Undergraduate Learning in Science Project

Working Paper 1

A perspective on undergraduate teaching and learning in the sciences

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A perspective on undergraduate teaching and learning in the sciences

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.

This paper describes the perspective on teaching and learning science at the undergraduate level which informs the Project, and the types of activities that have been undertaken so far.

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1 Introduction

The Undergraduate Learning in Science Project (ULISP), based at the University of Leeds, started in 1994 as a collaboration between lecturers in the Faculty of Science and science education researchers with interests in understanding and improving science learning at the undergraduate level. The project is an action research project: science education researchers and science lecturers have worked in collaboration to identify problematic aspects of undergraduate learning, to investigate learning in these areas through research studies, and to suggest and implement improvements to practice. In this way, undergraduate science curriculum development is treated as a research process based upon insights into learning.

The ULISP studies have been carried out during a period of rapid changes in Higher Education in the United Kingdom (e.g. White Paper 1987, White Paper 1991, CBI 1994). There has been a considerable increase in student numbers without an equivalent increase in staffing levels. New funding arrangements have been introduced together with new bodies to administer this funding. Universities and Polytechnics have been brought together into an integrated system and universities are now formally accountable for the quality of teaching and research in their departments. In addition government and employers are demanding a higher education system which supplies graduates with skills appropriate to the changing workplace.

In this period of intense change a number of initiatives have emerged which aim to influence the quality and nature of teaching and learning at the undergraduate level. One of the largest and most influential of these has been the Enterprise in Higher Education initiative funded by the Department of Employment. In addition, there has been an increase in the provision of courses on teaching and learning for lecturing staff (Times Higher 1995). Many of these initiatives have focused upon developing the so-called 'transferable skills' of undergraduates. Although learned in particular contexts, these skills are intended to be transferable to other situations. Examples include using libraries and technology, making presentations and so on. A further focus has been upon developing undergraduates' abilities to take responsibility for their own learning. It appears that courses in teaching and learning for undergraduate lecturers tend to focus upon ways of developing students' generic skills. Far less attention has been given to understanding the ways in which students learn particular subject matter, and how this learning can be improved through particular teaching approaches. The focus of ULISP studies is upon the ways in which undergraduates learn science in particular discipline areas, rather than the development of generic or transferable skills.

Our interest in science learning in particular discipline areas has broad origins. A number of lecturers in the Faculty of Science had raised concerns about the difficulties experienced by undergraduates in learning about the ways in which scientists handle data, evaluate research literature, construct models, plan investigations and so on. They wanted advice as to how to improve teaching to prevent some of these difficulties from arising. We argue that these areas are *discipline-specific*: Skills in data handling, model construction and literature evaluation in science are based upon knowledge of the concepts and practices *of science*. For example, undergraduate history students and science students will both be involved in handling data, constructing models and evaluating literature, but the concepts and practices used will be very different. There is no sense in which undergraduates from science and history could transfer their skills simply between the two disciplines and it does not, therefore, seem appropriate to view these skills as 'transferable'. Furthermore, we believe that such skills may rely upon different conceptual understanding and knowledge of practices in different science disciplines: although there may be some commonalities, there is no reason to assume that data analysis and modelling are carried out in exactly the same ways by theoretical physicists, geologists and geneticists.

These difficulties in learning amongst science undergraduates, identified by their lecturers, did not come as a surprise to the science education researchers involved in ULISP. Research into the ways in which students of school age learn science, and in particular the ways in which they understand the nature of science itself, indicate that science learners hold a range of images of the purposes of scientific work, the relationships between data and theory, the nature of scientific investigation and the social processes involved in science (Driver et al. 1996). Furthermore, Driver et al. argue that young people's images of the nature of science itself may influence their ability to understand scientific concepts when these are introduced in teaching.

This working paper describes the perspective on teaching and learning science that has been developed to inform ULISP research on undergraduate science teaching and learning. The development of a perspective on teaching and learning science was a central aspect to this research, particularly as learning is influenced by so many interacting factors. In order to investigate undergraduate teaching and learning it is necessary to highlight the particular factors which are of interest to those participating in the research, and to place these factors in a broader context of other issues which may influence teaching and learning.

We have already stated that our primary focus, on undergraduate learning in science, is discipline-specific. In section 2, we consider the nature of science itself and the influences that this might have upon the contents of an undergraduate science curriculum, and in section 3 we describe a perspective on the nature of science learning. Bearing in mind these views of the nature of science itself and the nature of science learning, in section 4 we discuss the purposes of undergraduate science courses, and in section 5 the possible curricular contents of courses and teaching approaches. Section 6 then gives an account of our research questions and section 7 describes the various studies that are planned or have been carried out. A list of the working papers in this series can be found at Appendix 1.

2 Learning science - learning what?

At first sight, answering the above question might seem a trivial matter. When students learn science, they learn the concepts that are described in a curriculum. Although scientists and science educators might have a range of views about which concepts should be included, there is broad agreement about the concepts themselves. To give an example, although there may be different views about the importance of teaching the laws of thermodynamics to undergraduates, no-one seriously disputes what the laws of thermodynamics are, at the level of undergraduate teaching.

But there is more to science learning than acquiring a defined body of knowledge. If one considers the actual work undertaken by professional scientists, this might involve using scientific knowledge with an implicit understanding of its power and limitations, designing and carrying out empirical enquiries, evaluating the importance of scientific work of others, generating new knowledge, communicating science with various audiences and so on. The literature often referred to as ‘science studies’ incorporates disciplines such as history of science, philosophy of science and sociology of science. The main focus of this literature is upon the ways in which science and scientists operate, and the generation, validation and status of scientific knowledge. We have already seen that the majority of the contents of undergraduate degree courses - the concepts, laws and theories that are being taught - are broadly agreed by experts. Although some content during the final stages of undergraduate study may be contentious, most is normally broadly agreed within the scientific community. This is certainly not the case for the other features of science discussed above - literature on the history, philosophy and sociology of science is characterised by dispute about the purposes of science, the nature of scientific knowledge and its relationship to enquiry and the nature and role of social processes in science. It is not possible to identify one perspective on ‘the nature of science’ which is broadly agreed and could be taught in undergraduate courses.

2.1 What is ‘the nature of science’?

Debates about ‘the nature of science’ tend to centre around *epistemological* questions and *sociological* questions. Epistemology is a branch of philosophy concerned with our grounds for believing knowledge claims to be *true*. In science studies, an example of an epistemological debate would be the various perspectives about the nature of scientific knowledge and its relationship to evidence. Sociologists of science are concerned with the social processes through which scientific knowledge is generated and validated. This is not the place for a review of the science studies literature[2], though the continuing debate amongst philosophers, sociologists and scientists about the nature of science tends to focus around a number of fundamental issues. Members of ULISP have considered the

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[2] Interested readers are directed to Chalmers 1982 for an accessible introduction.

following issues as characterising 'the nature of science' as an enterprise:

The purposes of various sorts of scientific activity
Philosophers and sociologists of science have proposed a wide range of purposes for scientific activity, and debate on this question remains fierce. However, there is broad agreement that, to a large extent, scientific activity is characterised by diversity rather than similarity of purposes. Consider three types of scientific activity: research on astrophysics in an international research institute, research and development work in a chemical company, and testing of river water samples in a government environmental laboratory. The purposes of research in astrophysics might involve generating and publishing new, theoretical accounts of the nature of the universe. But the purposes of research and development work tend to be more practically focused, involving the creation of new techniques and products in a commercial environment. The purposes of routine testing relate primarily to the appropriate use of established procedures with a view to producing reliable knowledge about particular phenomena. Although each of these examples involves using scientific knowledge, the purposes can be seen to differ significantly.

The nature and structure of scientific knowledge
In a similar way, there is agreement that different types of knowledge are used in different disciplines, for various purposes. The generation and testing of theories is a central part of some science disciplines. In astrophysics, notions such as curved space are not directly visible: the knowledge is highly mathematical and abstract. In other disciplines, established theories tend to be used to inform novel applications. For example, contemporary increases in genetic knowledge and applications are based more on the improved techniques and novel applications than on the development of overarching theories. Compared to astrophysics, some disciplines have relatively few core theoretical commitments. The idea that scientific models are developed by scientists thinking *creatively* about experimental data, rather than being developed by careful observation and logical inference, is also broadly shared in science studies.

The methods through which scientific enquiries are carried out
'The scientific method' is often presented as a process of proposing hypotheses and testing them through carefully controlled experiments. Although many disciplines do rely on experimental methods, many other sorts of empirical enquiry are used. In disciplines such as geology and astronomy, for example, it is not possible to carry out experiments in the classic sense as the events under study have already happened. However, empirical enquiries can proceed by studying the geological record or making observations of astronomical events.
The social dimensions of science

Most philosophers and sociologists of science agree that social processes have an important role in the scientific enterprise. For instance the process of peer review of research articles submitted for publication influences what becomes accepted as reliable knowledge by the scientific community. However, there is much contemporary debate about the role and importance of social processes in the generation and validation of scientific knowledge, and the relationships between science and other aspects of society.

2.2 The nature of science and the undergraduate curriculum

Although studying the history, philosophy and sociology of science may be of general interest to scientists, it is harder to make a case that such knowledge is centrally important in their day-to-day work. As the philosopher of science Imre Lakatos is reported to have said, ‘A scientist needs the philosophy of science like a fish needs hydrodynamics.’ It does not matter whether scientists are able to make explicit the nature of what they do, as long as they can do it effectively. On the other hand, scientists do have a rich *implicit* knowledge about the nature of science that is used to inform work within their own disciplines. Part of the process of *learning* science must therefore involve developing this sort of implicit knowledge about the nature of scientific practice in particular scientific disciplines.

How can the science studies literature inform decisions about the science curriculum and teaching and learning at the undergraduate level, bearing in mind the variety of contradicting perspectives within that literature? We have already suggested that science learning involves students in developing implicit knowledge of the purposes of science, the nature and status of scientific knowledge, the methods through which scientific investigations are carried out and the social dimensions of science. These issues revolve around the epistemology and sociology of science. Although it is not necessary for scientists to have explicit epistemological and sociological knowledge for their practice as research scientists, we would argue that a part of effective science *teaching* involves introducing this sort of knowledge to students. In order for undergraduate science lecturers to plan for student learning in these areas, their tacit knowledge needs to be made explicit.

We are suggesting that learning science involves, amongst other things, developing implicit epistemological and sociological knowledge. How might this be taught and learnt in a curriculum?

The Contents of Science

A major component of curricula in science undergraduate courses revolves around the *contents* of science. By the contents of science we mean the scientific knowledge of a given discipline. This is the sort of information included in course text books and presented in lecture courses.

Teaching about the contents of science is likely to refer explicitly to particular concepts, laws and theories. But such teaching also carries implicit messages about the epistemology of science, and implicit assumptions are made about the nature of science. For example, it is often taken for granted in teaching that students know about the forms in which scientific knowledge tends to be expressed - laws, mechanisms, models, theories and hypotheses. Each of these forms of knowledge carries a different status in the scientific community. For instance, individual scientific theories can underpin the work of whole communities of scientists (e.g. quantum mechanics or gene structure) whilst hypotheses can be unique to scientists within small research groups.

A central part of the scientific enterprise involves constructing theoretical models and checking their validity against data. When scientific models are generated, they sometimes include new entities, not previously referred to in explanations. For example, in order to explain the behaviour of objects in free fall Galileo proposed a new meaning for the term *acceleration*. Previous explanations of motion had used acceleration as the change in velocity over a given *distance*. In reformulating acceleration as the change in velocity over a given *interval of time* Galileo was able to demonstrate that falling bodies fall with a constant acceleration. The critical contribution of Galileo was not in terms of collecting new data on free fall motion. Rather, he constructed a way of thinking about that data which resulted in a new formulation of the concept of acceleration.

The point that is being made is that understanding particular scientific concepts involves understanding something of epistemology. Part of understanding Newtonian mechanics or gene theory involves understanding why we believe in these theories, appreciating that the theories and the component concepts are constructs, knowing something about the contexts in which they are useful, and knowing something of the circumstances in which the predictions and explanations generated by the theories start to break down. For example, the Bohr model of the atom as a nucleus with electrons in planetary orbits generates accurate predictions and explanations in many chemical contexts, and is frequently used. But scientists using this model of the atom understand that it is a crude model: they do not believe that ‘real’ atoms are like that. Implicit in this is a recognition that the *models* of science go beyond empirical data - rather, they are ways of *interpreting* data generated and agreed upon by scientists. Models of atomic structure cannot be *inferred* logically from data: they involve using constructed entities in the *interpretation* of data.

We are not arguing for an ‘anything goes’ view of scientific knowledge. Claiming that scientific knowledge is ‘model-like’ does not preclude the possibility that some scientific theories model events and phenomena better than others. Indeed, there may well be rational criteria for claiming that some scientific theories are likely to be better models than others. In this sense, understanding scientific theories involves having some knowledge of our warrants for believing in the theories as useful (or, some would argue, ‘true’) models of the world.

Much scientific knowledge is model-like, and the models tend to be generated for use in the controlled environment of the laboratory. Modelling the chemistry of carbon dioxide and other gases in the laboratory is different from knowing about their behaviour in the atmosphere. For this reason, although there is broad agreement within the scientific community about the reactions of carbon dioxide, it is still possible for there to be dispute about the effect of carbon dioxide in the atmosphere on global warming. In this case, understanding the scientific concepts relating to global warming has an epistemological dimension - how can concepts generated to explain the controlled world of the laboratory be applied to complex actual phenomena?

The methods of science

Developing an understanding of subject matter is clearly an important component of an undergraduate science education. However few people would argue that undergraduate courses should be based solely on the contents of science. The majority of undergraduate science courses in the UK include some teaching activities designed to develop students’ understanding of the *methods* of science - that is, the methods by which scientists carry out systematic enquiries. Some typical teaching activities are referred to later in this paper.

The methods of science include more than experimental investigation. Theoretical investigation through the development of explanatory models is a key part of the methods of science. Observation of natural processes without deliberate manipulation is the source of much astronomical data. Also, thought experiments have had a decisive influence on many areas of theoretical development (for example Schrödinger’s cat in quantum mechanics and Einstein’s light clocks in special relativity). It seems clear that there is no single ‘scientific method’ - a rational set of rules which are followed by all scientists which enables them to uncover truths about the world. What aspects of the methods of science might be addressed through the undergraduate science curriculum?

Understanding the methods by which scientific knowledge claims are made has an epistemological dimension. For example, it is necessary to understand the nature of evidence in various fields, the norms of evaluation of evidence, the nature of acceptable explanation, the norms for evaluating theories, the principles by which predictions from theories can be generated and evaluated and so on. It also seems that the methods of science differ considerably in different fields of science. In terms of the undergraduate curriculum, it is therefore likely that teaching about the methods of science would have a different emphasis in different discipline areas, even if the teaching focused on the broad epistemological issues described at the beginning of this paragraph.

Science as a social enterprise

Science is a human activity which takes place within a complex social setting. Organised into subject disciplines scientists form into smaller research groups. Within these research groups scientist have particular roles and career development paths. Within disciplines scientists communicate their findings using journals, seminars, conferences, electronic networks and other more informal means. This institutional complexity means that science has a social dimension.

One of the key roles of the scientific community is the validation of scientific knowledge claims. Before work is published, it goes through a process of peer review in order to ensure, amongst other things, the quality of presentation, the validity of argument, the relationship between theory and data and the potential significance to a discipline. Following publication, replication studies may be carried out, counter-arguments may be presented, or the work may not catch the attention of other scientists. This process of deliberation and judgement within scientific communities to establish public knowledge is a central part of the scientific enterprise. This is particularly true in the event of scientists disagreeing about the status of new scientific knowledge claims. A possible role of the undergraduate science curriculum is to develop students' knowledge of how the social aspects of their own disciplines work - the key journals, conferences and networks used for communication between researchers, the range of current lines of research in the discipline, the seminal papers of particular fields, the ways in which groups of scientists contribute to the validation of knowledge claims as public knowledge.

In addition to the internal social features of science discussed above science also interacts with other parts of society. Political policy makers have had a substantial influence in recent years on the sort of science which is seen to be worthy of financial backing. This has led to what Ziman (1995) has described as the 'collectivisation of science'. Furthermore recent concern over the 'public understanding of science' has emphasised that scientists have a role to play in the communication of science to the broader community. In the UK, this has lead to initiatives such as the British Association for the Advancement of Science's high profile science festival week and diploma courses in science communication. Public concern over nuclear power and waste disposal, genetic engineering and genetic screening reflect the relationship between science and society. Many research bodies have set up ethics committees to examine these issues. It may be particularly important for undergraduates to be introduced to some of these external social factors in certain disciplines - graduate geneticists, for example, might be expected to know something of the ethical standards which govern research in their field, current patenting issues and so on.

3 Views of teaching and learning science

Having considered the nature of the subject matter under study in undergraduate science courses, we now move to address perspectives on teaching and learning which have informed our work. Traditionally, teaching has been planned around the subject matter, decisions focusing upon what content should be taught, what should be omitted, and in what sequence. Assessment by teachers is carried out in order to summarise learners' achievements. If students do not perform well, it is because they have not learned the subject matter properly due to lack of ability or effort. We refer to this view as a 'transmission view of teaching and learning', in that knowledge is seen as being transmitted from teachers (or textbooks) to learners.

The perspective on teaching and learning adopted in this project might be called an 'interactive view of teaching and learning'. We view science learning as a process of communication which involves both learners and teachers, and is critically influenced by the nature of the subject matter. Learners are involved in making sense of ideas and information presented to them in terms of their existing knowledge. In some cases, this will be unproblematic: the information presented will make good sense in terms of existing knowledge, and will be incorporated into that knowledge. In other cases, however, learners may find new ideas and information unintelligible in terms of their existing knowledge, with the result that no changes in knowledge will occur. Alternatively, students may reach partial or unintended understandings as existing knowledge and new ideas and information interact in unpredictable ways.

Research into student learning conducted in Higher Education institutions has demonstrated that students achieve a broad range of subject matter understanding. These have been termed 'surface' and 'deep' learning (Entwistle and Tait 1990). 'Surface' learning involves a superficial understanding of subject matter knowledge characterised by the ability to recall information and mechanically solve standard problems. Through 'deep' learning students develop a conceptual understanding of the subject matter knowledge which enables them to think creatively, and integrate their new understanding with other subject matter areas. The key message for science lecturers from this research is that the nature of student understanding of subject matter knowledge (deep or surface) is strongly influenced by course structure and assessment methods and is not solely dependent on the attitude and motivation of the student (Entwistle and Entwistle 1991, Sheppard and Gilbert 1991). Studies of learning during high school science lessons show similar findings (e.g. Shapiro 1989).

Teaching is also viewed as an interactive process. Teachers make decisions about appropriate approaches for presenting subject matter. Although some assessment is carried out to summarise learners' achievements, other assessment is more diagnostic in nature. Problems in learning are identified either formally or informally, and teaching approaches are modified to promote better learning.

A further issue relevant to science learning is the distinction between scientific and ‘everyday’ modes of reasoning. There is evidence that people reason in characteristic ways about particular natural phenomena, and that many of these differ from accepted scientific viewpoints. For example, when asked why a pushed object stops moving as the push is stopped, many people (including physics undergraduates) will respond that a constant force is required to maintain a constant speed (see Viennot 1979 and McClosky et al. 1980 for undergraduate studies). This is, of course, in contrast to the Newtonian view that a constant force produces a constant *acceleration*. It is not hard to see why such responses are common: in a world of friction, you *do* need to maintain a constant force to maintain motion. A number of studies have now been conducted with science learners at the school level and beyond, which characterise the nature of students’ conceptions in science domains and about the nature of science itself (see Carmichael et al., 1990, for a bibliography of references).

We have seen that the nature of the scientific subject matter to be taught and the nature of students’ existing knowledge are important in influencing science learning. But what can be said about the processes of communication between teachers and students through which learning takes place? Seely Brown et al. (1989) describe learning as a process of enculturation. They argue that

> *‘Unfortunately, students are too often asked to use the tools of a discipline without being able to adopt its culture. To learn to use tools as practitioners use them, a student, like an apprentice, must enter that community and its culture. Thus, in a significant way, learning is, we believe, a process of enculturation.’*
> (p.33)

Viewing teaching and learning as a process of enculturation of novices into a discipline by experts is helpful in understanding science learning at the undergraduate level. It is not enough to present scientific content knowledge (‘tools of the discipline’) in isolation from their use within the culture of science. Students are too often able to acquire these tools but remain unable to use them. This raises questions as to what might be appropriate contexts for teaching about the use of the ‘tools’ of scientific disciplines, and the enculturation of undergraduates into the communities of science, issues which are addressed later in this paper in section 5. But first we consider the purposes of an undergraduate science curriculum.

4 Learning what it means to be a scientist - a focus of undergraduate science education

Enculturation into the communities of science emerges as an important aspect of undergraduate science education for theoretical reasons, as described in the last section. The issue also emerged from early discussions with university science departments about the learning difficulties experienced by undergraduate students. Lecturers frequently referred to the need of students to ‘know what it means to be a scientist’. In this paper we take this phrase to be *inclusive of all* aspects of being a scientist in a particular discipline, such as understanding scientific concepts, being acquainted with the subject content, thinking like a scientist, planning like a scientist, performing experiments like a scientist, interpreting results like a scientist, using models like a scientist and communicating and relating to the scientific community and other social structures like a scientist. It is worth emphasising that different areas of science have their own particular cultures, as we saw in section 2, and for this reason we will refer to enculturation into the *communities* of science. Teaching and learning about what it means to be a scientist is the central focus of the studies carried out through ULISP to date, and in section 5 we will explore in more depth the variety of aspects involved in ‘being a scientist’.

All teaching contexts enable the student to gain an understanding of what it means to be a scientist. This includes lectures, tutorials, problem classes, practical classes and research projects. It could be argued that the research project is the only authentic experience the student will get of ‘being a scientist’ during their university career, because this is the only case where they will be directly involved in original empirical work. However, as we saw in section 2 scientists are involved in all sorts of work other than empirical investigation, such as reading and critiquing papers, working with theoretical models, applying for funds, and communicating about their work to members of other social or professional groups. We believe that students gain images of ‘what it means to be a scientist’ from all aspects of their undergraduate course, whether teaching is designed primarily for this purpose or not. Activities such as tutorials which focus on original research papers, lectures in which scientific subject matter is presented, and laboratory classes in which data are collected, analysed and critiqued are all important in teaching students what it means to ‘be a scientist’. A major aim of ULISP studies is to make explicit what it is about science that students are learning through these activities. The question of *how* students can most effectively learn about the various aspects of science is explored in section 5.

A wide variety of perspectives on the purposes of an undergraduate science course exist (see section 6.1.1). In focusing on ‘learning what it means to be a scientist’ how do ULISP concerns relate to the wider view? Introductory training as a professional research scientist is a major purpose of an undergraduate science course. In the departments involved in ULISP studies around half of the students choose to enter research work either through Ph.D./M.Sc. studies or by entering industrial research institutions. Focusing on the activities and thought processes of scientists as well as the subject matter knowledge will clearly be of benefit to these students. A significant proportion of undergraduate science students enter employment as science communicators (science teachers, reporters, advertisers, politicians and historians of science). People involved in these activities have a central role in the culture of science and are instrumental in shaping peoples images of science. We believe that the kind of undergraduate science curriculum discussed in this paper will be of significant benefit to these students. A case can also be made that many individuals who are not employed as scientists are likely to encounter science in various aspects of their personal and professional lives, and as such will benefit from knowledge of what it means to ‘be a scientist’ (Driver et al., 1996). As a result, we believe that the ULISP focus on ‘learning what it means to be a scientist’ is relevant for all undergraduate students of science.

5 Science in the undergraduate curriculum

In this section we attempt to draw together issues raised in preceding discussions and show how these relate to the content of the undergraduate science curriculum. In section 2 we described science in terms of its contents, methods and social relations. Section 3 addressed the teaching and learning of science. Finally section 4 discussed the purpose of the undergraduate curriculum and stressed the importance of enabling the student to gain a deeper understanding of all aspects of their subject. We are now in a position to use these insights to discuss the content of an undergraduate science curriculum and its implementation in undergraduate courses.

The content of any science curriculum will of course be dependent on the discipline (physics, biochemistry or geology for example). However our discussion here will focus on five aspects of science which run across all disciplines. The aspects we have identified are *subject matter knowledge, the nature of scientific knowledge, the processes of scientific enquiry, craft knowledge* and *the culture of science*. These are characterised more precisely later in this section. It is important to stress that ultimately the content of each of these aspects can only be described by reference to a particular discipline. For instance many of the processes of scientific enquiry used in palaeontology will be very different from those followed by the particle physicist.

The five aspects of science curriculum that we have identified do not represent a unique classification. Each aspect is strongly related to the others and many alternative formulations exist. Our selection is based on insights from the contemporary literature on science studies discussed in section 2 and findings from ULISP studies (see working papers 2 to 7). We have extended the contents, methods, social relations classification used earlier in this paper with curriculum aspects which are more appropriate to a discussion of the undergraduate science course content. Furthermore, we have tried to reflect concerns about the purpose of the undergraduate curriculum discussed in section 4 in our classification.

Framing a discussion of the undergraduate science curriculum around five aspects of science does not mean that we believe all should have equal weighting or even that all of these aspects should be incorporated into science courses. Our purpose is to highlight the breadth of issues which a science course can address and demonstrate how each issue can influence the students ability to gain a deeper understanding of their subject. Thus, our ‘aspects of science’ do not provide a blueprint for an undergraduate science course. Rather, we hope that raising these issues will enable science lecturers to assess the possible content of courses and appreciate how different content structures will provide students with different learning experiences. Another use is in specifying the pedagogical role of current curriculum content and new teaching approaches. Furthermore our discussion provides an additional framework to discuss teaching and learning at the undergraduate level. Lecturers can then use these insights, together with other concerns, to build a curriculum which best enables their students to acheive the goals of the course.

Each of the aspects identified need not be *explicitly* present in an undergraduate course - either as course content or course objectives. There is much curriculum material that is *implicitly* present. For example, all courses will teach elements of the culture of science whether or not the term is used in course materials or even identified as a course aim. Indeed we will argue that from a learning perspective many scientific issues are best covered in this embedded, implicit way.

Our discussion of each aspect will include the following:

a) a characterisation of each aspect using insights drawn from our general discussion of science curriculum content presented in section 2
b) a discussion of the extent to which an understanding of each aspect is required by the research scientist
c) a discussion of how an understanding of the issues will be useful to students who will not become research scientists
d) whether each issue is most effectively covered explicitly or implicitly within the curriculum
e) how students can learn about each aspect of science following from our discussion of teaching/learning in section 3
f) a review of some previous attempts to incorporate some of these issues in undergraduate courses

5.1 Subject matter knowledge

Subject matter knowledge is the knowledge which is currently in use by practitioners of the subject - the major laws, models and theories of the discipline. Subject matter knowledge is the most consensually agreed and easily defined of our aspects and was included as part of the ‘contents’ of science in section 2. Undergraduate science curricula traditionally contain teaching units which explicitly cover particular subject matter domains. For instance, the first two years of the Chemistry course at the University of Leeds includes modules such as Fundamentals of General and Inorganic Chemistry, Introductory Physical Chemistry, Reaction Kinetics and Chemistry of the Elements. All of these modules are defined primarily in terms of the subject matter knowledge that they contain.

Any discipline will contain an enormous amount of subject matter knowledge. It is inconceivable that any student or practising scientist could have an acquaintance with all of this information, particularly since subject matter knowledge is continually changing and expanding. As a result most undergraduate science courses aim to introduce students to all of the main subject matter areas of the discipline. Students are provided with a map of the ideas of their discipline and how they relate to each other. Options in the final year cover particular areas in more detail. Such an approach is ideal for those students who wish to become research scientists, particularly if final year options relate to their eventual research area. For those students entering science-related jobs (such as science communication), coverage of the main topic areas will give them a valuable insight into the language of their discipline. However, final year options which focus in on particular subject matter areas may be less useful to such students.

As discussed in section 3 the teaching of subject matter knowledge has often been based on a ‘transmission’ view of learning. Information is presented by the lecturer and the student listens passively. Subsequent research into how students *learn* in particular subject matter areas (mainly at the high school level) has shown that effective learning of subject matter requires the student to actively build upon *prior understandings* in order to make sense of new information. This involves engaging the students’ prior knowledge and encouraging them to develop their conceptual understanding through dialogue. In particular it is necessary to demonstrate to students how scientific reasoning is often distinct from intuitive or ‘everyday’ reasoning. There have been a limited number of studies at the undergraduate level into the forms of prior understanding that students have in particular subject matter areas (e.g. Viennot 1979, McClosky 1980 cited in section 3, and Brumby 1984).

Subject matter knowledge has always had a leading role in the development of the undergraduate curriculum. Most of this subject matter knowledge is introduced to students through lecture courses. However our discussion of learning implies that students can benefit from tutorials which allow them to discuss subject matter with other students under the guidance of a science tutor. Although not a primary focus of ULISP studies there have been a number of investigations into the teaching and learning of particular examples of subject matter knowledge in the undergraduate science curriculum (e.g. Viennot, 1979; Séré, 1993; and Cros et al 1988). Such studies emphasise that the details of teaching and learning science must be related to the knowledge within individual disciplines.

5.2 The nature of scientific knowledge

In section 2, we argued that understanding the nature of scientific knowledge is a critical dimension of understanding the contents of science, the methods of science, and social aspects of the functioning of science. We suggested that it is more important for science students to have an implicit understanding of the nature of scientific knowledge in their disciplines, than to have explicit knowledge of the history, philosophy and sociology of science. In this section, we consider how this implicit understanding of the nature of scientific knowledge might be developed in the science curriculum.

But can the requirement for understanding of the nature of scientific knowledge be justified for those students not entering the field of science research? Perhaps the most compelling justification comes from research which shows that the student’s ability to understand scientific concepts is dependent on their personal image of the nature of scientific knowledge. Several research groups have demonstrated that the learning strategy adopted by students is affected by their understanding of the nature of scientific knowledge. Edmundson and Novak (1993) show that those students who see scientific knowledge as a body of facts will generally follow a passive, rote-learning strategy, whilst those students who see science as ‘an ongoing process of concept development’ will tend to think about the new material and integrate their new understanding with other scientific knowledge. Schommer et al (1992) demonstrate similar findings:

> *“It is important the teachers be aware that students’ beliefs about the nature of knowledge - what knowledge is and how it is acquired - may function as unspoken barriers to learning.”*

How can aspects of the nature of scientific knowledge be incorporated into undergraduate curricula? Perhaps the most important message is that all undergraduate science courses provide students with images of the nature of scientific knowledge even though the issue may never be explicitly addressed. These images arise from the course structure, assessment methods and lecturer’s commentary. In the words of one chemistry lecturer:

> *“Everything we do in a classroom makes a statement about what we value. Both how we lecture and how much we lecture present images of science as authoritative or ever-changing. Course content tells students what is important: history and progress or facts and equations. The design of teaching strategies reflects how we expect students to learn. All these factors (...) either promote or negate intellectual growth.”(Finster 1991)*

For instance, lectures often present the details of scientific information without discussion of the conceptual base from which these details emerge. This can encourage students to merely digest the facts, rather than try to build a conceptual understanding of the lecture material. The following quote by a biochemistry lecturer illustrates this point:

> *“And in the past the problem has always been when they’ve had to learn the [biochemical] pathways they spend so much time in learning the pathway that they never get to the next level which was the function - and the function is what it is all about.” (quoted in Dall’Alba 1993).*

Lecturers can use a variety of strategies to challenge students’ images of science as a ‘collection of facts’. For instance students can be confronted with multiple theoretical models of a given phenomenon and be asked to evaluate each one. This can be done most effectively in a tutorial situation where students can discuss the relative merits of theoretical models with their peers. Where modern alternative theoretical formulations are unavailable, students can be encouraged to reflect on the status of the theoretical entities of the standard model. How sure are we that neutrinos exist? What is a neutrino? In this way students can come to appreciate that theoretical models do not arise directly from experimental data but involve a great deal of creative thinking (see section 5.3).

So far we have discussed the importance of an implicit understanding of the nature of scientific knowledge. All of the examples given above can be incorporated into standard modules defined in terms of the subject matter knowledge that they contain. However many educational researchers have advocated an explicit approach in developing students' understandings of the nature of scientific knowledge (Matthews 1994). It is common for science students to be offered modules on the History and Philosophy of Science which contain significant discussion of aspects of the nature of scientific knowledge. To date there appears to have been limited analysis of the extent to which students transport these insights into other modules. Giere (1991) describes a course which aims to 'help beginning students acquire cognitive skills in understanding and evaluating scientific material'. The book describing the course includes chapters on 'Models and Theories' and 'Data from the Real World' both of which discuss the nature of scientific knowledge. Again, it is an open question whether students will apply these insights whilst working on their 'normal' module work. Finally, Sheppard and Gilbert (1991) describe a module 'From Magic to Science' given as part of a physics undergraduate course. The course aims to introduce students to a broader view of their discipline and includes elements of the nature of scientific knowledge. In contrast to the two courses described previously, this course is strongly based in the context of the students' chosen discipline. Interviews with students following the course show that the course is well received by students:

> *"It's given me an understanding of how different areas of Physics 'clicked', which perhaps I didn't know before: how it's all branches from the same trunk, whereas I thought before they were all different trees in an orchard."*

This student at least has been encouraged to take a more integrated view of their subject through exposure to these broader issues.

5.3 The processes of scientific enquiry

By processes of enquiry we mean to describe what scientists do to develop and evaluate new scientific knowledge. In section 2 we described these as the methods of science: experimental investigation, theoretical development of models, identification of research questions, the evaluation and application of multiple models. In particular we showed that the interpretation of experimental evidence in terms of models of the real world requires creative input from the scientist - models do not emerge from data. Furthermore scientific enquiry is strongly discipline specific. Finally, in following the processes of scientific enquiry scientists will draw upon the 'craft knowledge' of their discipline. This feature of the undergraduate curriculum is discussed in section 5.4.

Individual research scientists will have a working understanding of the processes of scientific enquiry. Much of this understanding will be discussed explicitly by practising scientists - for example using experiments to decide between different theories and good laboratory practice. However, some of the features discussed above, though evident in the actions of scientists, will often be under-represented in their discussion of their activities - particularly the role of intuition and creativity in the development of theoretical explanations. Indeed, in a survey of 60 research scientists in the Netherlands, Samarapungavan (1992) identified distinct differences between what scientists say that they do, what they think they should be doing and what they actually do.

How can undergraduate students benefit from an understanding of the processes of scientific enquiry? At a pragmatic level an understanding of ‘good scientific practice’ will be of benefit in laboratory practical classes and open ended research studies. Students will be encouraged to be methodical, keep records and reflect on the meaning of experimental and computational results. The benefits of an understanding of the nature of research questions, the complex interplay of experimental evidence and theory and the role of creativity in science are less clear cut. However ULISP studies of tutorials where students work with models, experimental evidence and ‘real world’ data indicate that for many students the relationship between these knowledge forms is unclear and that students would benefit from an understanding of the issues involved (Ryder and Leach 1996).

There is an additional reason for giving all students some understanding of the nature of scientific enquiry. In order to assess the significance and validity of other peoples scientific work an insight into the processes of scientific enquiry is important. Researchers need to be able to judge work coming from research groups working in their field of expertise. More generally, members of the public need to make informed judgements when scientific work is reported in the media - particularly when this work may have an impact on their lives. The sort of insights relevant here are: has this scientific study been repeated and confirmed elsewhere, how representative was their sample, does the report in the media truly reflect what the scientists are saying?

To a great extent undergraduate science courses have dissociated subject matter knowledge from the enquiry processes which gave rise to it. Whilst some lectures will include informative stories about real scientific enquiry, most present scientific information as ‘revealed fact’. Though there are good reasons for presenting subject matter knowledge in this way, the scientific enquiry process is under-represented. Collins (1985) has referred to subject matter knowledge being presented to students as a ‘ship in a bottle’. Students see the finished product but gain limited insight into the complex processes that went into its creation. Latour (1987) refers to the scientific enquiry process as ‘knowledge in the making’ and points out that a scientist’s account of subject matter knowledge changes once the enquiry process is over and the knowledge has become ‘agreed’.

The inclusion of the methods of science in science courses has a long history - particularly in the UK following the laboratory-based approaches advocated by Armstrong in the last century. The Primary and Secondary School National Curriculum for Science in England and Wales includes a substantial component called ‘Experimental and Investigative Science’. At the university level all science courses include laboratory teaching modules. Such undergraduate modules typically involve students performing set experiments which should yield the ‘expected answer’. Although such work has a place in the undergraduate curriculum (for instance enabling students to become confident with experimental techniques and apparatus - see section 5.4) the image of scientific enquiry arising from such work does not reflect the complexity shown in our discussion above.

Most undergraduate courses do give students the chance to work on open-ended projects - usually in their second and third years. Such work is more likely to portray the full range of enquiry processes from choice of research question through to analysis, theory evaluation and presentation of results. The ULISP study of final year research projects has shown that when students are given the opportunity to work alongside practising scientists (postgraduate students, post-doctoral fellows and lecturers) they gain a much deeper insight into the actual practice of scientific enquiry. In section 3 we described such learning as an ‘apprenticeship’ into science. The key feature of such learning is that it is strongly placed within the context of the student’s discipline and is not isolated from the subject matter itself. A further aspect of open-ended projects is that students are learning about enquiry processes *implicitly*. Learning is embedded within a context which includes a wide variety of other aspects of science - subject matter knowledge, craft knowledge and the culture of science. We would argue that this represents the most effective way of introducing students to the features of science discussed in this section.

However, many explicit, de-contextualised methods of including discussion of enquiry processes have been used in undergraduate courses. Giere’s ‘Understanding Scientific Reasoning’ (1991) mentioned in the previous section describes a course which includes discussion of how scientists evaluate theoretical hypotheses using experimental data, the distinction between correlation and causation and ‘crucial experiments’. History and Philosophy of science courses include case studies of scientific enquiry. These courses also include discussion of ‘theories of science’ - particularly the writings of Popper and Kuhn on the development of scientific knowledge. An example of a course situated within a discipline is the Open University’s ‘Methods and Consensus in the Earth Sciences’ (Open University 1976) which describes ‘the scientific method’ and the ‘growth of science’ with extensive reference to subject matter knowledge in the earth sciences. All these examples can be described as ‘course add-ons’ which aim to enlighten students about the enquiry processes which have given rise to the subject matter knowledge that they encounter in other modules. However, as stated earlier, it is an open question whether insights from such courses will influence the student’s learning in other modules. Perhaps the most that can be said is that such courses ‘sensitise’ students to the complexity and variety involved in scientific enquiry. It is then up to students to transfer this understanding into other parts of their course.

5.4 Craft Knowledge

In our discussion of the methods of science in section 2 we talked about the general features of scientific enquiry without discussing the craft knowledge which enables scientists to follow these processes of enquiry. Craft knowledge includes the ability to use instrumentation associated with the discipline. For instance, experimental apparatus, data capture equipment, computer control software and data analysis software. Knowledge of this instrumentation includes how to use it and how to fix it if it goes wrong - trouble shooting. It is also necessary to understand the theoretical basis of experimental procedures - their ranges of applicability. Much of the above can be described as the ‘tricks of the trade’ - the kind of unwritten rules gained through long experience which allow scientists to get the most out of instrumentation.

In addition to competence with instrumentation, craft knowledge includes an understanding of the properties of the ‘materials of the discipline’ e.g. the delicacy of RNA samples or typical impurities found in alkali earth metal samples. Related to this is a key aspect of craft knowledge - safety. How can material and instruments be used safely, and which procedures/materials require particular attention to safety precautions?

Outside of the laboratory craft knowledge includes the mathematical ability to manipulate and evaluate algebraic equations. It also includes the ability to perform literature searches of disciplinary databases and citation indexes. The ability to access the Internet is becoming increasingly important in many disciplines.

By presenting craft knowledge as a distinct aspect of undergraduate science curricula we hope to emphasise that this is an important and often neglected part of undergraduate courses. However in discussing craft knowledge it is important to appreciate that almost all of it is highly dependent on the particular science discipline concerned. Geneticist need to be able to perform reliable Polymerase Chain Reaction (PCR) procedures, chemists need to appreciate the safety implications when working with hazardous materials. Despite its intensely discipline-specific nature craft knowledge is a central part of being a successful science researcher. Postgraduate students spend a substantial amount of their time in acquiring craft knowledge - largely through trial and error.

How can undergraduate science students benefit from an understanding of craft knowledge? Clearly this kind of knowledge will be extremely valuable for those students entering a research career. However it is hard to imagine that such context-specific information can be of use to students who do not intend to enter scientific research and development jobs. For these students craft knowledge is essentially a short term ‘enabling tool’. For example, it will enable them to complete their final year research project (and gain the many other benefits that such a project can give them). Craft knowledge will also enable students to use a computer to search for patterns in a data set. Students will then be able to use their subject matter knowledge and insights into the nature of scientific knowledge and enquiry processes to draw meaningful conclusions from their data. Seen in this way craft knowledge remains an important enabling factor for all students of science.

Much of the craft knowledge discussed above is acquired by scientists through long experience. However, students have a very short time to acquire these skills if they are to be of use to them during their undergraduate course. Perhaps the most crucial message is that students should be given many opportunities to practice these skills. This can be done through library projects, open-ended practical projects and ‘conventional’ laboratory teaching sessions. It is important to stress that students can only learn if these teaching contexts are sufficiently flexible to allow the students to make mistakes and learn from them. It is also important that lecturers - for whom craft knowledge is ‘second nature’ - appreciate that students can have great difficulty in acquiring these skills. Perhaps the most useful model of teaching/learning here is that of an ‘apprenticeship’ where students can watch an experienced scientist at work and are given plenty of opportunity to practice these skills. Even though craft knowledge is a very specialised aspect of science our discussion of it as an ‘enabling tool’ for students means that failure to acquire them may prevent students from getting the most out of open-ended projects and laboratory sessions.

5.5 Scientific Culture

Science is a complex, collective human activity. The global community of scientists has rules, institutions, communication methods, a shared language and history. Taken together these aspects constitute the culture of science. The key features of the scientific culture were discussed in section 2.3. Aspects of the culture of science include its disciplinary structure, the institutions of science, career paths in science, ethical considerations, the social validation of scientific knowledge and the communication of scientific ideas to scientists and the broader community.

Practising research scientists will acquire a deep understanding of all of these aspects of scientific culture during their careers. However, as with craft knowledge, their understanding of scientific culture will be strongly discipline-specific. A knowledge of some issues may be very important in one discipline but less so in others. For example, the ethics involved in deciding how to follow a line of research is a very important aspect of research involving human genetics, but is less relevant for the low temperature physicist (although both will need to consider the ethical aspects of collecting and reporting data, e.g. not inventing results). Undergraduate students who wish to become research scientists will benefit from exposure to these issues, though they are unlikely to acquire an in depth appreciation until PhD studies and beyond.

Do students who will not become research scientists need an insight into the culture of science? Certainly for those students entering accountancy, management, information technology and other non-science related employment the issues described above will be of limited use in their future careers. However, the opportunity to study issues such as ethical implications of scientific progress or conflicts of ideas in the history of science will provide such students with an opportunity to follow broader aspects of science within their degree course, particularly in the final year when modules based on advanced subject matter knowledge can seem increasingly irrelevant to some students. Furthermore, for those students entering science-related employment such as science teaching, science journalism or science policy, study of the institutional structure of science, ethical issues and career paths in science can provide important insights relevant to their future careers.

How can aspects of scientific culture be included in an undergraduate course? The broad disciplinary structure of science will be clear to students since high school courses and university modules are organised around disciplinary structure. However, the significance of research programmes may only become clear as students follow final year modules whose content is based on contemporary research areas such as protein structure and function, chemical reaction dynamics, palaeoclimatology or optoelectronics. Furthermore, undergraduate research projects will actively involve students in a research programme. However, ULISP studies have shown that students may benefit from an ‘orientation session’ as part of their research project. Such a session could include discussion of the key journals and institutions with influence in the discipline. Whilst this is often done naturally through informal discussion during projects, explicit inclusion of these issues may be beneficial.

The existence of key journals and the structure of research articles can appropriately be introduced to students in tutorial sessions. These can include a discussion of the purpose of each part of the paper and which parts to read first to get an overview of the content and major findings. An advantage of such a tutorial is that the structure of research papers is broadly uniform across the sciences. As a result ‘an appreciation of the structure of scientific research papers’ can be considered a transferable scientific skill.

Finally, as stated earlier, undergraduate modules can be constructed to cover issues such as the historical development of scientific ideas and ethical aspects of science. However, such modules should relate directly to the student’s discipline rather than general science. This will ensure that students see such modules as relevant to their degree rather than optional add-ons. Furthermore, such modules may be most appropriately included as final year options - the stage at which most students have firm ideas about their future career plans, and can make informed judgements about whether they wish to replace advanced subject matter knowledge with modules covering broader issues of the discipline.

6 Research Focus

In this section we will outline the aims of the Undergraduate Learning in Science Project and what we hope to contribute to work in this area. We start with an outline of general issues relating to undergraduate learning in the sciences. This is followed by a closer analysis of ULISP research questions.

6.1 Research issues

6.1.1 What are the purposes of an undergraduate science course?

This question can be addressed from a variety of perspectives. The student is looking for an understanding of science, a compelling learning experience and employability. The scientific community is hoping to raise awareness of their discipline and train future scientists. The government is looking for graduates who can contribute to the economic prosperity of the nation. All of these aspirations have implications for course content and structure.

Policy issues are a key influence on the nature of undergraduate courses. In the UK the move to a mass higher education system, vocational qualifications, course modularisation and teaching quality assessment is having a significant impact on undergraduate courses.

6.1.2 The undergraduate science curriculum - what should be included?

Undergraduate science curricula have traditionally focused on the subject matter knowledge to be included. However, as the output of scientific information increases many lecturers are moving towards a curriculum which emphasises the students ‘ability to acquire and use’ scientific information.

A further issue involves the current interest in studies of science. The interest of philosophers, historians and sociologists in the activities of scientists has caused debate about the nature of science. As industrial societies have become increasingly reliant on the activities of scientists and engineers, attempts have been made to include science, technology and society (STS) issues in science curricula. There has been increasing concern about the ‘public understanding of science’ and what scientists need to know about public perceptions of their discipline.

6.1.3 How do undergraduate students learn about science?

The science education research community has investigated many aspects of science learning. This has resulted in a variety of research perspectives: science learning as an introduction to a language community, science learning influenced by prior knowledge and the active participation of the learner, science learning as an enculturation into a science community, and science learning as influenced by student views of the nature of science. These issues represent the core concern of our work.

Undergraduate learning is also influenced by a number of special factors. Students are required to work in a university setting which is largely alien to them. Student-teacher interaction is becoming increasingly limited as student numbers increase. Teaching methods such as self-directed learning and open-ended projects put new demands on students. Students are also assessed on this work. Students adopt a variety of learning approaches in response to these pressures - not all of which lead to effective learning. Student welfare is also of increasing concern. Students must survive with limited financial resources and housing conditions are often very poor.

6.2 Research questions

The issues raised above outline a broad range of concerns: policy issues, curriculum design and delivery, studies of science, studies of learning, assessment and student welfare. The primary aim of ULISP is to improve our understanding of student learning in undergraduate science. In investigating student learning the issues raised above must be considered and taken into account. However, our main interest in these broader issues is in how they influence student *learning*.

A further issue is the extent to which our research interests are open to empirical research. By undertaking studies of undergraduates learning within science departments we can gather evidence which can be used to explore some of the research questions outlined below. However, there are questions which can not be investigated empirically. These questions will be tackled through an analysis of the literature and conceptual insights drawn from workshops with lecturing staff and student interviews.

As a collaborative project involving a broad range of science disciplines our research into student learning is not focused on the conceptual development of students when learning particular subject matter. Rather our work tries to capture the key features of learning in science generally. These insights can then be drawn upon and realised within subject contexts by lecturing colleagues from science departments.

The research questions outlined below emerge from the perspective on science, learning and curriculum presented earlier in this paper.

6.2.1 What are students learning within existing undergraduate teaching contexts?

Contexts of interest are tutorials, teaching laboratories and open-ended projects. We are particularly interested in what students are learning *about* science - i.e. about all of the aspects of science outlined in section 5. In addition we are interested in how actual student learning relates to departmental aims and lecturers aims for particular course components. Our approach to these issues is through empirical investigation: interviews with students and lecturers, analysis of departmental course objectives and observation of students during teaching.

6.2.2 What factors influence the effectiveness of student learning within existing undergraduate teaching contexts?

This question applies particularly to those teaching contexts identified as problematic by colleagues within science departments. Factors of interest include students' prior understandings of the purpose of the teaching unit and departmental organisation and assessment within the unit. Of particular interest are the images of scientific knowledge and scientific activity that students draw upon and develop through teaching, and how these influence their ability to learn effectively. We hope to develop appropriate models of learning which can inform our understanding of student learning within particular teaching contexts. Our analysis will include empirical investigation and insights drawn from educational literature.

6.2.3 What new approaches to undergraduate teaching can improve the effectiveness of undergraduate learning in the sciences?

Drawing upon insights from questions 6.2.1 and 6.2.2 adaptations to existing teaching units can be suggested, implemented and evaluated. Furthermore entirely new teaching units can be developed informed by our research. For example sequences of tutorials within departments which develop students images of scientific knowledge and activity within their discipline. A key question is whether students most effectively develop such understanding through explicit or implicit teaching methods.

6.2.4 How can science lecturers, educational researchers, staff development employees and students work together to investigate undergraduate student learning?

This particular research question is of a different nature to those above but is no less important to the success of the ULISP research programme. What is the role of each of the various participants in a collaborative research study such as ULISP? How can problem areas be identified, studies implemented, departments informed of research outcomes and subsequent changes evaluated? Is a model of 'action research' (outlined in working paper 2) helpful? ULISP participants have already gone a long way in addressing these important methodological questions. Future studies aim to develop these new ways of working.

7 ULISP studies in progress

7.1 The Research Project Study

The Research Project Study is an investigation of student and lecturer experiences on final year undergraduate science research projects. The study has followed 12 final year undergraduates and their project supervisors over a period of 7 months. Students have been interviewed at the beginning, middle and end of their project. They have also been visited when performing project work and asked to keep a regular diary of their experiences. Supervisors have been interviewed at the end of projects. Several ULISP workshops were held to discuss and develop outcomes from the study with science lecturers, and departmental information about the organisation and assessment of projects was collected. Further details of the design and methodology of this study is given in Working Paper 2 of this series. Working Papers 3 to 8 give detailed analyses of the data collected.

The research project study runs across all of the research questions identified in section 6.2. However, the final year project is often the undergraduate student's first contact with science research. As a result this study is particularly concerned with how students become encultured into a science research community and the influence this process has on their learning about science across the five aspects identified in section 5.

7.2 Tutorial Observations Study

This study focuses on tutorial sessions given as part of normal module work to science undergraduates in their first or second year of study. Four first year tutorials and one second year tutorial were observed. All the tutorials chosen aim to enable students to develop their 'scientific skills' - e.g. reading academic articles or interpreting scientific data. All five tutorials were observed by two researchers and audio-taped for subsequent transcription and analysis. Researchers asked tutors and tutees about their experiences in the tutorial once it had ended. One of the purposes of this small scale study was as a pilot for a larger study in the future.

The tutorial observations study addresses the following questions:

- What are the skills associated with 'thinking like a scientist'?
- In what contexts can these skills be successfully practised by students?
- How can these contexts be integrated into the undergraduate curriculum?
- How successful are current tutorials at helping students to master these skills?

These issues run through all of the research questions identified in section 6.2. By focusing on the 'skills of a scientist' this study is concerned with how students learn about the nature of scientific knowledge, the scientific enquiry process and to some extent the culture of science as identified in section 5 (see also Ryder and Leach 1996).

7.3 Future studies

Following from those described above, ULISP will begin two new studies in 1996. A particular focus will be laboratory work as part of our contribution to the '*Labwork in Science Education*' research project funded by the European Commission (February 1996 to January 1998). Undergraduate students spend a great deal of time in teaching laboratories and practical classes. These classes are expensive to run and time-consuming for both students and staff. What are the aims of teaching laboratories? What do they achieve? What is the nature of student learning when engaged in practical sessions? Is the student able to transfer what they have learnt into other teaching contexts such as open-ended research projects and tutorial work? What do teaching laboratories teach students about the nature of scientific knowledge and the scientific enquiry process? ULISP will investigate these issues as part of the Labwork in Science Education research project.

A second ULISP study is due to begin in 1996 funded internally by the University of Leeds - *Learning about the actual practice of science: tutorial support for undergraduate science students*. Interest in this proposal follows from both of the current studies - particularly the Tutorial Observations Study - and from discussions with lecturing colleagues during workshop sessions. Tutorial programmes will be developed within participating science departments. These tutorials will cover many of the aspects identified in section 5 of this paper. For example, the reasons for scientific conflicts, the relationships between data and models and the ways in which scientists identify research questions. The most significant feature of this project is that the tutorials will cover these issues *in the context of the departmental discipline* rather than for science in general. Products from the study will include piloted and evaluated tutorial programmes for each of the departments involved in ULISP. In addition the study will develop a framework for such tutorial programmes. This can be used by other science departments to develop their own in-house programme covering the broader issues and skills of their discipline.

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Appendix 1: 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 research projects and students' views 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 Case studies of science students doing undergraduate research projects

Several 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 Implications and messages 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.