of results and analysis of errors being seen as particularly important. Less emphasis was given to the interpretation of results and very little attention was paid to strategic planning of scientific work.

Many of the students also commented on individual scientists needing to relate their work to others in the field. It appears therefore, that in these cases, there is an appreciation of science as a social as well as an individual practice.

The characterisation of scientific knowledge claims and their warranting used by students at various points in the interviews is described in section 4.2.1. Longitudinal changes in this area are described in section 5.2.1.

TABLE 3: HOW CAN GOOD SCIENTIFIC WORK BE DISTINGUISHED FROM BAD SCIENTIFIC WORK?

		A	*B*	*C*	*D*	*E*	*F*	*G*	*I*	*J*	*K*	*L*	*M*	*pre*	*post*
(a) Procedural criteria	*pre*	•		•	•		na	na	na					3	
	post			•					•			•	na		3
(b) Critical approach to experimentation															
Controls	*pre*						na	na	na					0	
	post								•				na		1
Reproducibility	*pre*			•			na	na	na					1	
	post	•	•	•									na		3
Quantitative measures	*pre*						na	na	na					0	
	post	•		•									na		2
Errors	*pre*						na	na	na					0	
	post						•	•					na		2
Critical	*pre*				•		na	na	na			•		2	
	post												na		0
(c) Sceptical interpretation	*pre*		•				na	na	na			•	•	3	
	post	•	•							•			na		3
(d) Strategic planning	*pre*						na	na	na					0	
	post					•							na		1
(e) Relating to field	*pre*	•	•	•			na	na	na					3	
	post			•	•		•						na		3
(f) Ethical criteria	*pre*						na	na	na	•		•		2	
	post					•						•	na		2
(g) Communication skills	*pre*					•	na	na	na		•		•	3	
	post									•	•		na		2
										TOTAL				**17**	**22**

KEY
na = not asked this question

3.4 Question 4: Why do you think that some scientific work stands the test of time whilst other scientific work is forgotten?

This question was asked of most of the students in the first interview and all but one of the students in the final interview. Students' responses varied in their depth and detail, however, all the students were able to give a thoughtful response.

It was apparent from the responses that there were two main ways of interpreting 'scientific work'. One interpretation was to see scientific work as the research activity of scientists, both as individuals and in groups. In this case, scientific work which stands the test of time means lines of research which have kept going for a long time. The other interpretation was that scientific work is the product of what scientists do; the scientific theories and other knowledge claims proposed by scientists. From this perspective, scientific work which stands the test of time was taken to mean theories which have had a long history of being accepted within the scientific community.

There were five distinct reasons which students put forward to explain why some scientific work stands the test of time. Two of the reasons were used by the majority of the students, the other reasons were put forward by only a small number of students. These reasons are described and illustrated below.

3.4.1 Revolutionary breakthroughs

Students saw significant and long-standing scientific work as coming about when scientists in a field are aware that there is a problem and some individuals propose a new way of thinking about it which accounts for the evidence. A number of students named particular individuals as having made such a contribution.

> *If it is something ground-breaking, maybe Einstein or Watson and Crick.....like Watson and Crick, there was so much interest in DNA at the time and I mean the fact the race was on, and they got that molecule and I think it is of interest to the scientific community as a whole and it is quite ground-breaking stuff, then yes, those sort of things tend to stand out... 1.E.62.*

> *I suppose how revolutionary an idea is ... I just think of things like Watson and Crick 1.K.86.*

> *If it was something really significant then obviously people are going to remember it like when penicillin was discovered. 1.J.55.*

Comments were made on how such breakthroughs come about and the factors that promote and constrain such change. The importance of individual imagination and ability to think about a problem in new ways was recognised.

> *Yeah, I think that there's obviously certain theories that have lasted a lot longer than others and it obviously takes a certain brain intelligence to ... it's the brain that tells me something ... that one way to do is to go, you know leaps and bounds ahead of everyone else and so therefore it's taking everyone else to catch up, that seems to have happened in history.....and I think the development of ideas ... it's rarer. I think that that's the only way that the*

> *theory can stand the test of time and not be changed. 3.G.54.*

> *There'll always be a certain sort of, very intelligent people or people in the right field at the right time and they'll be a jump ahead of everyone else and they'll find something. 3.G.55.*

While the need for individual insight was recognised in making significant scientific breakthroughs, students also recognised the importance of new theories being viewed critically, even sceptically, before being accepted by others.

> *They would obviously have to do the experiment themselves a few times to make sure of the results. 3.B.39.*

One student acknowledged the resistance of some scientists to a change:

> *one problem that science has ... is that it doesn't like ...if people ...give a new theory ... people just can't say we will accept what you are saying and they will check it. People inherently say that can't be right and discount it and they don't properly look at it. 1.B.38.*

This same student, using an example from chemistry, then outlined how scientific intuition can influence whether or not an idea is accepted.

> *if you look at a reaction ... you look at it and think that goes to the product. If somebody says well no it goes somewhere else or it goes to the product but it goes via something else, you think to yourself well no it is very unlikely that it does , it seems like a ridiculous amount of energy needs to go via this sort of round the houses rather than go via a direct route and so people can be a bit clouded by it. 1.B.39.*

3.4.2 Coherent development of a field

This was a popular view among the students in this study. In contrast with the previous revolutionary view of science, this perspective tends to portray science in its normal phase as a painstaking task of building coherent and secure bodies of knowledge. From this point of view, a theory is seen to stand the test of time if it is built on and leads to other work.

> *If something's discovered that a lot of things lead on from, then it will never be forgotten because it's the basis behind a lot more scientific research. 3.A.43.*

> *If it led to further research into a particular field that will be more remembered than something that even though it was big and exciting at the time, if nobody follows it up it tends to get forgotten. 3.J.33.*

> *I would say because work that follows consequently supports it. For example something major like the Krebs cycle in biochemistry, everything that has been done since that was discovered supports its existence....so it's a fact that it's supported by lots of scientific groups in various ways and situations. 3.C.47.*

This view that there are areas of secure scientific knowledge which will not change was reflected in the comments by other students:

> *There's theories on the structure of proteins that've been decided on years ago and are still holding and they've not changed at all. Proteins have a certain structure and that's the way it is. 1.C.123.*

In a comment which hinted at Lakatos's concept of a progressive research programme, one student suggested:

> *I suppose it depends on how great a breakthrough it makes with the actual research and if it's [a] constantly evolving field. 3.K.33.*

One student made a thoughtful comment, which although it differed from many others in that it suggested that important work could be forgotten as it was subsumed into an ongoing research programme, also reflected the view of a progressive research field.

> *I suppose if it's something that other people have done a lot more work on afterwards and may be improved, got more accurate results or improved a method or something, then the original work is going to be forgotten because something better has been done afterwards. 3.F.62.*

For those students who viewed science as being undertaken through research programmes, the issue of how such programmes come to an end was raised.

> *It might be loss of interest...you've found out too much, so much on that area and you think and everyone's doing it, so at a certain point of time that you might run out of ideas ... or you've got so much information on that area that people might switch on to something else. Doing such work you tend to have lots of competition so you don't really stick to the one area [for a] very long time ...*

> *There's this particular person that's working in this area and he's working so hard because he knows some of the others working in the same area, the same gene, and he's just trying to ...find out what happened before the other person does. 3.I.68-71.*

These responses indicate that many of the students in this study were aware of science as more than an individual pursuit. They were aware of research programmes, how they evolve and how they can decline. The timescale for this was even commented on:

> *Science is very much, its a long procedure in what you are doing and what your eventual aim is. Projects that go on for a long, long time I mean usually they are very important projects so they have to be continued, like research for drugs against cancer (...) I mean Biochemistry is a relatively new field in that it has only been going for the last forty to fifty years, so a long-standing project in 'Biochemistry will be twenty years say, whereas Physics would be a couple of hundred years .... a long, long long long time!. 1.D.137.*

A biochemistry student described the careful process of making progress in a current field of science in the context of his own project, which involved finding out if there was a specific cleavage site or a range of cleavage sites on a specific protein. The student was aware that there was a difference in view between the laboratory he was working in and a laboratory in France.

> *I have a doubt in that this French thing for example the way they see it, they see it that the cleavage site is not a set cleavage site so I am going to examine the cleavage site and I am going to get say if I did this a number of times and I wouldn't find an exact cleavage site so therefore I could agree with them....If I get that result and find a number of cleavage sites then I will be agreeing with them but I could come out with it and say there are set cleavage sites that are cleaved there all the time and that's how it is cleaved so I could disagree with them.... The problem is the way they did it, so Dr. X sees that it could have been cut but then it could have been degraded because there are loads of enzymes in the cell that could still actually degrade the end of the cleavage site. 1.D.140-143.*

3.4.3 The inherent quality of the research

Some students argued that it was the inherent quality of the research that ensures that it will endure, and one student mentioned the status of the researcher as giving credibility to the particular work. Criteria for quality which were mentioned in this context were the consistency of a theory with evidence and reproducible techniques.

> *If its really important then of course it's going to last a lot longer than something which may be someone's interest but hasn't got any evidence. 3.D.42.*

> *I think the significance of results has a lot to do with [it] ...but reproducibility I suppose, if you can come along and do them again and again, then that's considered a good technique because if someone can come along and follow it any problems encountered can be overcome. 3.E.29.*

In some cases students combined these arguments .

> *Perhaps because of ...its relevance to other fields and also how the actual piece of work is valued that is produced. For example, if you had a dodgy scientist that came out with a theory and it's unlikely to be valued unless a whole group of people came out with the same theory and they had enough evidence to back it up. So it depends on how much work is done on something to prove it, and the overall relevance of that. 1.C.116.*

The idea of science as a kind of game where scientists try to disprove each other's theories was described by some students. In such cases theories that stand the test of time are those which are more difficult to challenge or disprove.

> *I guess the history of science, basically someone comes up with an idea and everybody clambers to debunk it and come up with a fresh idea, continuing on from that and making some alterations so that the person who immediately came up with the idea his name is kind of forgotten and the next person gets a bit of acclaim for it. And then someone who stood the test of time would have a theory that's a bit more difficult to pull apart by the other scientists. 3.L.43.*

3.4.4 Research with practical benefits

The argument that scientific work which has practical benefits is likely to stand the test of time was woven in to some students' responses.

> *it depends if it is really important ... say like drug pumps. 1.E.62.*

One student, however, did acknowledge that it is often problematic identifying what will be significant applications of scientific research when it is conducted.

> *... I don't think you can say a particular type of research is more important than another really. Because like this copper superconductors or something like that, I mean who, when they first found these conductors at such low temperatures...would you ever think that they're going to be useful....because they have found these other compounds, that these other copper superconductors that conduct above the nitrogen boiling point, there's suddenly great interest. 3.A.45.*

3.4.5 Theories which are difficult to test

One student pointed out that some theories are long lived simply because they are very difficult to test at the time.

> *There's also [theories] where you make predictions that basically can't be tested and they're going to last a long time because until people can actually test them ...the truth of them is not going to be tested. 3.G.55.*

This is not a trivial comment. There are many instances in the history of science of theories being proposed ahead of their time without being able to be adequately tested. This comment also draws attention indirectly to the distinction being made between the status of theories as conjectures or hypotheses and theories which have been accepted by the community of scientists as constituting reliable knowledge (for example the cases of the Krebs Cycle and protein structure, as mentioned by students).

3.4.6 Discussion

Overall, the emphasis in the students' arguments about what makes scientific work stand the test of time lay in the first two reasons, whether or not work reflects a major breakthrough or revolution and whether or not it supports a coherent research programme.

Some student responses combined a number of reasons as the following example illustrates:

> *what you are doing has got to be relevant to the field in terms of it has not already been done before and the outcome will have some importance and relevance to other people and you are pushing back some frontiers 1.C.112.*

It is interesting to note that whereas many students suggested more than one of the reasons given above for the continuing importance of fields of research, it was different students who put forward the revolutionary view to those suggesting the view based on the coherence of a research field.

There was little evidence for any change in students’ perspectives on this issue between the two interviews. One exception was in students’ discussions of scientific work being part of a coherent field. Table 4 summarises the use of the different reasons.

The characterisations of lines of scientific work and the nature of scientific knowledge used by students at various points in the interviews can be found in sections 4.2.1 and 4.2.2 respectively. Longitudinal changes in these areas are described in sections 5.2.1 and 5.2.2.

TABLE 4: WHY DO YOU THINK THAT SOME SCIENTIFIC WORK STANDS THE TEST OF TIME WHILST OTHER SCIENTIFIC WORK IS FORGOTTEN?

		A	***B***	***C***	***D***	***E***	***F***	***G***	***I***	***J***	***K***	***L***	***M***	***pre***	***post***
(a) Revolutionary	*pre*					•				•	•			3	
	post							•			•	•	na		3
(b) Coherent field	*pre*		•	•	•									3	
	post	•	•	•	•		•		•	•	•		na		8
(c) Inherent quality of work	*pre*			•	•									2	
	post				•	•							na		2
(d) Utilitarian	*pre*					•				•				2	
	post												na		0
(e) Untestable	*pre*												•	1	
	post							•					na		1
										TOTAL				**11**	**14**

KEY
na = not asked this question

3.5 Question 5: How are conflicts of ideas resolved in the scientific community?

Responses to this question were given to by all but three of the students in the first interview and by all but one in the third interview. All students acknowledged that there are disputes in science; some students provided examples from the history of science, others drew on their knowledge of the field relating to their project to provide evidence. In giving their comments, students addressed the issue of why differences between scientists may occur as well as how they are resolved.

3.5.1 Why differences between scientists occur

All the respondents accepted that disagreements between scientists occur. The reasons they gave for this focused on methodological issues, differences in the interpretation of evidence and differences in theoretical perspective.

5a Methodological reasons

The simplest reason put forward for scientists holding different views was that in some cases mistakes are made in methods and techniques. In the context of a discussion on how two research groups might disagree about whether or not a particular scientific problem was solved, a student commented:

> *I think it might occur quite frequently.... if you do a different approach, you encounter something different .... so you might make a mistake somewhere. You'll be using the same things, but when you start extracting from others it gives you different results .... I know of a particular, a few papers, that ...claim to discover something new but they ... sort of make a mistake somewhere. 1.I.115.*

Comments were made about differences in instrumentation, data collection and processing techniques. A geology student commented that the data itself might be the same but the results could differ if processed differently.

> *Well, it [a difference in view] would be differences in the use of the software. 1.F.149.*

A subtle point was made by a genetics student who argued that when you analyse the methods used by different researchers, it is possible that they are actually looking at different things.

> *This particular thing that...this group discovered might be different from the other groups-what they discovered... say in a cell, it interacts at different genes or in different stages so you can't really claim that the other group was wrong, actually. 1.I.118.*

The point being made here is that although superficially an experiment may appear to be conducted so as to replicate the work of others, in practice there will be differences in the way an experiment proceeds, so actually there will be subtle differences in the phenomenon being studied. This point bears some similarity to an argument put forward in Collins (1985) which questions the concept of replicability in science.

5b Difference in interpretation of evidence

One student commented that differences in the interpretation of evidence could be due to limitations in the accuracy of measurements. He argued that because of this it is never possible to prove a theory definitely and, by implication, different interpretations are possible:

> *no theory can [be proved definitely] because there is always a limit to experimentation and to our accuracy that we can prove something...no one can say they've definitely the correct theory. 1.G.124.*

A further reason for differences in interpretation of data was put forward by a geology student in discussing a dispute relating to her project. In this case differences in interpretation were presented as differences in how the data were construed.

> *Well, when you look at magnitude-frequency relations, a thing called a B line which is the slope of the dip [in the Earth's magnetic field], the correlation you get between magnitude and frequency - some people think those are really relevant to the structure of the Earth, focal mechanisms and earthquake mechanisms, and other people don't and dismiss it as being differences in recording stations. 1.F.149.*

5c Different theoretical perspectives

A number of students argued that conflicts arise because of the different theories or ideas that scientists hold.

> *I suppose like you hear different ideas from lecturers you know, or other people leading in the field have different ideas. 1.K.92.*

> *The conflicts arise because two sets of scientists have two sets of different ideas, so they are not in total agreement in their ideas about how a technique works. 1.D.121.*

The reason why scientists may come to different conclusions was portrayed by a number of students as being due to characteristics of scientists themselves; they develop a ‘mind set’ or a personal commitment to their ideas.

> *You can be affected by what you’re thinking-very much...perhaps you’ve not predecided but...you’ve been affected for some reason by some text or something you have gone through. 1.G.125.*

When asked whether he thought there were conflicts in science, one student argued at length that scientists disagree because of the personal commitment they have to their ideas.

> *Yes, I would say so. Definitely. People have their own personal opinion on certain issues...if someone does not want to believe something then they will call into question the experiment and techniques used or argue that it is a one-off situation. I think if someone doesn’t believe something then it is very difficult to prove it to them..... I would say that in their own field most people are opinionated. Obviously one scientist can’t know the whole area of science but in their own area most people have their own opinions on the major findings. 3.C.52-54.*

3.5.2 How conflicts are resolved

5d Decisions made between theories based on empirical evidence

A number of different points of view were identified from students’ responses. The most common perspective was that disputes are resolved in the light of empirical findings. This process was portrayed as involving experimental proof, evidence and logic. It was also seen as an activity involving individual scientists who need to resolve differences to their own satisfaction. In most responses of this type, the experiment was seen as providing a clear unambiguous basis on which to ‘prove’ or ‘disprove’ a theory.

> *How they resolve [disputes] in science is by carrying out experiments that prove one theory is right, proving without a shadow of doubt that theory is the correct one...A lot of people have two different theories and they do experiments to try and prove those theories and it will be only the one who eventually gets the right experiment at the right time and the theory’s proved. 3.D.46-47).*

> *They’d have to prove if a theory stood then they’d have to prove it. I mean they couldn’t just say no I don’t believe this, something else is going on, they’d have to prove it..... I suppose there must be a way of proving these things. I*

> *suppose it depends on the experiment, on the theory and the experiment really. 3.A.49,52.*

One student hinted at a Popperian perspective in making the point that it was the characteristic of ‘good scientists’ that they test their theories to the limit.

> *If they’re good scientists then they’ll argue their theory to the point which has proved to be wrong. But if they believe in their point then they’ll keep going until somebody can say, with experimentation or with a thought experiment, ‘that’s wrong, there is a reason why it cannot hold up’. And then if they are good scientists (they say) ‘Fair enough, it’s wrong’. 1.G.127.*

In a later interview, this same student made a distinction between the sciences in the extent to which a theory could be clearly evaluated.

> *It’s often that...two or three theories will always be there to explain a phenomena until maybe it’s proved experimentally. But even then people can change around their theory...I think it’s even worse in geophysics, it seems a less exact science than something like physics where ...eventually you will be able to prove whether someone’s completely wrong or right, but with geophysics and geology people seem to be able to change around their views a bit to sort of fit the data. 3.G.61.*

One student acknowledges that it is not possible to provide incontrovertible proof for a theory:

> *Science isn’t about proving things, it’s just about putting forward your theory and until somebody else comes along and says hang on a minute this isn’t right. So that person puts forward another theory which, if...he had proof, not proof, evidence to back up that theory, which is contradictory to this theory, then...but you can’t actually ...prove one hundred percent that something is right. I.J.59.*

5e Decisions made between theories involve a social as well as an empirical process

A minority of students’ responses reflected the view that resolution of scientific disputes involves social processes within the scientific community. The issue of reproducibility of results is an example of such a social process.

When asked how conflicts are resolved through experimentation, one student cited the example of problems of replication in the case of cold fusion:

> *Was it a German chemist or something or American, said they could get this cold fusion by, what did they do - have some electrodes or something - I can't really remember ... Well other people tried it, following exactly the same procedures and they did not get it at all. 3.A.57-58.*

Other students commented that particular theories become accepted when there is a 'weight of evidence' within the scientific community.

> *Basically proving by a lot of groups of scientists that what they have done is right. 1.D.122.*

> *If it's within a certain area then any conflict will be resolved because a lot of people are working on it and...if information comes through...if it's clear cut information, if it is something that actually resolves between the two then it will be accepted I suppose. But I think it's a case of ...who is interpreting the information... I think it really depends on the nature of the knowledge, who's carried it out. 1.E.65-66.*

The personality and beliefs of scientists were seen to influence the decision-making process in the scientific community.

> *Sometimes if one group has found one thing and they won't sway from that and another group has found something that contradicts them. It really depends on the personality of the scientists whether things go well. 3.E.30.*

The place of the scientist's emotions about their work came through in some responses. For example, when asked how a scientist would react to having a personal theory disproved, a student commented:

> *It depends how bitter they are...I suppose it depends whether they can accept the other person's work. If they've put a lot of work into it then they find out it's wrong, perhaps they go into that theory and find out more about it. I don't know how they would respond. It's difficult. 3.D.51.*

The influence of the support of a wide group of people for a theory was expressed in the following comment:

> *It takes just about absolute proof I think, for a lot of scientists especially if they developed the theory, it will take ... a lot of proof for them to say, no it's wrong because they'll have spent a long time working on these*

> *things and they'll really know the ins and outs of them and it'll take a really good new bit of data or a proof, a definite proof because of it's a realistic possibility as well they're bound to build up a sort of following of people that agree with them. 3.G.62.*

5f Resolution through compromise

Some students suggested that a conflict of ideas in science is resolved, not by the triumph of one theory over another, but by a process of compromise and use of some ideas from each competing theory.

> *Maybe both of them are wrong, maybe there's a few points that are correct in one - a few points correct in another. 1.G.126.*

> *Sometimes a balance is struck between the two. 1.K.90.*

A more complex argument was advanced by one student who suggested that conflict can occur between two theories, when the 'true' theory is different from both of them.

> *If both of the ideas really happens then it might be a link somewhere in between...I mean different theories conflict each other...both theories are correct but it is something in between that happens or some sort of other mechanism or other thing happens that's why you're getting different results but conflicting each other. 3.I.73.*

The student then illustrated the point with an example from biochemistry:

> *One group actually proved that this particular protein is involved in doing certain processes in the cell. And another group showed that its doing something else as well so...from one point its being diverged....it's going two different ways.. [it is] not just going straight, just leading to the same findings. 3.I.75.*

5g Conflicts remain unresolved

There was a recognition among some students that some conflicts remain unresolved or they are only resolved after an extended period of time.

> *I don't know whether all conflicts are resolved really... In lectures ...we did say a protein structure and they'll say 'Some people think it is this' and work in another lab they'll say 'it's not that' and I think in the end of the day they remain unresolved until somebody else picks up the thread later on. 1.E.63.*

> *I don't think they're really resolved. Everybody sticks to their guns - this is what I believe - publishes papers and other person says 'No, what you're saying is totally wrong' and the only way they can express their feeling that it's totally wrong is to publish papers to support their argument. It's like a battle of theories and I don't think it's really resolved. 3.J.34.*

This student continued to comment on the value of being forced to defend a theory in science:

> *It's kind of like a competition. It's quite healthy for science because all the time you're trying to find or discover something and you've got all this evidence to back it up, even though other people don't agree with it but still I think there comes a time where if they experience it themselves then they tend to agree. There's this really important theory about apoptosis - we recently watched a video about it. It's cell death. Twenty years ago this scientists said that apoptosis exists and nobody believed him. Recently a lot of scientists were doing other research and they were experiencing things that they could not explain at all, the only way that they could explain it was by apoptosis. So after twenty years they had to accept it. It does take time but they were very strong in their views saying it didn't happen but in the end they had to accept it. 3.J.35.*

3.5.3 Discussion

Overall, the responses to this question emphasised the resolution of conflicts through empirical evidence. This was a view which was much more commonly expressed after the students had completed their projects. There was also a strong commitment to the notion that theories could be 'proved' incontrovertibly. There was an awareness among some students of the social processes that are involved in the resolution of conflicts in science, but this view was expressed by a minority and there was no apparent change in students' views on this aspect as a result of doing their projects. Table 5 summarises the different types of responses given by students both before and after completing the project.

The characterisations used by students at various points in the interviews about the nature of scientific knowledge claims and their warranting are described in section 4.2.1. Longitudinal changes in this area are described in section 5.2.1.

TABLE 5: HOW ARE CONFLICTS RESOLVED?

A. WHY DIFFERENCES OCCUR

		A	*B*	*C*	*D*	*E*	*F*	*G*	*I*	*J*	*K*	*L*	*M*	*pre*	*post*
(a) Methodological reasons	*pre*						•		•					2	
	post								•				na		1
(b) Interpretation of evidence	*pre*						•	•						2	
	post		•										na		1
(c) Different theories	*pre*				•			•			•			3	
	post			•									na		1
										TOTAL				**7**	**3**

B. HOW DIFFERENCES ARE RESOLVED

		A	*B*	*C*	*D*	*E*	*F*	*G*	*I*	*J*	*K*	*L*	*M*	*pre*	*post*
(d) Empirical evidence	*pre*							•						1	
	post	•	•	•	•		•	•			•		na		7
(e) Social and empirical processes	*pre*				•	•						•	•	4	
	post	•				•		•				•	na		4
(f) Compromise	*pre*							•			•			2	
	post								•				na		1
(g) Unresolved	*pre*					•				•				2	
	post									•			na		1
									TOTAL					**9**	**13**

KEY
na = not asked this question

4 A framework for the characterisation of students' epistemological and sociological reasoning about science

In the previous section, students' responses to open-ended questions about the nature of scientific knowledge and science as a discipline were presented. However, important epistemological and sociological issues often reappeared several times in a student's responses to the five interview questions. Our question-by-question coding does not make transparent epistemological and sociological issues raised by students. As a result a second order, cross-question analysis of the students' responses was required. In this section, a general characterisation of students' epistemological and sociological reasoning about science is developed.

We had two broad aims in characterising students' epistemological and sociological reasoning. The first of these was to produce, at the population level, an account of the range of images of science likely to be used by undergraduate students. In order to do this, the extended responses of students to open-ended questions about the nature of science as a discipline were analysed in detail. Epistemological and sociological points made by students were characterised, and a framework was generated to encompass all points raised. This framework represents our best attempt at profiling undergraduate students' epistemological and sociological reasoning about science at the population level. It is recognised, however, that the sample on which the framework is based is very small indeed, and further work with a larger sample may allow for extensions and refinements to the framework.

Our second aim was to show individual changes in students' epistemological and sociological reasoning about science that may have occurred throughout the period of students' final year research projects. Whenever epistemological or sociological points were apparent on transcripts, these were coded with one or more categories from the framework. Two profiles of each students' epistemological and sociological reasoning were then prepared, one relating to the first interview at the beginning of the research project, the other to the final interview at the end of the project. Longitudinal changes were then identified and discussed.

This study was not designed to illuminate possible causes for longitudinal changes in students' epistemological and sociological reasoning about science. Although it is tempting to speculate that the experience of doing a research project might result in a more sophisticated profile of epistemological and sociological reasoning about science, it is equally possible that changes may result from work in other parts of the undergraduate curriculum, or beyond. We maintain a cautious position on this issue. In some cases, however, there are compelling reasons to assume that the experience of doing research projects has broadened students' epistemological and sociological profiles. This issue is discussed in section 6 by reference to particular case studies.

4.1 The development of a framework of students' epistemological and sociological reasoning

The five questions in interview 1 and interview 3 given in section 2 addressed students' epistemological and sociological reasoning about science in general. Responses to all questions in these sections were therefore used to characterise students' epistemological and sociological reasoning.

An ideographic approach was used. Three researchers independently read all transcripts, with a view to drawing out features of epistemological and sociological reasoning in students' responses, and independent lists were produced. These lists were then compared, and an overall framework was developed. The framework was then re-applied to the data, with a view to refining individual categories until all epistemological and sociological points in students' reasoning were covered. A full copy of this framework can be found in Appendix A.

4.2 Epistemological dimensions of students' reasoning

Two broad epistemological dimensions were apparent in students' responses to interview questions. These were the nature of knowledge claims in science, and the nature of lines of scientific enquiry.

4.2.1 The nature of knowledge claims in science (part A of the framework)

Students referred to the nature of scientific knowledge claims, and their warranting, at various points in the transcripts. In a small number of cases, it seemed that knowledge claims in science were conceptualised as descriptions of natural phenomena. Consider the following example:

> *I'm not actually too sure how I'm going to be analysing my data yet at all in fact. But what I... drawing graphs and using the details you get from the graphs (...)*
> *Student 1.A*

In this case, the student did not articulate any distinction between graphs to display data, and knowledge claims which might be proposed as explanations of data. Such responses are represented by section Aa of the framework.

It was more common, however, for students to recognise scientific knowledge claims as separate from data. There were examples of students who referred to empirical and social processes in the warranting of knowledge claims. Consider the following examples, both of which refer to the use of empirical data in warranting scientific knowledge claims:

> *Interviewer: How can good scientific work be distinguished from bad scientific work?*

> *Student: It can only be done in that there are standard practices, standard ways of doing things and they should be followed to ensure that something follows a standard.*
> *Student 3.C*
>
> *Interviewer: Do you agree that sometimes there are conflicts of ideas in science (...) How are they resolved?*
>
> *Student: How they resolve them in science is by carrying out experiments that prove one theory is right, proving without a shadow of doubt that that theory is the correct one.*
> *Student 3.D*

In the first case, the emphasis is upon critical procedures for ensuring the reliability of data collected, and hence the validity of conclusions. Such responses are represented by section Ab(i)a. In the second example, however, the emphasis is upon the use of experiments to distinguish between competing knowledge claims - such responses are represented by section Ab(i)b.

In the following example, the focus is upon social rather than empirical processes in warranting scientific knowledge claims:

> *Interviewer: Supposing two scientists disagree about what a set of results means (...) How are those conflicts resolved?*
>
> *Student: It's to do with what the general opinion is at the time and what other people think.*
> *Student 3.K*

Such responses are represented by section Ab(ii).

In some cases, it appeared that students viewed absolute proof of scientific knowledge claims as inherently problematic:

> *I think that's because geophysics is very inaccurate, it can be a very inaccurate science if you don't put the bounds on it. I mean it's a lot worse than physics because you're dealing with a lot more complex situations, so you have to put the bounds on (...) you could always have the qualitative idea of how accurate ... whether what you're saying is true.*
> *Student 3.G*

Such responses are represented by section Ab (iii).
Some students apparently viewed scientific knowledge as being conjectural in nature and extending beyond the data available in practice or in principle.

There were examples of statements from students which referred to the evaluation of knowledge claims as involving social processes [Ac(i)], empirical processes [Ac(ii)], and both social and empirical processes [Ac(iii)]. Further responses, suggesting that there is no obvious basis for evaluating competing knowledge claims, are represented by section Ac(iv). In some cases, students appeared to recognise the logical distinction between proving and falsifying knowledge claims, such responses being represented by section Ac(v).

In practice, students' comments about the conjectural nature of scientific knowledge tended to make points rather obliquely, and it was very difficult to characterise the precise meaning of what was said. Consider the following example:

> *Interviewer: How do you feel that conflicts of ideas are resolved in the scientific community?*
>
> *Student: In geophysics (...) people seem to be able to change around their views a bit to fit the data and that seems a bit silly but you can have it separate... I think having a number of separate theories and then just fitting to the data or new data coming in (...) then disprove one of them, or leave the two running along side.*
> *Student 3.G*

In this case, the student appears to recognise the model-like nature of knowledge claims in geophysics, and furthermore that this makes the notion of empirical proof problematic. This student appeared to view conflict in geophysics as resulting from the nature of geophysical knowledge claims. In other areas of the transcript, this student refers to the role of social processes in validating knowledge claims.

By contrast, some students' comments suggested a very different view of the nature of knowledge claims when discussing the reasons for, and resolution of, scientific conflicts. A number of students, for example, accounted for scientific conflicts in terms of the quality of data available to scientists, and argued that such conflicts would be resolvable by collecting more data of better quality as illustrated in the following example:

> *It might be that there's something else like... one particular group they get this result because of the way they do ... their different methods that they do, they use very different methods from the other lab, so something might have gone wrong or something. Or its not reproducible results.*
> *Student 3.I*

It is interesting to note that student G - a geophysicist - was carrying out a modelling project whereas student I - a geneticist - was carrying out a project involving protein characterisation using a detailed laboratory protocol. The ‘scientific knowledge claims’ being referred to by each student may well be quite different and each account of the origin of scientific conflicts may be valid in specific contexts.

4.2.2 The nature of lines of scientific enquiry (Part B of the framework)

In a number of places, students referred to the origins of the questions that scientists investigate and the nature of scientific enquiry. Students often suggested that scientific lines of enquiry emerge from the individual interests of scientists, though additional factors were usually mentioned. Such responses are represented in section Ba.

Other responses suggested that lines of enquiry emerged as part of the epistemology of particular disciplines. Questions were suggested as emerging as part of an ongoing process of generating ideas and questions. Consider the following example:

> *Interviewer: Why do you think that some scientific work stands the test of time while other scientific work tends to be forgotten?*
>
> *Student: I would say because work that follows consequently supports it. For example something major like the TCA cycle in biochemistry, everything that’s been done since that was discovered supports its existence. Something else may be called into question by one particular set of research and so it wouldn’t be quite as valid and so it’s a fact that it’s supported by lots of scientific groups in various ways and situations. It’s just like redoing the work again or using different ways of doing it with the same results.*
> *Student 3.C*

In this case, the student appeared to be suggesting that lines of work in biochemistry were cumulative, the findings from earlier work leading to, and possibly being supported by, future research.

Such responses are represented in section Bb.

In a number of cases, students suggested external factors which influenced the development of lines of scientific enquiry. Factors mentioned include lines of enquiry emerging in order to address a perceived social need [utilitarian; Bc(i)], and in order to make money [financial viability; Bc(ii)], as illustrated in the following example:

> *Also, if there are problems like environmental problems, saying what sort of species are in the atmosphere that*

cause asthma or something, then people, maybe because of the funding they'll get, develop an interest in it to do it.
Student 3.B

4.3 Sociological dimensions of students' reasoning: the nature of science as a community [Part C of the framework]

In some cases, students seemed to view scientists as individuals working in isolation. Such responses did not identify a community of scientists as having influence on the activities of individual scientists:

Interviewer: How do scientists decide which questions to investigate?

Student: I think a lot depends on that person's particular interest...
Student 1.J

Such responses are represented in section Ca.

Many responses, however, recognised that groups of scientists work in the same fields as each other, and interact with each other:

Interviewer: I recall that they seemed to be looking at the idea of a cleavage site in a very different way....

*Student: It wasn't the idea of the cleavage site, it was more the location of the cleavage site and how there was one particular place where Dr. **** thought that could be the case but he thought it would be at a different site to what they thought it would be. They did actually disprove themselves yet still said that was the cleavage site. They did say that further work would be required to characterise the cleavable site so my work was to try and go ahead and to do that myself in this lab. rather than let them do it through their methods.*
Student 3.D

Such responses are represented in section Cb.

In some cases, students referred explicitly to scientific institutions. Examples were noted which referred to the financial interests of various institutions as influencing the range of scientific work that is done [Cc(i)], and a community of scientists as having a role in the validation of public knowledge [Cc(ii)]. The following examples illustrate these two types of response:

Interviewer: How do scientists decide which questions to investigate?

> *Student: (...)And obviously there's funding. If they don't get funding for it. (...) They probably want to know what, how it could be of benefit to them.*
> *Student 1.J*
>
> *Interviewer: How are conflicts of ideas resolved in the scientific community?*
>
> *Student: (...) Actually getting together will probably solve the problem anyway...*
> *Student 3.E*

In addition, some responses identified named institutions or processes such as peer review as being involved in the validation of public scientific knowledge:

> *Interviewer: How are conflicts of ideas resolved in the scientific community?*
>
> *Student: Sometimes they are not really. Sometimes they get to conferences ...*
> *Student 3.E*

In practice, there were hardly any explicit and elaborated references to institutional procedures within the scientific community.

Such responses are represented in section Cc(iii).

5 Longitudinal profiles of students' epistemological and sociological reasoning about science

5.1 Method used for making comparisons

In order to produce profiles of individual students' epistemological reasoning in a given interview, every epistemological and sociological point in the interview transcript was allocated one or more coding categories from the framework. Agreement on this coding was reached between members of the research team. A profile was then produced which indicated the range of epistemological or sociological points from the framework used by the student within each interview. These profiles can be found in appendix B, with a commentary on the nature of any changes noted between the beginning and end of projects. In addition, brief commentaries on the projects themselves are included. These commentaries emphasise epistemological features of the project itself, such as the nature of the knowledge claims being used, and the nature of data collection and analysis. Appendix B includes a table showing the epistemological profile of our sample as a whole (page 115).

In many cases, students made the same point at more than one place in a transcript. However, each point was recorded only once, no matter how many times it had been raised. Many of the codes are hierarchical. For instance codes Aa, Ab and Ac each contain a set of sub-codes. In our usage of these codes a tick against, for instance, code Ac means that the student made a comment about knowledge claims going beyond data but that this comment is not represented by any of the sub-codes Ac(i) to Ac(v). Similarly, a tick against code Ab(i) shows that the student talked about knowledge being provable on empirical grounds but did not mention either critical procedures Ab(i)a or critical experiments Ab(i)b. In some instances codes are included in the framework which do not reflect any student responses (e.g. codes Ac(iv) and Cc). These are included for structural reasons, or to show explicitly that students did not make such responses.

Methodologically, identifying changes in reasoning of individuals over time is a difficult process. In this study, for example, the individual profiles generated do not represent complete maps of students' epistemological and sociological reasoning about science at a given time: it is not possible to conclude that a particular point was absent from a students' epistemological profile just because it was not mentioned in an interview. In addition, it was not possible to indicate with any degree of confidence how strongly students were committed to any particular statement made. For these reasons, the proposed longitudinal changes in students' epistemological profiles should be regarded as tentative. The case studies presented in section 6 discuss the changing images of science for three of the students in our sample.

5.2 Characterisation of the nature of longitudinal differences

5.2.1 Longitudinal differences in reasoning about the nature of scientific knowledge claims

The responses of the students in the sample were very diverse in this area. Some students (B, G, L) stated sophisticated positions about the conjectural and model-like nature of scientific knowledge at the beginning of their project. It is interesting to note that two of these students were Earth Scientists, and that the department of Earth Sciences addresses the nature of scientific knowledge explicitly in the curriculum. By contrast, the majority of other students viewed scientific knowledge claims as empirically provable in a straightforward way. Some students also mentioned the role of the scientific community in validating scientific knowledge.

There were few differences in students' reasoning in this area between the first and third interviews. Because different aspects of the nature of scientific knowledge claims tended to be raised in the first and third interviews, simple comparisons of entries on the epistemological profiles yields little information about students' reasoning. A more fruitful approach is to compare students' discussions of this issue qualitatively. Few qualitative differences of this kind were noted.

5.2.2 Longitudinal differences in reasoning about the nature of lines of scientific enquiry

In this area, the responses of some students in the first and third interview differed significantly, both in quality and content. This was particularly apparent for students A, C, E, F, I and J, when profiles and transcripts from the interviews are compared. In a number of cases, these students referred explicitly to the influence of their research projects as extending their knowledge of the factors influencing lines of scientific research. In particular, more students referred to the ways in which specific projects are embedded in broader lines of scientific research in the third interviews. This change is also evident in our question-by-question analysis. Table 4 in section 3.4 shows a big increase in the number of students discussing a 'coherent field' in response to a question about why some scientific work stands the test of time.

5.2.3 Longitudinal differences in reasoning about the nature of science as a community

A number of students mentioned the existence of a community of scientists which interact over particular areas of research. However, surprisingly few students made reference to the role of this community and its institutions in validating public knowledge.

In general, there were few longitudinal differences in students' reasoning about the nature of science as a community between interviews 1 and 3 (though see Student E as a notable exception).

5.2.4 *Some discipline-specific issues*

It is interesting to note some of the more obvious differences in the types of research carried out by students in the sample on their projects. In some cases, the purpose of projects was to produce a theoretical model to account for a data set. In these projects, the relationship of data and theoretical knowledge claims was the focus of interest. Some data sets were collected by students, whereas others used secondary data. Other projects involved students in refining established laboratory procedures in new contexts. Such projects were not about the relationship between theoretical knowledge claims and data. Rather, the focus was upon developing techniques to tackle specific problems in the laboratory. The purpose of some projects lay somewhere in between these positions.

It is important to recognise that projects of both these types make different intellectual demands upon researchers. Modelling projects require creative thinking about the relationship between theory and data, whereas projects which involve developing techniques require researchers to think creatively about substantive factors that might influence the outcome of a particular laboratory procedure.

The types of knowledge claims that result from projects of these types are also different. For example, models intended to be of general applicability result from some projects, such as models of the chaotic behaviour of reaction systems. Other projects may produce specific outcomes, such as the sequence of a particular protein from specific cells in a given species.

In looking at students' epistemological profiles, it is important to recognise that different scientific knowledge claims relate to data in different ways, and that it may be relevant to use different aspects of an epistemological profile in different contexts. The implications of this diversity in the nature of scientific research for pedagogy at the undergraduate level is discussed in section 7.

6 Case studies: the interaction of research project experiences and longitudinal changes in students' profiles of epistemological and sociological reasoning

Our primary purpose in presenting these case studies is to address research questions (ii) and (iv) given in section 2. Thus we are interested in those features of project work which might influence a student's images of science and the significance that a student's images of science might have for what they learn from project work. Two of the cases described below were chosen because the student's responses indicate significant changes in their epistemological profile. Furthermore, these cases give some indication of the reasons behind these changes. All three cases highlight the influence epistemological views had on each student's experiences of project work.

Case studies are presented on students A, G and J. Profiles for these students can be found in appendix B. The projects of students A and G both involved the evaluation of models using data, though the epistemological reasoning used by the students was rather different. Student A's project involved collecting data in order to evaluate models of the kinetics of a particular reaction. At the start of her project, Student A's views of scientific theory appeared to focus upon descriptive aspects: she made little reference to the process of modelling using data. By contrast, student G was carrying out a modelling project in the Earth sciences, and talked about the nature of modelling in his project from an early stage.

Student J's project, however, did not focus upon relating theory and data. Rather, it involved applying established biochemical and molecular biological techniques in a particular context. This case study is included to illustrate changes during the project in Student J's views about the nature of scientific lines of work.

6.1 Student A: The relationship between experimental data and scientific theory

6.1.1 The project

Student A's project was an investigation into the kinetics of a particular reaction in the gas phase. The student was looking for a transition from periodic to chaotic behaviour during the reaction - a phenomenon which had already been observed for similar reactions. The apparatus had previously been used by the student's supervisor and by PhD researchers within the research group.

The student's day-to-day activities involved preparing the experimental rig for data collection. This included flushing the apparatus with the appropriate gas mixtures, calibrating and checking measurement instruments. The student could then perform an experimental run using a specific stoichiometric combination of gases at given temperature, pressure and flow rate. Data from an experimental run were recorded on a long stream of chart recorder paper which showed the fluctuations of temperature in the combustion chamber.

The student worked in a large room alongside other undergraduate project students and postdoctoral researchers in the non-linear chemistry group. From time to time group meetings would be held in which everyone involved in the group would discuss their ongoing research. In this sense student A was part of an active research group.

During her project work the student did see evidence of a transition from periodic to chaotic behaviour for the reaction. Towards the end of her project the student used a computer to try to represent this observed behaviour using a theoretical model of the reaction. At the end of the project the student was awarded a very good mark. The student’s own reflections on the project showed that she felt that it had been enjoyable but had largely involved reproducing other people’s results. She did not see her project as original research.

6.1.2 The nature of scientific knowledge claims

The most striking feature of student A’s epistemological profile is the shift from being very unclear about the distinction between data and theory in interview 1 (code Aa) to an explicit discussion of the role of theory in generating lines of enquiry (code Bb) and the role of data in validating theory (codes Ab). Although a similar change was seen in many of the students in our sample (particularly student I), the shift was most dramatic for student A.

During her first interview student A used the terms ‘knowledge’ and ‘data’ without any reference to theory:

> *Student: But I do think that all science is important (...) And anything just to gain knowledge must be important I think.*
>
> *Interviewer: So this gaining knowledge, what does that mean?*
>
> *Student: That’s something that you don’t know about. Could be in anything couldn’t it. Just finding out more about something very little is known about. (1A42)*
>
> *Actually on the point of good science I would also say that good experimental techniques are obviously very important (...) That’s really important to get good data. (1A37)*

These responses contrast strongly with those from other students during the first interviews which included explicit reference to scientific theories and their interaction with experimental data.

One of the key characteristics of student A’s project was the sheer amount of data that she was able to collect. Furthermore this data had a physical presence in the form of sheets of chart recorder paper. These factors may have encouraged this student to focus on the collection of data when talking about good science. Another possible influence, from outside of her project experience, was that of second year work in the undergraduate teaching laboratory. At one point in her final interview the student described this experience in very negative terms: *‘a bore and a drag (...) just mixing things’*. For this student second year laboratory work seemed largely procedural. It is interesting to speculate whether this experience contributed to her initial tendency to see experimental work as the collection of good data.

At two points in the first interview the student talked about what she might do with the chart recorder data that she was collecting:

> *I’m not actually too sure how I’m going to be analysing my data yet at all in fact (...) drawing graphs and using the details you get from the graphs to work out … to put into to rate equations and work out things like activation energy for reactions. (1A37)*
>
> *Rate equations … I guess we will probably be trying to prove that they’re correct and maybe prove that the rate constants are the same as the ones you’re given. (1A38)*

These two quotes indicate that the student has some notion of using empirical evidence to prove knowledge claims (code Abi). However, at this stage knowledge claims are seen as constants in equations, rather than theoretical claims about underlying mechanisms.

By contrast, student A referred to the role of theory from an early stage in the third interview:

> *Interviewer: Let's switch now and think about your view of science in general (...) to start off with I wonder how you feel scientists decide which sort of questions to investigate?*
>
> *Student: I suppose they must look at the theoretical background and see where there might be something different or interesting happening. Must stem from theory I suppose. (3A32)*

In this case the suggestion is that lines of scientific enquiry follow from the theoretical interests of the discipline (code Bb).

The student goes on to describe the role of experimental data:

> *To verify whether their theory was correct (...) to prove or disprove (3A34)*

Here the student is explicitly stating that empirical data can be used to prove or disprove a theory (code Abi).

Student A went on to discuss the role of explanation in science with reference to her project work:

> *I mean for example the complex behaviour that I've found - all that was said about it, oh it's due to self-heating and sort of you know exothermic reaction and then having secondary reactions. But that's not really (...) a mechanistic explanation, you know, in terms of the great laws and things. (3A41)*

Here the student is suggesting that data analysis should attempt to account for data in terms of theoretical models - preferably those already accepted and established ('the great laws'). This contrasts with her earlier description of data analysis (in the first interview) as 'putting the data into rate equations'.

Our discussion above shows that student A was far more explicit about the role of theory and its relation to empirical data towards the end of her project. Earlier we suggested that her focus on data at the start of project work may be related to the nature of her project work in the first few weeks, and to her experiences of the second year laboratory course. In a similar way it is also possible to identify some features of her later project experience which may have helped her move towards a more explicit discussion of the importance of theory in scientific enquiry.

As stated in section 6.1.1, during the final few weeks of project work student A used a theoretical model to try to explain her experimental findings. This involved her working alongside another undergraduate student who had spent his entire project modeling reactions in this way. This period of work may have encouraged student A to see the theoretical issues underpinning her project. In addition occasional group meetings involving the whole of the research group may also have helped student A to appreciate that her work was part of a broader research programme into the theory of reaction kinetics (e.g. quote 3A32 above).

In the final interview student A was asked whether or not she felt that her project experiences had influenced her ideas about science. Her initial response was that her views had probably not changed that much. However, on probing by the interviewer the student stated that she had learnt:

Maybe the fact that things have to be proved by reproduction (...) but apart from that I don't think my views would have changed really that much. (3A6)

This emphasis on getting reproducible data again reflects the dominance of this activity during her project. Indeed, despite her increasingly sophisticated discussion of the role of theory in science, student A's actual activities during her project work indicated that she tended to view the collection of data as the end point of her scientific investigation:

Interviewer: *What sort of things would you want to find out if you could extend your project for six months?*

Student: *There is a diagram that showed a big pressure range and a big temperature range and how the behaviour varied within that. I'd probably just try and reproduce that - prove that I suppose.*

Although student A's espoused views about science at the end of her project showed far more awareness of the importance of theoretical issues and the role of empirical data in proving or disproving scientific theories, her activities did not necessarily reflect these insights.

6.2 Student G: A sophisticated view of the relationship between multiple models and experimental data

6.2.1 The project

Student G's project involved the investigation of an anomalous peak in seismic data collected during a field experiment. His first task was to collect more data and repeat experiments that had already been done. This involved firing a shot into the ground and measuring vibrations along the surface of the earth up to 50 metres away - a standard experimental procedure used by earth scientists. The student then entered this data into a data bank and used a computer to test several models of how vibrations from the impact of the shot travel through the Earth. The aim of the project was to test a specific hypothesis to explain this phenomenon.

Having collected the data Student G spent several weeks learning about the computer techniques that he would use to analyse his data. He felt that these weeks were 'wasted time' and that he had achieved nothing. Once he had mastered the computer he began to try out the theoretical models and see how well they fitted his data. His intention at this stage was to find out which of the two models he was considering would correctly explain the anomalous seismic peak.

Although the student had no contact with researchers other than his supervisor, he did a great deal of reading. One of the research papers he read described a new model which his supervisor had not considered. This discovery changed the future course of the project considerably. The student now had three models to choose from. By the end of the project student G had become frustrated because he had not definitely proved which model was the correct one. One of the three models did not seem to fit his data, but his data did not enable him to decide between the remaining two models.

6.2.2 *Student G's epistemological profile*

Student G demonstrated sophisticated images of science even before he had begun his project work. In particular, he showed a very sophisticated view of the relationship between theoretical models and experimental data in both of his interviews. These were seen as intimately related and feeding off each other in a cycle of development which characterised this student's image of scientific progress:

> *I've got some data, then ... well, somebody else has got the data then it has come up with the theory and then I'm investigating it again. But that's the thing with science because, it's a learning process all the way through. It only takes one experiment to come up with something slightly strange for a theory then to be brought up and then another experiment will be designed specifically for that theory where before the experiment wasn't for that. So, it's leading on all the time.(1G119)*

> *...a theory comes up first and the experiment is designed to solve that theory, obviously the experiment then creates more theoretical work afterwards but I think it's always (...) to disprove or prove somebody's theory because that's the way it goes (...) there's no need to do an experiment if there's no sort of theory that needs to be proved or disproved (3G48)*

Student G's image of 'good science' focused on the need to have an overview of the big question of which each individual scientist's work is a part. Again this was evident in both interviews.

> *Keeping a perspective on what I'm aiming at all the time rather than getting bogged down in analysing one particular area (...) Always thinking about what conclusions I'm trying to draw at the end - what I'm trying to come up with.(1G113)*
> *[Good science is] being able to sit back and view which way a problem is really going (3G58)*

Such a view contrasts strongly with student A's focus on the collection of reproducible data as the key to good science. This is not to say that student A is incorrect. Getting reproducible and reliable data is vital in science, and in some disciplines (e.g. metrology) is the central focus. However, in many contexts good data is a necessary but not sufficient condition for good science. In student G's project the ability to use the data and relate it to several theoretical models was perhaps as important as the actual quality of the original data source.

Student G discussed the existence of multiple theories in both of his interviews:

> *Student: ...it'll probably be that one [theory] proves the other one's completely wrong, and there are reasons why maybe there's a bit of right in either one.*
>
> *Interviewer: A bit of right in either one, that's still possible?*
>
> *Student: Oh yes definitely, well maybe both of them are wrong, maybe there's a few points that are correct in one - a few points correct in another. (1G125-126)*
>
> *I think having a number of separate theories and then it [is] just fitting to the data or new data coming in (...) and such that then disprove one of them, or leave the two running along side. (3G61)*

Student G accepts that there can be multiple models, that each of these can be partly 'correct' and that scientists may allow each of these to be used 'along side' each other. Such a view is compatible with this students activities on his project. As stated in section 6.2.1 this project started with two models being applied to one data set. By the end of the project student G had discovered another model in the literature, bringing the total number of models to three. However for some students, such as those involved in gene sequencing, the consideration of multiple models may be entirely inappropriate. The issue of different images of science being appropriate in different scientific contexts is a major theme of this working paper.

6.2.3 Student G's epistemological outlook: Origins and influences

As discussed above there was no major development in the depth of student G's thinking about the nature of scientific knowledge claims through his project. This issue was explicitly referred to during the final interview:

> *Interviewer: Do you feel that your experience on the project has influenced what you think scientists do?*

> *Student: No not really. I think, I think it's backed up what I already knew, sort of thing, the work, but I don't think it's changed my [views]. (3G64)*

The student describes the project as a consolidation and reinforcement of what he already thought about science. One instance from his project experience provides a good example of this consolidation process. Section 6.2.2 describes how student G felt that multiple models could often have 'a bit of right in either one' and that they are often used side by side. At the beginning of his project work student G described his project as an attempt to find out which of the two models was correct. By the end of his project he had discovered another model, discounted one of the original models but was unable to distinguish between the remaining two models. The student described his reactions to this experience:

> *Student: I think I've learnt from [the project] I couldn't accept the fact that there was no proper conclusion to begin with, I was really quite annoyed with that and it took me a while to sort of accept there's no way I can prove it either way. (...)*
>
> *Interviewer: Do you feel that you have learnt from that experience?*
>
> *Student: Yeah, I think it helps as long as you can prove one way or another specific points either for or against and as long as you argue your case well - but you can't prove it either way - that's generally good science. (3G76-79)*

Although student G had discussed multiple models and the possibility that different models may have to be used at the same time before the project started, he still felt that his project experience had given him an insight into this aspect of the nature of scientific knowledge claims.

At two points in the final interview, following a description by the student of a particular view of science, the student was asked how he had developed that particular view. In both cases the student did not refer to experiences on his research project, but to his overall knowledge about science - particularly his own discipline of geophysics:

> *Interviewer: How can good scientific work be distinguished from bad scientific work? What are the factors that make one better than the other?*
>
> *Student: I think description .. you know description of errors and uncertainties as one of the key things in good scientific work (...) as long as you can quote how accurate*

> *your work is (...) I think that's the key to the sciences to know the bounds of your predictions.*
>
> *Interviewer: Where have you got that sense from, because that's quite a subtle realisation in a way isn't it? Did you have that before you started the project?*
>
> *Student: I think it's something ... I think because geophysics is very inaccurate, it can be a very inaccurate science if you don't put the bounds on it. I mean it's a lot worse than physics because you're dealing with a lot more complex situations, so you have to put the bounds on and a lot of our courses, especially the sort of in the department, in geophysics anyway you get a sort of spectrum from mathematical geophysicists to sort of geological geophysicists (...) obviously some sciences are just descriptive but you could always have the qualitative idea of how accurate what you're saying is true. (3G50-51)*

This extended quote shows the student drawing upon his overall insights into the nature of his discipline - particularly how it differs from other subject areas such as physics. These disciplinary differences are discussed again later in the same interview:

> *... at least two or three theories will always be there to explain a phenomena until maybe it's proved experimentally (...) I think it's even worse in geophysics, it seems a ... it's a less exact science than sort of something like physics where eventually you will be able to prove whether someone's completely wrong or right, but with geophysics and geology people seem to be able change around their views a bit to sort of fit the data. (3G61)*

Student G's case demonstrates the relationship between a student's images of science and general experiences of their subject throughout the whole of their undergraduate career. Furthermore, the Earth Sciences department at Leeds has made a special effort to include explicit discussion of models and modeling in their course. Whilst we have seen that project work does develop many student's images of science (particularly the nature of scientific lines of enquiry) the nature of the student's discipline and implicit or explicit messages from the undergraduate science curriculum appear to be equally influential.

6.3 Student J: Changes in views of the nature of lines of scientific enquiry

6.3.1 The project

This student's project built upon a funded studentship that she had been carrying out in her supervisor's laboratory during the summer vacation at the end of her second year. She had been selected to work on the studentship on a competitive basis. As a result of this, Student J already appeared to have a clear understanding of the research questions of her project, and how it related to other work in the field, from a very early stage. Although the project was supervised by a member of the University staff, the overall line of work in which the project was located was being carried out in conjunction with medical geneticists based in a local hospital.

The purpose of the project was to isolate and clone a protein (MutS) which is involved in correcting errors in the replication of DNA, from a thermophilic bacterium. Similar proteins have already been isolated, cloned and sequenced from organisms such as *E. coli*, and the gene sequences are available on a database. The advantage of working with material from a thermophile is that the protein is likely to be stable at temperatures up to 70^{o}C, whereas proteins from other bacteria tend to denature at much lower temperatures. It had been suggested in the literature that proteins of this type could be used in medical genetics for detecting the locus of particular mutations - the obvious advantage of a thermostable protein being its relative stability during diagnostic laboratory work.

The laboratory work for this project involved isolating a gene, then sequencing it using polymerase chain reactions (PCR). Once the protein has been sequenced and the sequence is compared to similar genes from other organisms, it is possible to find out that the wrong gene has been isolated and the process has to be started again. In addition, a good deal of craft knowledge is involved in getting PCR to give clear results. To this extent, data collection for this sort of project is a long process: it takes some days before researchers are aware whether they have correctly isolated a gene. Interpretation of data in this sort of project is often a straightforward process: the results of PCR are clear, or they are not. The main intellectual demand on researchers is in determining why a standard laboratory protocol is not working, and in making appropriate adjustments to make it work. This is illustrated by the following extract from the first interview:

> *(...) When I started writing up the project I had to decide which piece of data I needed to include, and just try from that data to extract the information I needed and try to integrate the data. (...) What was happening and why it was happening and obviously at times things weren't going right and you had to explain why they weren't going right.*

At the end of the project, Student J saw the main finding as relating to this process of data collection:

> *I wrote in my project that I needed to go back and redesign the primer and start from that.*

[The student was using primers that had already been designed.]

When asked why she was interested in this particular project during the first interview, the student gave a response in terms of the value of work to society in general:

> *(...) it seemed quite interesting when I was talking about the clinical implications. I'm more interested in things that are of human or clinical implication.*

This motivation appeared to underpin many of the student's views about science as a discipline during the first interview.

6.3.2 The nature of scientific knowledge claims

Student J referred to scientific knowledge claims at a number of points during the first interview. Perhaps not surprisingly, the emphasis tended to be upon ensuring the quality of data in order to make valid inferences, bearing in mind the nature of the project. When talking about preparing her project proposal, the nature of good supervision and the nature of her own labwork, the emphasis was always upon making the right choices to ensure that techniques would yield useable data.

The student referred to other scientists working on similar areas of work from the beginning of her project, often referring to literature that she had read during her summer studentship. During the first interview, it was apparent that the student recognised a role for the community of scientists in establishing knowledge claims in science:

> *Interviewer: How do you prove something?*
>
> *Student: Well you can't really... science isn't about proving things, it's just about putting forward your theory and until somebody else comes along and says: 'Hang on a minute, this isn't right.' So that person puts forward another theory (...) But I don't think you can actually prove 100% that something is right. (...) If you read the papers and you read the evidence it really depends on you which you feel is more plausible than the other and unless somebody else comes along and is supporting one of them and then that obviously becomes more convincing. (...) That means it's more acceptable. That*

> *means it might not be perfect, it might not be exactly right but it is near - more near to the truth...*

Although the student suggests that the scientific community has a role in validating knowledge claims, she did not mention any specific mechanisms through which this role is realised. Although she mentions evidence and plausibility, it appears that individuals, rather than the scientific community as a whole, are seen as reaching judgements about the validity of knowledge claims.

During the final interview, however, a different slant was put on this argument:

> *Interviewer: Why do scientists do experiments?*
>
> *Student: There's no other way they can prove (...) their particular theory. Science is very practical, you can't say that something is happening without having substantial evidence. Having said that if you've got some evidence to back your argument that doesn't necessarily mean that it's 100% foolproof and nobody can change it. (...) In scientific work if you publish a paper, every fact that you write you have to evidence to back it up.*

Here, the student suggests that the scientific community's judgement is evidence-based, and that one mechanism through which these judgements are made is the publication process.

6.3.3 The nature of lines of scientific enquiry

During the first interview, Student J stated that lines of scientific research emerge due to their broad social and financial significance on a number of occasions. When asked about how her project compares to the work of professional scientists, the student's response was in terms of the broad significance of the work:

> *(...) You are not doing it just because it's something that you want to do, it has certain importance or significance.*

In later extracts, this 'significance' appeared to relate to broad utilitarian or financial issues. The following response was given to a question about how scientists decide which questions to investigate:

> *I think a lot depends on that person's particular interest and what that particular person might perceive will be beneficial to mankind or will be of any use to the human race in general. (...) And obviously the case of funding. If they do get funding for it. (...) I think (the funders) probably want to know what, how it could be of benefit to*

> *them obviously you know if they're investing a certain amount of money into a particular project it has to be beneficial to them as well.*

Shortly afterwards, the student argued that good scientific work could be distinguished from bad by assessing its broad social benefits:

> *(...) Good scientific work in my personal view is when actually it benefits people in general. When it's not just exploitation of animals or whatever they're working on. (...) It should be of real benefit.*

Similarly, it was argued that scientific work stands the test of time because of its broad social relevance:

> *If it was something really significant then obviously people are going to remember it like when penicillin was discovered, I mean everybody remembers that and nobody's going to forget it, but if it was something that wasn't that important (...) probably people won't remember that.*

All of the above points are relevant to how lines of scientific research emerge. However, some scientific research questions may be investigated due to their theoretical relevance to a field, and with little relevance to utilitarian factors. It was striking that Student J did not mention how research questions might emerge from ongoing lines of work during the first interview.

A more complex position, involving features both external and internal to science, was articulated during the final interview. When asked how scientists decide which questions to investigate, the response was still in terms of areas of broad social relevance. However, the significance of work to a particular discipline was mentioned in response to a question about why some scientific work stands the test of time:

> *I think it really depends on how important that work was and not just then. If it led to further research into a particular field that will be more remembered than something that even though it was big and exciting at the time, if nobody follows it up it tends to get forgotten.*

At the end of interview 3, Student J was asked about the features that she saw as having developed her view of the nature of lines of scientific enquiry. She stated that her project had contributed to the development of her views, but the strongest influence appeared to be a television programme about changing views on the phenomenon of apoptosis (programmed cell death) in biochemistry, which had been presented as part of a seminar. The programme illustrated how work initially seen as insignificant had led to important lines of research in the biological sciences.

6.4 An overview of the case studies

Students A and J both showed significant changes in their images of science during their project. Student A developed a much more sophisticated view of the role of scientific theory both in the interpretation of data and the development of lines of scientific enquiry. Student J moved to an awareness that scientific questions depend on theoretical issues, rather than solely on a desire to ‘do good’. By contrast student G demonstrated a sophisticated epistemological profile from the outset. His project experiences served to consolidate these views.

Our study is not able to identify specific reasons for the epistemological development of individual students. However, these three case studies do give some indication of possible influences. There are differences *between* the profiles of epistemological and sociological reasoning of all three students in these case studies. It is striking that the nature of these differences relates strongly to the nature of the project work that was undertaken. For example, the most striking changes in student J’s profile related to the nature of lines of research. The focus of her project was not upon relationships between particular knowledge claims and data, and there were no apparent changes in this area of her profile. By contrast, student A’s project did focus on the relationship between knowledge claims and data, and this area of her profile did change. At the beginning of her project, the quality of research was described solely in terms of the collection of good quality data, whereas by the end of the project she also referred to the quality of knowledge claims advanced to explain data. An argument can be made that both the quality of data and the quality of knowledge claims are important in evaluating scientific research. Student A’s learning did not involve moving from ‘incorrect’ to ‘correct’ ideas, but rather extending the range of ideas that she applied in a given context, to give a richer description of that context.

In addition to their undergraduate project, other important influences upon their epistemological and sociological reasoning were apparent. Student J mentioned a television programme which was shown during another part of the final year curriculum. This programme addressed specifically the way in which one aspect of agreed public knowledge had been developed over a period of time. It is also likely that the curricular focus upon the nature of modeling in the Earth Sciences had influenced student G’s epistemological and sociological profile.

These case studies also give some indication of the influence a student’s images of science can have on their approach to project work. Student A tended to see data collection as the end point of her investigation. Her aim was to reproduce the ‘accepted values’. This reflects her tendency to describe data and experimentation without any reference to scientific theory. Despite a move towards a more sophisticated espoused view by the end of her project, her actual *activities*, even in the final stages, did not reflect an awareness of the significance of her data in terms of scientific theories. This suggests that we should be cautious in expecting changes in a student's espoused images of science to necessarily be reflected in a more sophisticated approach to actual project activities. Student G's project was similar to student A's, at least in terms of the requirement that the student relate experimental data to theoretical models. Student G's sophisticated epistemological views enabled him to interpret his data in a meaningful way, using several different theoretical models.

7 Discussion and educational implications

In section 1, a distinction was made between knowledge *of* science and knowledge *about* science. A case was made that in order for students to develop their knowledge *of* science - that is, to learn the *contents* and *methods* of science - it is also necessary for them to learn *about* the nature of science itself. In sections 3, 4, 5 and 6 of the paper, a characterisation of students' images of science is made, and evidence is presented about how these images of science relate to students' undergraduate project work. In this final section of the paper we begin with a brief summary of the main images of science held by final year undergraduate science students. This is followed by a consideration of the pedagogical and curricular significance of undergraduate students' images of science.

7.1 What are the main images of science held by final year undergraduate science students?

The first two of our research questions given on page 8 ask what are the main images of science held by students and how these images of science change through project work. In this section we will summarise our findings relating to these questions. We will draw on the tabulated codings for the question-by-question analysis in section 3 and the epistemological and sociological profile for the whole student sample given on page 115 appendix B. We also compare our findings with those from some of the earlier studies discussed in section 1.1.

General findings

Our study indicates that individual students hold a range of images of science which they refer to in different contexts. Rather than holding a single image of science students exhibit a *profile* of images of science. By the end of their project work students tended to exhibit an extension of their image of science profile rather than a movement from one image of science to another. Many students held very sophisticated images of science, showing an awareness of the contingent nature of knowledge claims and the social factors which might influence the acceptance or rejection of knowledge claims. Other students exhibited far less sophisticated profiles, for instance making little reference to the influence of theoretical ideas on the evaluation of data or the development of research questions. Generally speaking the importance of empirical data in validating knowledge claims tended to be well represented in students responses. On the other hand very few students made any reference to social factors in the validation of knowledge claims, or the influence of scientific institutions on the progress of science.

The nature of lines of scientific enquiry

Students at the beginning of their project tended to focus on lines of scientific enquiry as being dictated by the personal interests of scientists, areas in which funding could be obtained and the desire to solve problems for the benefit of society[2]. In addition to these factors, many students at the end of their project described how scientific enquiry develops in coherent fields of work. This increasing emphasis on the coherent development of a field is evident in the students' responses to the question: 'Why do you think that some scientific work stands the test of time whilst other scientific work is forgotten?' Significantly more students referred to a coherent field as being an influence on whether scientific work stands the test of time. This evidence suggests that project work encourages many students to extend their image of science profile to include a view of science as involving coherent research programmes.

The nature of scientific knowledge claims

Most of the students in our sample referred to experiments as being used to evaluate existing theories or ideas. A minority of our student sample have a view that data alone can be used as a scientific description of phenomena[3].

A majority of our student sample felt that theoretical ideas are evaluated solely through empirical processes. There was little reference to the impact social factors might have on the acceptance or rejection of knowledge claims[4] (such social factors might include the status of the individual scientists involved, or the status of the journal in which the research is published). Indeed our data suggests that this position increased towards the end of project work[5]. Students also talked more about critical experimental procedures in their final interview[6]. There was little consideration of the strategic aspects of scientific work such as identifying the important scientific questions, or being aware of how a finding relates to the work of other scientists.

The epistemological profile also shows that a minority of students made explicit statements that knowledge claims go beyond the data[7]. Few students stated that knowledge claims were conjectural in nature and might involve

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[2] This is shown in table 1 on page 16 for students' discussions about how scientists decide which questions to investigate, and also in section B (the nature of lines of scientific enquiry) of the epistemological and sociological profile for our student sample in appendix B.

[3] Table 2, page 23. See also the balance between code Aa (knowledge claims as description) and codes Ab (knowledge claims as provable) in appendix B.

[4] This is shown in the balance between codes Ab(i) - knowledge claims as provable on empirical grounds - and Ab(ii) - knowledge claims as provable on social grounds - in the epistemological profile.

[5] Table 5 on page 51 shows that significantly more students referred to empirical evidence as being important in the resolution of conflicts in their final interview.

[6] Table 3 on page 31 shows that many more students mentioned the use of controls, the need for reproducibility, and consideration of errors towards the end of their project.

[7] This is shown in the balance between codes Ab - knowledge claims as provable - and codes Ac - knowledge claims go beyond the data - in the epistemological profile on page 115.

the scientist in making assumptions or extrapolations beyond the available data.

Rowell and Cawthron (1982) found that undergraduate students tend to advance a rational, hypothetico-deductive view of scientific investigation rather than a Kuhnian view of science as subject to occasional revolutions in what is accepted as scientific knowledge followed by periods of ‘normal’ science. The data reviewed above suggests that the students in our sample see science as progressing through a series of puzzle-solving activities, which steadily improve our scientific understanding. Indeed this viewpoint was enhanced through project work. In response to the question: ‘Why do you think that some scientific work stands the test of time whilst other scientific work is forgotten?’ a minority of students described science as involving ‘revolutionary’ work which give rise to sudden advances in scientific understanding[8]. Thus our findings tend to support those of Rowell and Cawthron (1982). Such a finding is perhaps not surprising given that the students’ research projects were essentially puzzle-solving activities which typify the day-to-day activities of most professional scientists.

The social dimension

The epistemological and sociological profile in appendix B shows that students gave little emphasis to the social dimension of science. For instance, whilst students recognised that scientists often work as a community, how these communities might influence the nature of lines of enquiry or the evaluation of knowledge claims was not emphasised any more at the end than at the beginning of project work. There was virtually no mention of key scientific institutions.

Fleming (1988) reports that the images of science held by his sample of undergraduate scientists investigated using the VOSTS probes were not significantly different from those images of science held by high school students. Our study has shown that for our sample of final year undergraduate project students there are some significant changes of emphasis - particularly in the existence of coherent lines of scientific research and the significance of careful procedures for the collection of reliable and valid scientific data.

7.2 What significance can be attributed to our findings?

In order to work as professional scientists, or to understand science as an activity, it is necessary to have an appropriate profile of epistemological and sociological reasoning to draw upon in particular contexts. In some cases, it is appropriate to recognise the model-like status of scientific knowledge. In the case of Student G’s project, for example, discrepancies between data and theory might well be attributable to the model-like nature of the theory itself. In other cases, it might be more appropriate to view particular items of scientific knowledge as taken-for-granted, and focus upon the quality of data

[8] Table 4 on page 41

that is being collected. In the case of Student J's project, for example, progress was made by refining data collection techniques rather than by challenging the fundamental principles of molecular biology. Different aspects of science are underpinned by different methods: part of understanding science involves being able to recognise this diversity and to appreciate why particular approaches are used in specific situations.

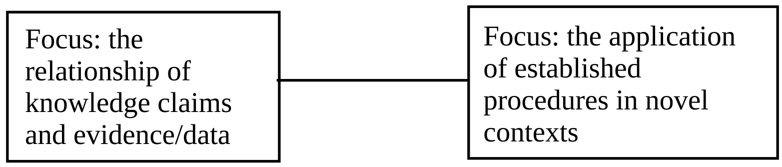
Generally, professional scientists do not spend very much time justifying the epistemological basis of their work. The important issue is that they can *use* appropriate methods rather than make explicit statements about their epistemological underpinnings. Writing papers for publication or proposals for funding is possibly the nearest that professional scientists ever get to making explicit statements about the nature of lines of scientific enquiry, methodology and the nature of scientific knowledge. That is not to say that scientists are naive about these matters, however. The issue is that scientists use knowledge *implicitly* to inform actions in specific *contexts*.

This raises important methodological issues for a study investigating undergraduate students' images of science. If the purpose of the study is to find out about the implicit images of science that inform action in various contexts, there seems little point in probing students' images of science without any reference to a situation in which images of science are used. This study therefore focused upon undergraduate research projects as a context where students were using epistemological and sociological reasoning to inform actions (what data to collect, how to handle it, what papers to read and refer to and so on).

Of course, it is methodologically impossible to elicit the implicit knowledge that is drawn upon by an individual when performing a specific task (knowledge that will be termed 'implicit knowledge'). The best that can be done is to collect data and make inferences about the reasoning that might underpin it. In this study, interviews were designed to maximise the opportunities for students to talk about their epistemological and sociological views of science in general, and the epistemological and sociological reasoning that underpinned work on their projects. We recognise that there is a wide gap between these espoused statements about science in general, or in the context of the project, and the implicit knowledge that informed students' actions during the projects. However, we do think that these explicit statements may give insights into the implicit knowledge used by students to inform their actions in various contexts. This view is supported by the fact that many of the students referred to specific experiences during their projects when talking about the nature of science in general. The question of how this implicit knowledge can be developed through the undergraduate curriculum is addressed in section 7.4.

7.3 Science as a contextual activity: implications for undergraduate learning

The methods, data, knowledge claims and institutional location of science are all contextual: it is not possible to refer to *the* nature of science or *the* scientific method. We have already noted a number of examples where students' profiles of epistemological and sociological reasoning seem to relate to the actual project that they were engaged on. We have found it useful to characterise the methodological focus of the 12 research projects on the following spectrum:



Some projects were primarily involved with evaluating particular scientific knowledge claims in terms of data: the relationship between data and knowledge claims was the focus of such projects. The projects of students A and G are examples of this sort of project (see section 6). Other projects did not focus on the nature and warranting of knowledge claims. Rather, they involved students in developing established methods for use in novel contexts. Student J's project is an example of this sort of project (see section 6). It is possible to characterise the other projects along this spectrum.

Projects at both ends of the spectrum make considerable intellectual demands upon researchers, though the focus of these demands is rather different. In one case, the focus is upon the knowledge claims themselves. Intellectual work might involve proposing new models, suggesting new boundaries of application of existing models, collecting different data sets and so on. In the second case, however, the focus is upon the application of procedures. The focus of intellectual work is likely to be upon contextual factors that might influence the application of established procedures.

It is also important to note that each type of project is likely to foster particular images of science. It appears likely, for example, that projects focusing on models of reaction kinetics or the Earth's structure are likely to foster a view of scientific knowledge as conjectural and model-like, whereas projects focusing on techniques might well foster images of science that focus upon the quality of data necessary to 'prove' a knowledge claim.

In this study, it is striking to note that the only projects focusing on the relationship of knowledge claims and evidence/data were in the physical sciences (geology, geophysics and physical chemistry), and that the only projects focusing on applying established techniques were in the biological sciences (biochemistry, molecular biology and genetics). We are aware of undergraduate projects in the physical sciences that focus upon established techniques, however, in areas such as organic chemistry. In the biological sciences, some areas of research do focus upon knowledge claims and evidence/data. An example of this sort of work would be models of the factors influencing gene expression, or models of the interactions at membranes that influence the functioning of ionophores.

It is interesting to speculate upon the reasons for us having seen the types of projects that we did in the physical and biological sciences, and in particular the absence of projects focusing upon knowledge claims and evidence/data in the biological sciences. Much routine work in the biological sciences involves using established techniques, and both students and supervisors of research projects talked about the importance of learning particular laboratory techniques during research projects for getting Ph.D. places. This may explain the particular focus of the projects that we saw in this study. It could be argued that students are being presented with a limited view of the nature of scientific practice in their disciplines if they are not exposed to work which focuses upon knowledge claims and evidence/data. In order to achieve this, it may not be necessary for students to carry out original research work which focuses upon knowledge claims and evidence/data during their projects, providing that they are given insights into the broad lines of work in which their projects are based.

In some cases, it is easy to see how particular images of science might act as barriers to progress. Consider the case of student A (section 6.1). At the beginning, this student seemed to view the knowledge claims of her project as purely descriptive. In order for her to make progress with her work it was necessary for her to recognise the model-like nature of the knowledge claims that she would encounter, and the implications of this for data collection and analysis. A descriptive view of knowledge claims would restrict her progress. However, in other cases a descriptive view of knowledge claims may be quite adequate. In the case of student J, for example, it appears quite reasonable to view knowledge claims about the sequence of amino acids on a particular protein as descriptive. Of course, broader images of the nature of knowledge claims may well be necessary in other areas of student J’s discipline.

7.4 Learning about science: curricular implications

A number of different approaches to developing students’ epistemological and sociological knowledge about science have been advocated. Giere (1991) argues that students should follow courses where the focus is upon the history and philosophy of science, in addition to conventional courses. A similar argument is made by Matthews (1994). Although courses such as these may well influence the profile of epistemological and sociological reasoning that students are able to draw upon to inform action in specific contexts, questions arise about the extent to which explicit teaching in *general* contexts will influence the implicit knowledge drawn upon by individuals to inform action in *specific* contexts.

If the purpose of developing undergraduate students' profiles of epistemological and sociological reasoning is to influence the implicit knowledge drawn upon to inform actions, we see an argument for basing teaching in specific contexts. For example, students' understanding of the model-like nature of particular scientific knowledge claims and the implications of this for data handling in their disciplines might better be developed through research projects, other laboratory-based work or work with secondary data sets, rather than by attending philosophy of science lectures on the nature of scientific knowledge. In this way, knowledge is being learnt in contexts similar to those in which the knowledge is used by professional scientists (Seely Brown et al 1989). Such contexts will be termed 'authentic' in the remainder of this paper.

Approaches to developing students' implicit epistemological and sociological knowledge of science in authentic contexts can be characterised on a spectrum. One extreme might best be characterised as a form of 'osmosis': put the student in an authentic context and wait for appropriate learning to happen. At the other extreme, explicit instruction would be presented about the epistemological and sociological underpinnings of authentic contexts. The research projects investigated in this study fall at various points on this spectrum. In some cases, project supervisors commented that they used particular teaching techniques to make the nature of an area of research explicit to students, whereas in other cases it was apparent that no attempt was made to address this issue explicitly in projects. (The approaches of supervisors to this aspect of teaching are discussed in Ryder and Leach 1996a). Some departments also address the nature of knowledge claims and their warranting in their particular discipline area explicitly in tutorials and lectures.

One powerful way of explicitly encouraging students to reflect on their work in an authentic setting is to require them to give talks about their project work to other students and researchers. Such seminars can be made a regular feature of student project work and could also include seminars given by experienced researchers in which they describe their activities as a scientist. Furthermore, students whose project work takes place within an active research laboratory and who feel that they are part of a small research community will be continually exposed to images of authentic science. Such a working environment also encourages informal exchanges between the student and other researchers (particularly PhD researchers) which can help to develop the student's images of the activities of a scientist in their discipline.

The 'osmosis' approach to developing students' implicit knowledge has some merits. There is considerable evidence that implicit, useable knowledge is often developed in this way (e.g. Nunes et al 1993). However, it is not hard to imagine that students' learning in authentic contexts could be enhanced if particular aspects of the context were made more explicit. We saw a case of this in student J's response to a TV programme describing an example of theory change in her subject area. On the other hand, teaching could easily become laboured if excessive time was spent making epistemological and sociological points explicit. What factors might influence decisions about an appropriate balance?

Explicit treatment of the nature of knowledge claims might be more important in some disciplines than others. For example, the Earth Sciences department at The University of Leeds considers the nature of modelling to be a critical part of Earth Science disciplines. It is therefore addressed from an early stage in undergraduate courses, because lecturers have judged that undergraduate students find learning in this area hard. An additional factor is the diversity of particular students: in the case of undergraduate projects, supervisors' judgements about what needs to be made explicit are likely to differ according to the needs of particular students.

Earlier in this section, it was argued that professional scientists do not tend to need to make the epistemological and sociological underpinnings of their disciplines explicit. The case is different for science *teachers*, however. If science lecturers are to structure undergraduate curricula in order to develop their students' implicit epistemological and sociological reasoning, it is necessary that they are clear and explicit about the understandings that they want their students to develop.

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Appendix A: Framework used for characterisation of students' epistemological and sociological reasoning about science

A EPISTEMOLOGICAL DIMENSION: THE NATURE OF SCIENTIFIC KNOWLEDGE CLAIMS

a *Knowledge claims as description*
-No appreciation of theories and concepts as constructions. No clear separation between description and explanation.

b *Knowledge claims as provable*
-Knowledge claims recognised as separate from data, and provable:

(i) on empirical grounds:

a Mention of critical procedures for ensuring reliability of data, and hence the validity of conclusions;
b Mention of 'critical experiments' to distinguish between theories in the classic sense.

(ii) on social grounds

(iii) Recognition of difficulty of absolute proof

c *Knowledge claims go beyond the data*
-Knowledge claims recognised as conjecture:

(i) Social processes involved in evaluating theories;
(ii) Empirical processes involved in evaluating theories;
(iii) Both social and empirical processes involved in evaluating theories;
(iv) No obvious basis for evaluating competing knowledge claims.
(v) Recognition of logical difficulty of absolute proof, as opposed to logical possibility of falsification

B EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY

a *Location in individual interests of scientists*
-Lines of enquiry are based solely on the personal interests of scientists.

b *Internal location in epistemology of discipline*
Lines of enquiry are intellectually located - i.e. in terms of an ongoing process of generating ideas and questions

c *External location*
Lines of enquiry are socially located - i.e. in terms of questions of broad social relevance:

(i) *Utilitarian: for 'the greater good';*
(ii) *Financial: in terms of financial viability.*

C SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY

a *Individualist view*

-Scientists are essentially individuals working in isolation; no recognition of a community of scientists.

b *Recognition of a community of scientists*

-Awareness that other scientists may work in the same field and interact with each other.

c *Recognition of the institutions of science*

(i) *Financial interests of various institutions recognised - as having some influence over the range of work that is done;*
(ii) *Community of scientists recognised - as having a role in the validation of public knowledge;*
(iii) *Named institutions, or processes such as peer review recognised - as having a role in the validation of public knowledge.*

Appendix B: Epistemological profiles of students in the sample

Student A

This experimental project in the field of non-linear kinetics involved the collection of data using a highly specialised piece of apparatus which was already available within the laboratory. The aim of the project was to reproduce experimental evidence for theoretically predicted phenomena. Most of the project involved refining data collection techniques. Towards the end of the project the student used a computer model to account for some of the data collected.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*	•	
Ab	*Knowledge claims as provable:*		•
Ab(i)	-on empirical grounds	•	•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity		•
Ab(i)b	Mention of ‘critical experiments’		•
Ab(ii)	-on social grounds		
Ab(iii)	Recognition of difficulty of absolute proof		
Ac	*Knowledge claims go beyond the data*		
Ac(i)	Social processes involved in evaluating theories		
Ac(ii)	Empirical processes involved in evaluating theories		
Ac(iii)	Both social and empirical processes involved		
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification		
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*		
Bb	*Internal location in epistemology of discipline*		•
Bc	*External location*		
Bc(i)	Utilitarian: for ‘the greater good’	•	
Bc(ii)	Financial: in terms of financial viability		
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*		
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised		
Cc(ii)	Role recognised in validation of public knowledge	•	
Cc(iii)	Named institutions or processes recognised		

The most striking difference in this students’ responses at the end of the research project was the recognition that scientific theory is important both in the interpretation of data, and the generation of lines of scientific enquiry. Student A made very little reference to scientific theory in her first interview.
This particular project did not appear to have immediate applications, but rather was generated to develop understanding of non-linear kinetics.

Student B

This project involved extensive computer modelling of a system which had already been investigated experimentally. The student used two different models of the system, eventually deciding to use only one of these models. The main activity of the project was getting the software to work and then using the model to reproduce experimentally observed phenomena by assigning appropriate values to the variables in the computer model.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*		
Ab	*Knowledge claims as provable:*		
Ab(i)	-on empirical grounds		•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity	•	•
Ab(i)b	Mention of ‘critical experiments’	•	•
Ab(ii)	-on social grounds	•	•
Ab(iii)	Recognition of difficulty of absolute proof	•	
Ac	*Knowledge claims go beyond the data*	•	•
Ac(i)	Social processes involved in evaluating theories		
Ac(ii)	Empirical processes involved in evaluating theories		•
Ac(iii)	Both social and empirical processes involved		•
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification	•	•
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*		•
Bb	*Internal location in epistemology of discipline*		
Bc	*External location*		
Bc(i)	Utilitarian: for ‘the greater good’		•
Bc(ii)	Financial: in terms of financial viability		•
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*		
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised		
Cc(ii)	Role recognised in validation of public knowledge	•	•
Cc(iii)	Named institutions or processes recognised		

This student made sophisticated statements about the epistemology and sociology from the beginning of the project. The quality of discussion in the first and third interviews did not appear to be appreciably different. The nature of lines of scientific enquiry was not discussed during the first interview.

A television programme about Linus Pauling’s work linking vitamin C intake and cancer was referred to in both interviews. The programme focused upon the lengthy process of Pauling’s ideas being given serious consideration within the scientific community. This programme appears to have been a strong influence in the development of Student B's epistemological and sociological reasoning about science.

Student C

This experimental project involved the isolation and sequencing of a specific gene fragment. Activity focused on the use of experimental protocols. Experimental difficulties meant that the student spent a considerable amount of time refining the protocols and repeating procedures in an attempt to generate a bigger yield of genetic material.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*		
Ab	*Knowledge claims as provable:*		
Ab(i)	-on empirical grounds	•	•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity	•	•
Ab(i)b	Mention of 'critical experiments'	•	
Ab(ii)	-on social grounds		
Ab(iii)	Recognition of difficulty of absolute proof	•	
Ac	*Knowledge claims go beyond the data*		
Ac(i)	Social processes involved in evaluating theories		
Ac(ii)	Empirical processes involved in evaluating theories		
Ac(iii)	Both social and empirical processes involved		
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification		
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*	•	
Bb	*Internal location in epistemology of discipline*	•	•
Bc	*External location*		
Bc(i)	Utilitarian: for 'the greater good'	•	
Bc(ii)	Financial: in terms of financial viability	•	•
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*	•	•
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised		
Cc(ii)	Role recognised in validation of public knowledge		
Cc(iii)	Named institutions or processes recognised		

At the beginning of the project, the student had a strong image of scientific knowledge as being empirically provable, although there was some recognition that the process of empirical proof may sometimes be difficult. This position was still apparent at the end of the project, if anything being stated more forcefully. Although the existence of a scientific community was recognised, empirical evidence was viewed as able to resolve disagreements.

During the final interview, the student stated that she had learnt a good deal about the economic exploitation of research findings, and how this issue influenced the lines of work pursued. In each interview, however, she described how lines of research work are located within the epistemology of particular disciplines.

Student D

The aim of this project was to isolate a particular enzyme and then sequence the cleavage site. Experimental work involved the repeated use of protocols which had previously been developed within the research laboratory at Leeds. The main activity of the project was to refine the protocol to try to make it work. Ultimately, experimental difficulties meant that the cleavage site could not be sequenced.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*		
Ab	*Knowledge claims as provable:*		
Ab(i)	-on empirical grounds	•	•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity	•	
Ab(i)b	Mention of ‘critical experiments’	•	•
Ab(ii)	-on social grounds		
Ab(iii)	Recognition of difficulty of absolute proof	•	
Ac	*Knowledge claims go beyond the data*		
Ac(i)	Social processes involved in evaluating theories		
Ac(ii)	Empirical processes involved in evaluating theories		
Ac(iii)	Both social and empirical processes involved		
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification		
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*		•
Bb	*Internal location in epistemology of discipline*	•	•
Bc	*External location*		
Bc(i)	Utilitarian: for ‘the greater good’		•
Bc(ii)	Financial: in terms of financial viability	•	•
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*	•	•
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised		
Cc(ii)	Role recognised in validation of public knowledge	•	
Cc(iii)	Named institutions or processes recognised		

There was little difference in the content of discussion between the first and final interview for this student. In discussing the nature of lines of scientific enquiry in the final interview, however, the student presented a much more elaborated position, drawing upon a broader range of factors which were seen to be of influence.

Student E

The purpose of this project was to isolate, cleave and sequence a particular protein. The project supervisor was particularly interested in this protein as it may be important in the mechanism of receptor sites. The main activity of the project therefore involved applying established biochemical techniques to a novel context, and getting the techniques to work. Developing or refining biochemical knowledge claims was not the primary focus of the project.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*		
Ab	*Knowledge claims as provable:*		
Ab(i)	-on empirical grounds	•	•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity		•
Ab(i)b	Mention of 'critical experiments'		
Ab(ii)	-on social grounds	•	•
Ab(iii)	Recognition of difficulty of absolute proof	•	
Ac	*Knowledge claims go beyond the data*		
Ac(i)	Social processes involved in evaluating theories		
Ac(ii)	Empirical processes involved in evaluating theories		
Ac(iii)	Both social and empirical processes involved		
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification		
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*		•
Bb	*Internal location in epistemology of discipline*	•	•
Bc	*External location*		
Bc(i)	Utilitarian: for 'the greater good'		
Bc(ii)	Financial: in terms of financial viability	•	•
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*	•	
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised		
Cc(ii)	Role recognised in validation of public knowledge		•
Cc(iii)	Named institutions or processes recognised		•

During the first interview, this student suggested that scientific knowledge claims are empirically provable. Intriguingly, there was also a statement that different individuals might make different interpretations of given data. The student did not appear to see any tension between these two positions, both of which were articulated during the final interview.

During the second interview, the student elaborated an involved description of the multiple factors that influence lines of research work. This was more detailed, and involved more factors, than the account given in the first interview. In addition, comments about the role and function of the scientific community were more elaborated in the final interview than in the first.

Student F

The aim of this project was to use published data on seismic activity to locate a possible fault line. The student spent a great deal of time becoming familiar with the data sources and the data analysis software. Towards the end of the project the student was able to use the data to provide insights into the nature of the faulting in the area of interest. These insights were gained from a search for ‘patterns’ in the data, rather than the application of a theoretical model of fault zones and seismic activity.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*		
Ab	*Knowledge claims as provable:*	•	
Ab(i)	-on empirical grounds		•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity		
Ab(i)b	Mention of ‘critical experiments’		
Ab(ii)	-on social grounds		
Ab(iii)	Recognition of difficulty of absolute proof	•	
Ac	*Knowledge claims go beyond the data*		
Ac(i)	Social processes involved in evaluating theories		
Ac(ii)	Empirical processes involved in evaluating theories		
Ac(iii)	Both social and empirical processes involved		
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification		
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*		•
Bb	*Internal location in epistemology of discipline*		•
Bc	*External location*		
Bc(i)	Utilitarian: for ‘the greater good’		
Bc(ii)	Financial: in terms of financial viability	•	•
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*		•
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised		
Cc(ii)	Role recognised in validation of public knowledge		
Cc(iii)	Named institutions or processes recognised		

Student F was strong in both interviews on the distinctiveness of experimental evidence and theoretical ideas. Evidence was used to decide between theories. In both interviews student F felt that it was usually possible to decide between theories on the basis of empirical evidence alone.

Student F showed a change in her final interview towards recognition of a community of scientists whose work interacts and who have common research goals. Such a view had not been evident in the first interview.

Student G

The aim of this project was to decide which of two theoretical models could best account for anomalous seismic data collected by the student's supervisor during a field experiment. The student started out by repeating the original experiment and confirming the existence of the anomaly. The student then used computer software in an attempt to reproduce the experimental anomaly from within either of the two theoretical models. The results were inconclusive leading the student to identify another possible theoretical model in the literature which could account for the anomaly. By the end of the project none of the three models could convincingly account for the anomaly, though the student felt that he had discounted one of the models.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*		
Ab	*Knowledge claims as provable:*		
Ab(i)	-on empirical grounds	•	•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity		
Ab(i)b	Mention of 'critical experiments'		•
Ab(ii)	-on social grounds		
Ab(iii)	Recognition of difficulty of absolute proof		•
Ac	*Knowledge claims go beyond the data*		•
Ac(i)	Social processes involved in evaluating theories		
Ac(ii)	Empirical processes involved in evaluating theories	•	•
Ac(iii)	Both social and empirical processes involved		
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification	•	
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*		•
Bb	*Internal location in epistemology of discipline*		•
Bc	*External location*	•	
Bc(i)	Utilitarian: for 'the greater good'		
Bc(ii)	Financial: in terms of financial viability		•
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*		•
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised	•	
Cc(ii)	Role recognised in validation of public knowledge		
Cc(iii)	Named institutions or processes recognised		

This student made sophisticated and elaborated comments about the epistemology and sociology of science during the first interview. In particular, he made explicit comments about the tentative nature of geological knowledge claims. A similar position was articulated during the final interview.

The most noticeable longitudinal difference was in the description of the nature of scientific lines of work offered during the final interview. A broader range of factors were mentioned as being relevant.

Student H

[Missing from sample]

Student I

The aim of this project was to isolate, clone and sequence genetic material from a plant. Activity focused on the isolation and amplification of genetic material. Several experimental difficulties were encountered and most of the student's time was spent adjusting laboratory protocols in an attempt to increase the yield of genetic material.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*	•	
Ab	*Knowledge claims as provable:*	•	
Ab(i)	-on empirical grounds		•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity		•
Ab(i)b	Mention of 'critical experiments'		•
Ab(ii)	-on social grounds		
Ab(iii)	Recognition of difficulty of absolute proof		•
Ac	*Knowledge claims go beyond the data*		
Ac(i)	Social processes involved in evaluating theories		
Ac(ii)	Empirical processes involved in evaluating theories		
Ac(iii)	Both social and empirical processes involved		
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification		
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*		•
Bb	*Internal location in epistemology of discipline*		•
Bc	*External location*		
Bc(i)	Utilitarian: for 'the greater good'		
Bc(ii)	Financial: in terms of financial viability		
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*	•	•
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised		
Cc(ii)	Role recognised in validation of public knowledge		
Cc(iii)	Named institutions or processes recognised		

It was very difficult to characterise the epistemological and sociological views of this student. During both interviews, it appeared that the student viewed scientific knowledge claims as essentially descriptive. Evidence for this came mainly from what was *not* said in response to questions about scientific disputes and the nature of good and bad science. During the final interview, the student suggested that although empirical proof is *possible*, it can sometimes be difficult to achieve.

During the third interview, this student suggested a more elaborated view of factors that influence lines of scientific research than in the first.

Student J

The purpose of this project was to characterise a particular protein. The main activity of the project therefore involved applying established techniques to a novel context, and getting the techniques to work. Developing or refining knowledge claims was not the primary focus of the project.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*		
Ab	*Knowledge claims as provable:*		
Ab(i)	-on empirical grounds		•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity		
Ab(i)b	Mention of 'critical experiments'		
Ab(ii)	-on social grounds		
Ab(iii)	Recognition of difficulty of absolute proof		
Ac	*Knowledge claims go beyond the data*		•
Ac(i)	Social processes involved in evaluating theories	•	
Ac(ii)	Empirical processes involved in evaluating theories	•	•
Ac(iii)	Both social and empirical processes involved	•	
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification	•	
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*	•	•
Bb	*Internal location in epistemology of discipline*		•
Bc	*External location*		
Bc(i)	Utilitarian: for 'the greater good'	•	•
Bc(ii)	Financial: in terms of financial viability	•	
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*	•	
Cb	*Recognition of a community of scientists*	•	•
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised	•	
Cc(ii)	Role recognised in validation of public knowledge		
Cc(iii)	Named institutions or processes recognised		

The most striking difference in the responses given by this student in the first and final interviews related to her description of the nature of lines of research. In the first interview, the strongest influence on lines of scientific work appeared to be utilitarian and financial. By the final interview, however, an elaborated response was given describing how research questions emerge within the knowledge structure of a discipline.

Student K

This project involved trying to find matches in specific gene sequences in bacteria, using secondary data sources. As such, a major part of the project involved finding and extracting information from a data base, and using software to suggest matches. If no matches were found using one particular gene, the process was repeated with another gene. If matches were found, evolutionary lines between species of bacteria could be proposed. A good deal of experience of secondary data sources was required to suggest which genes to start with in trying to find matches.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*		
Ab	*Knowledge claims as provable:*	•	
Ab(i)	-on empirical grounds		•
Ab(i)a	Mention of critical procedures for ensuring reliability/validity		
Ab(i)b	Mention of 'critical experiments'		
Ab(ii)	-on social grounds		•
Ab(iii)	Recognition of difficulty of absolute proof		
Ac	*Knowledge claims go beyond the data*		
Ac(i)	Social processes involved in evaluating theories		
Ac(ii)	Empirical processes involved in evaluating theories		
Ac(iii)	Both social and empirical processes involved		
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification		
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*	•	•
Bb	*Internal location in epistemology of discipline*	•	•
Bc	*External location*		
Bc(i)	Utilitarian: for 'the greater good'		
Bc(ii)	Financial: in terms of financial viability	•	
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*		
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised		
Cc(ii)	Role recognised in validation of public knowledge		
Cc(iii)	Named institutions or processes recognised		

This section of the interview transcript was very brief in both the first and third interviews. Viewpoints were generally not elaborated in any detail.

Student L

This project involved a six week period of field work followed by data analysis and report preparation. The main aim of the project was to produce a detailed geological map of a mountainous area. In some cases different students mapped the same areas independently. The student's work did not involve original research work. The main focus of the project was to provide practice in geological mapping techniques.

A	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY**	*Int. 1*	*Int. 3*
Aa	*Knowledge claims as description*		
Ab	*Knowledge claims as provable:*		
Ab(i)	-on empirical grounds	•	
Ab(i)a	Mention of critical procedures for ensuring reliability/validity	•	
Ab(i)b	Mention of 'critical experiments'		
Ab(ii)	-on social grounds	•	
Ab(iii)	Recognition of difficulty of absolute proof		
Ac	*Knowledge claims go beyond the data*	•	
Ac(i)	Social processes involved in evaluating theories	•	•
Ac(ii)	Empirical processes involved in evaluating theories	•	•
Ac(iii)	Both social and empirical processes involved	•	
Ac(iv)	No obvious basis for evaluating competing knowledge claims		
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification		
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**		
Ba	*Location in individual interests of scientists*	•	•
Bb	*Internal location in epistemology of discipline*	•	•
Bc	*External location*		
Bc(i)	Utilitarian: for 'the greater good'	•	
Bc(ii)	Financial: in terms of financial viability	•	•
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**		
Ca	*Individualist view*		
Cb	*Recognition of a community of scientists*	•	•
Cc	*Recognition of the institutions of science*		
Cc(i)	Financial interests recognised		
Cc(ii)	Role recognised in validation of public knowledge	•	
Cc(iii)	Named institutions or processes recognised		

This student made sophisticated, elaborated points about the epistemology and sociology of science during both interviews. There were no appreciable longitudinal differences in the substance of the discourse.

Student M

As the final interview was not carried out, longitudinal comparisons are not possible.

Profile for the whole student sample

A	EPISTEMOLOGICAL DIMENSION: THE NATURE OF EXPLANATION AND THEORY	*Int. 1*	*Int. 3*	*Totals*[1]
Aa	*Knowledge claims as description*	2	0	2
Ab	*Knowledge claims as provable:*	3	1	11
Ab(i)	-on empirical grounds	6	10	
Ab(i)a	Mention of critical procedures for ensuring reliability/validity	4	5	
Ab(i)b	Mention of 'critical experiments'	3	5	
Ab(ii)	-on social grounds	3	3	
Ab(iii)	Recognition of difficulty of absolute proof	5	2	
Ac	*Knowledge claims go beyond the data*	2	3	3
Ac(i)	Social processes involved in evaluating theories	2	1	
Ac(ii)	Empirical processes involved in evaluating theories	3	4	
Ac(iii)	Both social and empirical processes involved	2	1	
Ac(iv)	No obvious basis for evaluating competing knowledge claims	0	0	
Ac(v)	Recognition of the logical difficulty of absolute proof, as opposed to logical possibility of falsification	3	1	
B	**EPISTEMOLOGICAL DIMENSION: THE NATURE OF LINES OF SCIENTIFIC ENQUIRY**			
Ba	*Location in individual interests of scientists*	4	9	10
Bb	*Internal location in epistemology of discipline*	5	10	10
Bc	*External location*	1	0	10
Bc(i)	Utilitarian: for 'the greater good'	4	3	
Bc(ii)	Financial: in terms of financial viability	7	7	
C	**SOCIAL DIMENSION: THE NATURE OF SCIENCE AS A COMMUNITY**			
Ca	*Individualist view*	1	0	1
Cb	*Recognition of a community of scientists*	6	7	8
Cc	*Recognition of the institutions of science*	0	0	7
Cc(i)	Financial interests recognised	2	0	
Cc(ii)	Role recognised in validation of public knowledge	4	2	
Cc(iii)	Named institutions or processes recognised	0	1	

[1] These totals give the number of students making statements coded within the main coding categories either in the first or third interviews.

Appendix C: ULISP Working Papers

As part of the dissemination of research findings to ULISP participants and others interested in teaching and learning of undergraduate science, a series of working papers has been prepared. Details of these are given below.

1 A perspective on undergraduate teaching and learning in the sciences

This paper sets out the perspective which participants in the Undergraduate Learning in Science Project have developed towards the broad range of issues associated with undergraduate teaching and learning in the sciences. The paper draws upon discussions within ULISP and is informed by the studies that ULISP participants have been involved in.

2 The Research Project Study: Design and Methodology

Focusing on the Research Project Study this paper gives an account of the design of the study. It also includes the reasons for designing the study in this way and the limitations and strengths of the data obtained.

3 Final year projects in undergraduate science courses

This paper gives an account of the role of projects and how they have been implemented in departments as discussed in the interviews with supervisors. The paper covers the suitability of projects for undergraduate work, the allocation of projects to students, supervision of students and assessment of projects.

4 Undergraduate science research projects: The student experience

This paper focuses on students' views and experiences of projects. Using interview data and entries in personal diaries a variety of issues are addressed from the student's perspective.

5 Undergraduate science research projects and students' images of the nature of science

This working paper focuses on the students' views of science and science research as discussed in the interviews.. What themes are evident in the students understanding of science? In our sample of students how do views of these themes develop in time? For particular students how do their views of science develop through the research project?

6 Three case studies of student and supervisor experiences during undergraduate science research projects

These detailed case studies from the Research Project Study are used to highlight particular features concerning research projects in the undergraduate curriculum. These can be used as a teaching resource for use in tutorials with second year students.

7 A survey of students' and supervisors' experiences of research projects in undergraduate science courses

Following from the 12 case studies reported in working papers 2 to 6 a survey was designed and administered to students (N~250) and supervisors (N~120) at the University of Leeds. Results and conclusions from this questionnaire survey are presented in this paper.

8 A summary of findings and recommendations arising from the Research Project Study

This paper reflects on all of the work described above. It attempts to summarise the salient features and draw some implications of these findings for undergraduate teaching in the sciences.