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# **The Nature of Scientific Work**

- a study of how science is used in work settings and the implications for education and training programmes

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## **Abstract**

This thesis explores the work of scientists and shows how a description of the main characteristics of scientific work can be constructed. This description forms the basis of a critical appraisal of how scientific education and training could develop to better match the needs of those who wish to pursue a career in science.

In the early chapters authoritative reports on science, technology and mathematics in the context of work are analysed to create an overview of how scientists work, of their role within the UK economy and of the knowledge and skills which characterise their expertise.

The main part of the research study is the creation of an evidence base which includes data from interview, work observation and documents. Scientists from 28 organisations contributed information and opinion, these people covered the main domains of science. The organisations included both public and private and ranged from small departments to research units in multi-national companies. The data is summarised under headings which have a bearing on the education and training of scientists. Particular attention is given to scientific explanatory concepts, concepts concerned with planning experiments, practical skills and analytical skills. The research has revealed the critical importance of a range of non-scientific skills.

A commentary on the views of working scientists on aspects of scientific education and training is given and a preliminary match and mismatch analysis of work practice and general educational provision is summarised.

The thesis covers ground which is poorly researched therefore some theoretical constructions have been developed to aid research of this kind.

The research shows how the analysis of practice has potential for modernising educational provision, leading to more efficient use of resources and bringing greater relevance to educational courses.

## Acknowledgements

I am indebted to the people who gave up their time to participate in this research study. I also thank all those people in the organisations involved who facilitated my visits to their organisation and set up the interviews with their colleagues. Many organisations have contributed to this study - some directly, others indirectly - my thanks to them, there are too many to mention here; all are listed in annex A to the thesis.

A mass of raw data was collected during the first three years of the research. I am very grateful to Sarah Safraz and Sally Rowland for helping me with transcription of interview data and field notes.

The research work has been completed during a period when I was “sponsored” by the National Council for Vocational Qualifications as a Research Fellow at the University of London Institute of Education. I am especially indebted to Gilbert Jessup and Tim Oates for encouraging and supporting my work in this field. I hope they feel the process and the product justify their support.

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Finally thanks to my two supervisors who, at first, were unnervingly confident in my ability to pull off a large-scale study on a part-time basis. Their encouragement soon turned to guidance and later to insightful commentary on my thinking. Study and research for a higher degree has been challenging, developmental and enjoyable; for contributing to all three of these characteristics I am most grateful to Denis Lawton and Janet Harland.

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## Preface

The need for some empirical research into scientific knowledge and skills became clear to me in 1990 when I was working on the English National Curriculum for Science. I was surprised to find that scientifically trained people could understand the process of scientific investigation in sharply differing ways.

Having practised science in industrial research laboratories working on such problems as the life expectancy of chemical waterproofing used on large African dams and how to make high explosive in the purest form, I thought I had learned scientific method by doing it. I also worked in technical (and manual) jobs on zinc/lead smelters and assisted with first-hand investigations into improving output. Words such as hypothesis, prediction, experiment, and error seemed to make logical sense to me in all these settings. My reading of philosophers such as Popper seemed to help me appreciate a general form of scientific enquiry. Twelve years in the secondary school classroom teaching science reinforced my thinking about scientific method; Nuffield Combined Science emphasised structured practical work and the Schools Council Integrated Science Project emphasised the importance of searching data for patterns and trends.

On the other hand I found it odd that the explicit teaching of scientific approaches in school seemed to be 'down-graded', and the learning of other concepts appeared to be much more important. Practical work with examination classes appeared to be designed to illustrate concepts rather than lead to understanding and criticism of scientific methods. At the time I put this down to the difficulties of assessing practical work and I tried, where I could, to restore the balance by talking with classes about the nature of experiments and to what extent we could believe the conclusions we had reached through experimental work.

From my teaching years I sensed a lack of relevance in many examination syllabuses. There seemed to be too little interaction with issues related to people, the environment and the economy. I felt that young people should have the opportunity to sample the mix of activities which working scientists do in their work; they would then be able to make career decisions based on firmer, first-hand experience. I believed a good grounding in the way science is used to solve problems and make sound decisions is needed in everyday life. If we all had better scientific capability we would be able to contribute more to our own well-being and remain more in control when faced with difficult decisions.

As a schools adviser in Suffolk I came into closer contact with teachers in primary schools trying to teach science. There was, it seemed to me, a healthy confusion between science and

technology and the “fairness” of a test was of paramount importance. The contexts used to study science were generally directly relevant to the children’s interests.

When I joined the government agency developing the National Curriculum for schools (in England, Wales and Northern Ireland) in 1989, it was my responsibility to evaluate the national consultation on the form and content of the proposed Science National Curriculum. The latter had been constructed by a body of well-respected people, mainly educationalists but also including an industrialist. The surprise came when I discovered how difficult it was to describe the content, structure and development of scientific work. Could a prediction be a hypothesis? Did a hypothesis have to be testable by definition? Was an experiment the same as an investigation?

Scientific investigation as included in the National Curriculum (DES/WO, 1989) roughly took the form:

- make an observation;
- make a prediction/hypothesis;
- test the prediction/hypothesis by identifying and testing key variables;
- draw conclusions;
- estimate reliability of results/validity of conclusions.

Increasingly sophisticated investigations draw on more difficult scientific concepts, are set in more complex contexts, use more mathematics and have more insightful discussions of implications.

During the next five years, which included another review of the National Curriculum, the form of scientific investigation and its implementation and assessment was arguably the single most important curriculum issue for science teachers.

The attainment target concerned with scientific investigation provided a framework for structuring practical work. However many people believed the scientific investigation attainment target went beyond the common form of practical work and this made it a taxing new aspect of the science curriculum (see Coles and Gott 1993). Some teachers, especially those who taught the most able, had an interest in maintaining what had gone before, namely the routine assessment of specific practical skills, often in isolation, where they had to date been very successful in terms of GCSE and GCE A level results. The specification of scientific investigation was seen as a step forward by many teachers, but one which needed more time for thought and development of appropriate schemes of work.

For me the striking reaction was from those who claimed that the way scientific investigation was described was not part of science as they saw it. Some stated that even when they worked on their scientific doctorate, they did not plan or evaluate in the way the new attainment target implied. Many of these people believed that there was no single scientific method, instead there was an approach which changed its form to suit the circumstances of the inquiry. The negative reaction from many teachers to the attainment target concerned with scientific investigation was strong and was coming from teachers in influential positions, for example in the most highly regarded public schools. There was pressure on the Secretary of State for Education to withdraw National Curriculum requirements for scientific investigation. Yet how could senior thinkers in education and government reach a position where something so fundamental as designing, carrying out and evaluating an investigation, could be considered not to be central to science education? Perhaps they considered it was best learned later in life, with the basic facts and principles of science forming the focus of school education.

Turning to industry for views on the new scientific investigation attainment target was not helpful at the time of the introduction of the National Curriculum. Many of those consulted found the language of the National Curriculum jargon-ridden and felt ill-at-ease interfering with the work of science education professionals. Some were simply pleased that science was now a core subject (compulsory) in the school curriculum, and major areas of science knowledge would not be “dropped” by students at age 14.

The lack of research evidence about the methods scientists use in their work was possibly one reason why many science educators found it difficult to be confident in the teaching of scientific approaches. The idea for research reported in this thesis emerged from this thought. However a further career move broadened the research focus to include a more comprehensive review of the work of scientists.

In 1993 I began work for the National Council for Vocational Qualifications and managed the development of the new General National Vocational Qualifications (GNVQs) in science. These qualifications were aimed at students who wanted to work in science-based businesses and consequently need to be vocationally relevant. Employers and tutors in higher education were consulted about what they felt constituted relevant science for those who were likely to make a career in the subject. Gradually the product of this work was incorporated in to the new Science GNVQs. Since 1993 the GNVQs have been revised twice and consultation with employers and tutors in higher education has continued. Some of the data analysed in this thesis has been used to improve the relevance of the content of Science GNVQs.

In his comprehensive review of professional knowledge and the professions (Eraut, 1994, p 102) Michael Eraut gives some advice to those embarking on the mapping of the knowledge-base of professions. He first makes the point that all such maps are bound to be fuzzy at first but he goes on to justify the pursuit in terms of:

- correcting oversimplified views in current circulation;
- illuminating the debate between theory-practice links and learning on-the-job;
- bringing attention to aspects of knowledge currently missing from educational provision;
- informing the debate on competence based approaches to occupational standards and qualifications.

This study may help with all of these but the main aim is to contribute to our knowledge-base in terms of the ways science works in practice and, in the light of this, begin the process of critical appraisal of the science curricula in schools and colleges.

## Chapter 1: Introduction

The research reported in this thesis focuses on what it is that people who work with science actually do. The general description of the work of scientists could be useful in matching education and training to the functions of people who use science in their jobs. I hope that the work might also be useful for developing general science curricula: for example by providing an idea of the relative importance of different aspects of science education (the knowledge-base, practical skills, problem solving abilities).

The concept of science is an immensely broad one. People conceive of science in many ways; these different conceptions rarely cause problems and can be accommodated within a general notion of science with comfort. Some regard science as a body of knowledge which has been validated by skilled enquiry; others see it as a means of exploring the natural world through logical thought, dispassionate inspection of evidence and accurate analysis. Science means a route to health, wealth and progress to some people; others view science as unnatural, damaging and dangerous. It can be viewed as powerful and undeniable or as limited and futile in the great scheme of things; as fixed and absolute by some, a social construction by others. Some people see the fruits of science as stable and made of fundamental theory; others will only regard them as temporary generalisations.

With such a range of interpretations of science there are clearly some definitions to be made before the work of scientists can be used in the critical appraisal of science education and training.

### The research study

The work reported in this thesis is an attempt to identify the features of the work of scientists. Two points of clarification arise immediately.

- How will *scientist* be defined?
- What constitutes *work*?

A *scientist* will be defined as a person who uses scientific knowledge or skill at some point in their work in a way which is critical to a successful outcome. The definition will also be limited by the constraint that those who are carrying out the work will have some recognised scientific training. This can be the recognition of a professional body (e.g. Institute of Animal Technicians) or a scientific qualification.

*Work* for the purposes of this study means an activity which uses scientific skills and knowledge in some way. Moreover, the application of scientific skills and knowledge are essential if the activity is to be carried out successfully.



This study is not limited to those working at the higher levels of scientific activity. People work on tasks which can be regarded as scientific or technical at all levels (CSTI, 1993, p6) and this research aims to take that into account. However scientific work is usually highly specialised and as expected the higher level workers outnumber junior technicians, this factor is taken into account in the research methods used.

### **The nature of science**

By now it will be evident that this research study is not directly linked, at least through theoretical discourse, with the philosophical quest to improve our understanding of the nature of science itself. There is an immense literature on the nature of science, beginning, perhaps, with the thinking of Greek philosophers such as Thales through to modern thinkers such as Popper and Kuhn. The existence of a range of theoretical perspectives on what makes a process *scientific* has, over time, led to a generalised public notion of what constitutes science and scientific methods. This broad generalised appreciation of the realm of scientific work is the starting point of this study. In work settings there may be considerable variations in the interpretations of what is science - this variation is particularly strong at the interface with technology. The aim is to produce a generalised model of the nature of the work of scientists. The latter has to be general because there are many different types of scientists. These people may work in research, providing services to people, production or management; they may use science in their work for only a small proportion of their time. Further studies in this area could be conducted with a more restrictive definition of what constitutes scientific work, this tighter definition could then lead to research findings which could test philosophical constructions.

### **Some important difficulties**

Using documented evidence together with interview data to form a representative sample of scientific workers poses some problems. Firstly some things are easier to describe than others, for example skills are more difficult to put into words than scientific facts. Secondly the more familiar an aspect of knowledge or know-how is to a person the less likely s/he is to articulate it at the crucial time. Careful questioning is required. This is close to what Polanyi (1967) termed *tacit* knowledge; people use tacit knowledge but cannot tell what they know. Thirdly, important aspects of professional competence cannot be represented in propositional form (Schon, 1983; Eraut, 1994), making it necessary to seek out examples of work situations where the totality of what is expected can be described. This evidence of practice also helps to focus on 'useful' knowledge and skills - a sort of 'theoretical and practical understanding' which gets one away from the idea that a person can have knowledge which they do not understand.

There is a full discussion of the problems encountered in carrying out this research in chapter 5.

### **Evidence from different countries**

The context for the fieldwork aspect of this research has been largely employment in science-based organisations in the UK, however published reports from outside the UK have been considered (see Chapter note A). There have been consultations with employers about the education system in many countries, for example Dearing in England, Wales and N. Ireland (1996), Rowell et. al. in Canada (1997) and Unger in Germany (1995). In the UK the Confederation of British Industry<sup>1</sup> has reported on many educational issues on behalf of its member companies. Similar business forum arrangements exist in other developed countries.

Globalisation of business opportunities has led to many common working practices in companies in different countries; the research findings reported in this thesis may well be of value to education and training systems outside the UK.

### **The research continues**

Even if studies of this kind had been published in the past the conclusions in them may well have become invalid because the practice of science changes as do employment conditions. At the time of writing this thesis a substantial amount of current primary data about employment needs in science-based organisations has been collected, sufficient to lead to some useful conclusions. It would be useful to continuously monitor the needs of science-based employment to ensure the feedback to the education and training system remains relevant. Therefore the work in this thesis should be seen as a statement about employment in science-based organisations for the end of the 20th century and the beginning of the 21st century. The data needs to be updated and an analysis carried out every five years or so.

Some areas of scientific work are not included in this study but may have a bearing on the nature of scientific work. For example the behavioural sciences demand careful examination and might be included in the next update of the fieldwork.

### **Reasons for finding out about the practice of science**

*"The greater part of what is taught in schools and universities does not seem to be the most proper preparation for that which is to employ them for the rest of their days."*

**Adam Smith, Wealth of Nations, 1778**

The purpose of this study is to generate a description of how science is practised in such a way that it can inform the content of general science education and training programmes. The

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<sup>1</sup> for example Towards a Skills Revolution, 1989 and Routes to success: careership: a strategy for all 16 - 19 year old learning, 1993.

general nature of these programmes, which should lead to a broad appreciation of the knowledge and skills involved in scientific thinking and practice, means that they need to support many functions. These functions range from the development of a foundation for further academic study, where the focus is on systematically developing a large and deep knowledge-base, to programmes which familiarise students with the 'landscape' of science, its impact on society, the economy and the environment. Some programmes prepare people for the skills they need in work, others aim to provide people with basic scientific literacy. Vocational programmes are closely related to the occupational activities and are, as a consequence, specific about the competencies required. There is no such specific focus for general education in science. Programmes are varied as a consequence. In recent years there have been many initiatives which have placed emphasis on one particular aspect of science. Sometimes this has reduced emphasis on other aspects of science. For example the Nuffield science approach concentrated on discovery learning and this left relatively less time for the systematic development of a traditional science knowledge-base. Teachers and students have been able to choose a course according to their perceptions of the long term validity of its design parameters.

In some countries general education in science has become centralised; for example in the UK, Canada, Australia and Japan there are national schemes for science. This often leads to a reduction in diversity of approaches since one key aim of introducing national curricula is to enhance comparability of assessed outcomes so that those receiving and delivering programmes can have reliable measures of quality. Where large scale general science programmes are developed it is intended that the content (skills and knowledge) will enable the aims of the curriculum to be met. These aims are often very broad, for example - to improve living standards through better decision making, or producing sustainable development in terms of maintaining a healthy environment and sensible use of natural resources. The dominance of the knowledge-base of facts and principles, can leave little time for a serious attempt to make students aware of these broader aims. Often the development of the scientific knowledge-base is seen as the crucial first step towards enabling students to function as scientists and then contribute towards these aims.

An up-to-date description of scientific capability will provide a reference for curriculum designers against which to evaluate their curriculum in terms of how far it reflects science as practised. I recognise that there are many other considerations that curriculum planners will also need to be take into account. For example the extent to which the curriculum responds to the needs of different groups in society and how well it lends itself to reliable assessment.

### **In summary**

The research questions are:

1. What are the main features of the work of scientists?
2. How could science education and training respond to a model of scientific working practice?

The research offers the opportunity to improve general science education and training by:

- keeping content up-to-date with practice;
- maintaining relevance of contexts;
- keeping teachers up-to-date with work practices;
- keeping aspects of scientific activity in appropriate balance;
- making the process of educating future scientists more efficient;
- creating a basis for further development of curriculum and assessment.

### **Methodology**

A full description of the methodology used in this study and the problems which were encountered is given in Chapter 5. By way of introduction for the reader I offer a short summary of the methodology and the methods used in the study.

This is essentially a qualitative study. It is concerned with constructing a representative sample of science-based industry, public services and academic research and interviewing people in different types of scientific work. Those interviewed ranged from junior technicians to senior managers. People were interviewed about their background, the way science is used in their work and the ways their work is changing.

The research process began with a series of pilot interviews and a survey of the most recent statements about the education, training, recruitment and professional development of practising scientists. The survey was extended to cover policy statements from major agencies involved with science-based industries and services.

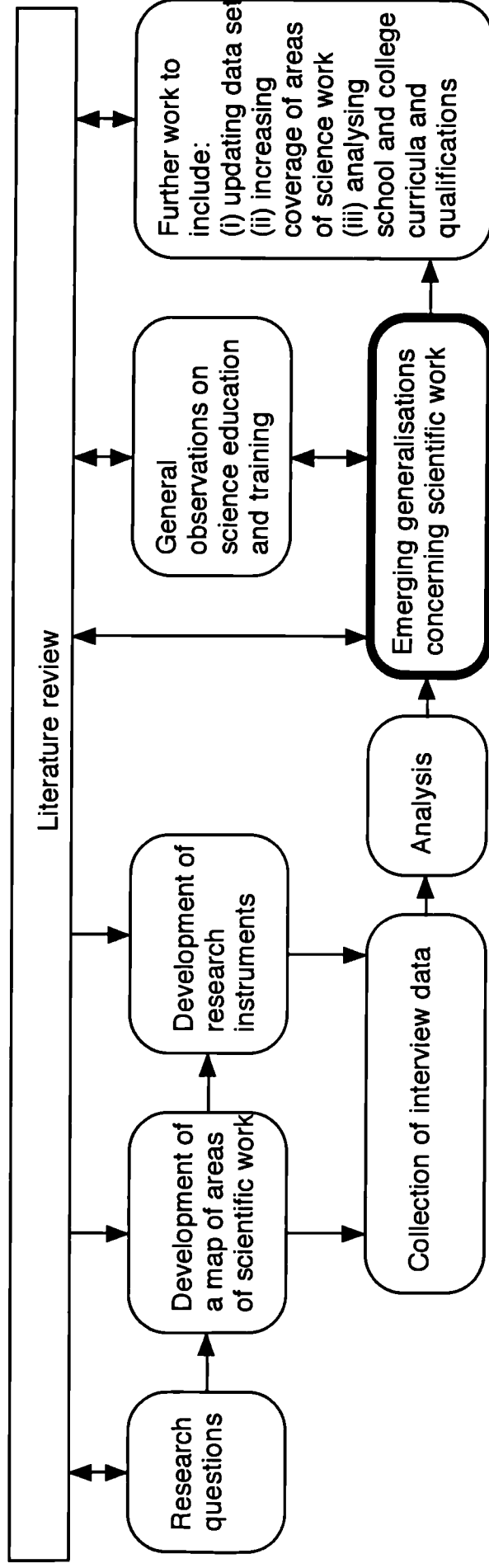
During the interviewing and analysis there was no reference to specific frameworks for occupational competence (e.g. functional analyses) or direct use of theoretical perspectives on the work pattern of professional groups. The data was treated as the primary material for theorising. The study draws heavily on grounded theory methodology (Glaser and Strauss, 1967) and recognises Lave's (1988) work on situated cognition, which stresses the importance of the socio-cultural dimension of practice. The latter focused attention on the need to make the interviews as subject-centred as possible, following through the interviewees lines of thought as far as possible within the constraint of interview. Lave's

work also placed additional emphasis on carrying out the interviews at the place of work and, where possible, to sample the on-going work environment and to discuss developments with co-workers. Often a series of interviews were conducted with different individuals in a work group.

The data gathered was transcribed and coded. Analysis was carried out with software designed to aid qualitative research.

An overview of the research study is given in chart 1 on the next page.

**Chart 1: An overview of the research study**



### Structure of the thesis

The first part of the thesis focuses on determining the characteristics of the use of science in work from the reports of the research of others (chapters 2,3, 4). This is followed by a description of the methodology and methods (chapter 5) and findings from the fieldwork (chapter 6).

The next three chapters (7, 8 and 9) review the findings and discuss their implications for education and training. Analysis of the findings (chapter 7) leads to a model of scientific capability. The discussion which follows (chapter 8) begins the process of evaluating education and training systems in terms of this research. There is only scope here to begin this analysis; if this line of enquiry should prove a fruitful basis for this task, then a review of curricula, syllabuses, training schemes and qualifications could follow. This would be a major undertaking. Chapter 9 includes some suggestions for changes to science education and training in the UK which could align it better with the way science is practised in work.

Chapter 10 includes a review of the key points made in this thesis, some areas for further research are identified and some personal perspectives on the research study are outlined.

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### Chapter notes

A Publications from outside the UK include the following<sup>2</sup>.

- A summary report of the Conference Board of Canada. This Board aims to promote science and technology education.
- Proceedings of the 8th International conference on Science and Technology Education which was held in Edmonton, Canada in August 1996. This conference was concerned with education industry links and bringing relevance to schools education.
- Various company reports from Hoechst (Germany). In depth research with key personnel (such as the main graduate recruiters) was carried out.
- The EU funded Industrial Research and development Advisory Committee of the Commission of the European Communities (IRDAC) publication *Schools and Industry* which describes how industry's needs are changing and how schools might best respond to the changes. The same committee has published *Skills shortages in Europe* which outlines where most effort needs to be applied to maintain Europe's competitiveness in a world market.

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<sup>2</sup> Full references are given in the reference section.

- Presentations on lifetime learning by Bert Cras (Netherlands) and Roland Oesterlund (Denmark) provided at a School Curriculum and Assessment Authority conference (9 and 10th November, 1995).
- Education and training for professions with future: vocational education and training in Austria, Federal Ministry of Economic Affairs.



## Chapter 2: The work of scientists

A major part of the research study reported in this thesis has been the collation of published evidence from employers, researchers, politicians, analysts, educators and other commentators about the needs of private and public science-based organisations in terms of scientific capability and capability more generally. This evidence is reviewed in the next three chapters. In this chapter I focus is on evidence about the ways scientists work.

### A framework for scientific work

For education to respond to the needs of employers in science-based organisations it is essential that the work of people who are employed as scientists is considered. Analysts working outside education do not find it necessary to distinguish between science and technology (for example: Advisory Council on Science and Technology, Cabinet Office, 1991; Realising our Potential, Chancellor of the Duchy of Lancaster, 1993; Engineering Employers' Federation, 1994). It is clear from a review of many reports in this area that the breakdown into specific disciplines (e.g. chemistry, mathematics, engineering, environmental science) or even pure and applied subject areas (e.g. physics and aeronautics) is not helpful. From the perspective of work it is more useful to break down science and technology along the lines of the type of activity being undertaken. The consultants working on the functional mapping of the science, technology and mathematics domain (Council of Science and Technology Institutes, 1993) identified six types of work activity. These were (within the context of scientific, technological and mathematical work) to:

- expand the body of knowledge and understanding;
- develop novel applications and processes;
- manage and/or direct people;
- carry out complex operations without supervision;
- carry out complex operations under supervision;
- using scientific, technological and mathematical knowledge and understanding as a significant part of occupational competence.

Whilst this broader focus is, on the evidence of published reports, more helpful for defining employment needs in science-based organisations, a clearer focus on the *scientific* aspects of work would be more helpful in terms of developing the scientific curriculum in schools, colleges and universities. The approach taken in the research reported here is to focus on the scientific without losing sight of the technological, mathematical or the general skills and attributes which are seen as important.

Perhaps the most significant recent study of *what scientists do* was that carried out under the auspices of the Council of Science and Technology Institutes (CSTI, 1993). This study was an analysis of the function of scientists in different occupations. The analysis was wide-

ranging in its sampling of types of work. The report lists 46 occupations where science is the main part of the job (such as a medical technician), or is a critical<sup>3</sup> part of the job (such as a nurse). Some 2.3 million people fall into these categories in the UK work force; this is about 10% of the total UK work force.

The CSTI report states the broad description of the task of scientists as:

*to explore, establish, apply, manage and administer safe and ethical practices and procedures of science, technology and mathematics to generate new knowledge, and to exploit this knowledge to serve the economy, the environment and society.*

This description was broken down into sub-categories. Three layers of sub-categories are described. In the first (least detailed) layer the essential function of applying scientific abilities is accompanied by a communication function and a managerial function. These are then broken down into the next layer of detail. Table 1 on the next page contains details of this break down.

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<sup>3</sup> The definitions of *main* and *critical* are given in chapter 3, chapter note B.

**Table 1: The Consortium of Science and Technology Institutes' analysis**

<b>Applying scientific abilities</b>	<b>Communication</b>	<b>Managerial</b>
<ul style="list-style-type: none"> <li>• generate own ideas, hypotheses &amp; theoretical models and/or utilise those postulated by others</li> <li>• design investigations, experiments, trials, tests, simulations and operations</li> <li>• conduct investigations, experiments, trials, tests and operations</li> <li>• evaluate data and results from the processes and outcomes of investigations, experiments, trials, tests and operations</li> </ul>	<ul style="list-style-type: none"> <li>• determine current and projected requirement from within and outside the organisation, for science mathematical and technological skills/services</li> <li>• research all potential sources of information to establish current knowledge, understanding, practices and procedures</li> <li>• communicate the results and outcomes of present and previous scientific, technological and mathematical investigations and/or activities</li> <li>• teach, train and assess students/clients/trainees in the knowledge, understanding and practices (both new and established) of science, technology and mathematics</li> </ul>	<ul style="list-style-type: none"> <li>• develop policies and strategies which will lead to the achievement of objectives (set by self and others) and the efficient, effective and safe execution of the operation/organisation</li> <li>• determine appropriate policy/practices for the safe and effective utilisation of resources</li> <li>• administer policy/strategies to ensure achievement of objectives</li> <li>• monitor and evaluate the efficient and effective running of an investigation, programme, initiative, section, department, branch or organisation</li> </ul>

CSTI, 1993

This functional analysis of the work of scientists (and technologists and mathematicians) may seem inadequate to research scientists who are committed to the development and explanation of theories. They may sense that the analysis has been skewed towards an industrial/commercial use of science and that the description (and use of) of a knowledge-base has insufficient emphasis.

There is also perhaps an overemphasis on the objectivity of science in the CSTI description and insufficient emphasis on the social dimension of being a scientist. In a study (Charlesworth, 1989) of scientists working in a large biomedical institution there are descriptions of the types of social interactions which appear to be crucial to the success of work programmes. The social interaction between scientists is important (Mitroff, 1974): the reliability of scientific knowledge derives partly from the interactions between scientists. Researchers engage socially with other researchers and use a broad range of professional skills, perhaps signalled in the CSTI work by the strong emphasis on communication, in order to convince others of the reliability and usefulness of the work they have done and the conclusions they have reached. The North American National Academies of Sciences (NAS)

and Engineering (NAE) and the Institute of Medicine (IOM) describe in *On being a scientist* (1996) a social interaction amongst scientists - an unwritten code of conduct - which helps an idea or technique gain widespread approval. This works through journals, conferences, professional groups, exchanges of staff and other means of collaboration. A fuller description of this process, including descriptions of how individual scientists and scientific institutions develop reputations, is given in Scientific establishments and hierarchies (Elias et. al., 1982, p332 - 333).

Notwithstanding the CSTI survey, the view of science as an academic pursuit dominates the literature on scientific method. A perspective of science at work (in private and public service) is rare, it tends to be classified as technology. Professor Sir Herman Bondi (Physics World, 1996) writes of the popular misconception that:

*“denigrates technology and arises from the widely held view that technology is purely derivative and therefore trails science.”*

The academic view of science is sustained through university undergraduate courses. A senior manager of a large chemical research group explained why graduates joining companies often see themselves as specialist scientists until they begin to deal with company problems.

*The system doesn't really produce people who are well rounded in a variety of competencies, it produces fairly narrow people....but then you have to ask the question in 3 years or 4 years (of higher education), what spectrum of study could you really accommodate. We've got it down to individual subjects like chemistry or maths or physics or chemical engineering.*

**Senior Manager, large chemical research group**

The benefits of a union between theory and practice was a common theme in the interviews held with working scientists and is reported in chapter 6 - Findings.

### **Vocational qualifications**

One way in which it possible to gain an insight into the tasks that scientists do is to look at the requirements of competence-based qualifications such as National Vocational Qualifications (NVQs). These qualifications recognise competence in specific work practices. People are assessed as they carry out their work. There have been some notable developments in this area (for example the NVQs in Laboratory Operations and published by the Chemical Industries Association and the Association of the British Pharmaceutical Industry) but as the CSTI report (1993) concluded comparatively few competence-based vocational qualifications existed during their study and very few were being developed for this domain. The few NVQs that are available include job requirements in fine detail. The

recently published Laboratory And Associated Technical Standards Initiative (LAATSI) describes standards for laboratory workers in the chemical and pharmaceutical industries. It is a good example of the level of detail which NVQs can provide. A sample of the LAATSI standards is given at Annex B. The value of these standards is that they have been developed with the agreement of a wide range of companies that employ technicians. Representatives from these organisations have considered the work of technicians within their company (actual and desirable) and then discussed practical and assessable ways of describing their requirements.

### **Descriptions of scientific posts**

Science-based organisations produce and disseminate literature for public use describing the work the organisation carries out. Science posts within organisations often carry job descriptions but these are generally not publicly available. Analysis of this documentation can provide insights into the work of scientists.

Most of the literature from organisations is promotional in nature, the products and services on offer are described. Sixteen booklets, mostly from private companies were made available for this study during research visits. The organisations were generally large and the international nature of scientific work is clear from most booklets. Legal aspects of work such as regulated procedures and meeting industry, national and international standards were prominent in many booklets. This reflects a significant change in working practice over recent years. The importance of scientific research is indicated in many booklets through the highly specialised description of different projects, each project being assigned an expert manager. The economic imperative to deliver an outcome is a key objective in the booklets from private companies: the point is made through descriptions of past projects and the analysis of the costs of investment in (long term) research.

The job descriptions are more helpful than the general literature from the viewpoint of trying to determine the features of scientific work. Job descriptions were made available to this research study on a confidential basis. Job descriptions at all levels were made up of the following requirements.

- Formal qualifications required such as A levels, HNC/HNDs, degrees, doctorates
- Minimum work experience required, in terms of time served in specified work areas
- Job specific skills and knowledge. This is usually specified in detail in scientific terms. Practical skills are often required but not specified. Number skills, IT skills communication skills and safety awareness are identified.
- General competencies or abilities includes such things as information seeking, results orientation, analytical thinking and thoroughness.

One large company set out its requirements for trainee scientists (entering with a level 3 qualification) as follows.

- A genuine interest in science
- A determination to succeed
- An alert inquiring mind
- Initiative and adaptability
- An ability to work quickly and accurately
- Good communication skills
- The ability to work successfully in a team

This is typical of the qualities companies seek at this level.

In contrast to the NVQ specifications, the examples above indicate the lack of specificity with which jobs are described. This could be explained by a lack of certainty or stability in the actual work, or the dominance of general qualities over science specific requirements. I discuss this issue in chapter 8.

Looking to literature from organisations to describe the work of scientists does not yield the detail required to develop a useful description. However it does provide a perspective on the priorities for general qualities/abilities which are valued in new recruits. We now turn to the research concerned with the scientist as a professional. It has proven possible to gain some insights into what scientists do through study of more general research into the work of the professions.

### **The scientific professions**

Most accounts of the ideology of professionalism follow a functionalist approach and give primacy of place to specialist knowledge (Eraut, 1994). This would certainly be true of the science profession. The titles of the scientific professional bodies indicate the primacy of the knowledge-base; this is illustrated by the short list of names of such bodies which follows. As one reads down the list the focus becomes more specific in terms of the knowledge-base itself or the jobs which draw on a specific aspect of the knowledge-base.

The Royal Society  
Foundation for Science & Technology  
The Geological Society  
Institute of Biomedical Science  
The Institution of Chemical Engineers  
Biological Engineering Society  
Royal Pharmaceutical Society  
Institute of Brewing

The Biochemical Society  
Institute of Biology  
Royal Society of Chemistry  
Institute of Physics  
Institute of Electrical Engineers  
Institute of Animal Technicians  
British Pharmacological Society  
Society for General Microbiology

Many of these bodies have codes of professional behaviour for their members which include specifications of levels of specialist (propositional) knowledge. This is a broader view of professional behaviour which encompasses specialist propositional knowledge and extends to knowledge of how the system works for scientists, for example a knowledge of reliable sources of secondary data, of established practices for practical laboratory work and of ways in which results are processed and communicated. I have taken this perspective of professional knowledge when framing the questions and prompts for use in the interviews which are part of this research study. It is important that professional knowledge is taken into account since a significant number of professional educators may not have experience of working within a broader commercial enterprise and will be more familiar with propositional knowledge than knowledge of practice. For this reason and others, there may be a danger that propositional knowledge could be given disproportionate emphasis in the preparation of professionals.

The professional knowledge of a scientific worker can be considered to be made up of two aspects - personal knowledge and public knowledge. To use Eraut's definitions of these terms:

*a personal knowledge-base includes notes and memories of cases and problems which have been encountered, reflected upon and theorised to varying extents and with varying significance for current practice;*

*a public knowledge of which the worker has cognisance will be an individual selection from a much larger public knowledge-base, influenced by public knowledge encountered during professional education and independent reading, by personal interest and experience, and by social interchange with fellow professionals.*

**Eraut, 1994, p 17**

These two types of knowledge are important in defining what scientists do. By seeking feedback on both sets of knowledge in the context of work reported in this thesis it will be possible to filter out redundant public knowledge and concentrate on that which is used more frequently. This type of knowledge - a synthesis of forms of knowledge through use - is sometimes termed *action* knowledge. Scientists usually work under pressure and action knowledge usually dominates practice. Scientists only need to go beyond the domain of action knowledge when they come across new and difficult problems in different contexts to those they normally encounter.

A more common distinction between types of professional knowledge is that between propositional knowledge (knowledge of facts, principles, and theories)<sup>4</sup> and knowledge of the processes by which professional work progresses. The latter is often referred to as process knowledge (Ryle, 1949). In education propositional knowledge can dominate and obliterate process knowledge if scientific process knowledge is not well-defined (Gott, 1996). The relatively weak definition of important process knowledge can leave educators unsure in their planning and assessment. Yet knowing how to conduct scientific processes as part of professional practice is critical (Sparkes, 1994; CSTI, 1993). Eraut (1994) lists five kinds of process knowledge for professions. To each I have added notes specific to science.

i) Acquiring information. *This is dependent on how a scientist sees the problem, what they already know, the scientific tests and experiments they can envisage as being useful in gaining more information, the skills they have in those procedures and how good they are at interpreting their raw data.*

ii) Skilled behaviour. *This can be defined as a complex sequence of actions in carrying out tests and experiments which has become so routine through practice and experience that it is performed almost automatically.*

iii) Deliberative processes. *These are the ways the scientist manoeuvres through uncertainty of evidence to a considered conclusion; even in science things are not often definitive. The processes will include using information in planning, problem solving, analysing and decision making.*

iv) Giving information. *This will depend on the scientists' oral and written skills as well as what they know and what they think their client (scientist or non-scientist) needs to know or wants to know.*

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<sup>4</sup> Until now this category of knowledge has been called scientific propositional knowledge. In chapter 4 a potentially more transparent term "knowledge of explanatory concepts" is proposed and used in succeeding chapters.



v) Metaprocesses for directing and controlling own behaviour. *This is project management for a scientist. It involves awareness of how to optimise resources and a knowledge of the degree to which an action has been a relative success or a relative failure.*

All of these aspects of process knowledge could have key roles in scientific professional behaviour and they demonstrate the importance of taking a very broad view of what constitutes knowledge in a study of scientific capability. It follows that the study of scientists' professional knowledge reported in this thesis needs to be based on both public knowledge and personal knowledge and should include process knowledge as well as scientific propositional knowledge.

One particularly well-researched field is the practice of medicine. We can learn something of scientists as professionals from some studies of clinical practice.

### **The work of physicians**

The medical profession has been studied in depth by researchers seeking to define the key characteristics in physicians. Analyses such as that of Norman (1985) are particularly relevant to the work described in this thesis. Physicians have a mainly scientific training and much of their work is generally regarded as scientific. Norman concluded that the work of physicians has five aspects, which embrace propositional and process knowledge.

- **Clinical skills:** the ability to acquire information and interpret its significance.
- **Knowledge and understanding:** the ability to remember relevant knowledge about clinical conditions.
- **Interpersonal attributes:** the expression of personal and professional character.
- **Problem solving and clinical judgement:** The application of clinical skills, knowledge and interpersonal skills in the diagnosis, investigation and management of a clinical problem.
- **Technical skills:** the ability to use special procedures and techniques in investigation and management of clinical problems.

This categorisation is particularly useful since it describes a broad view of the work of physicians similar in scope to that attempted in this thesis. I return to this evidence in the discussion of the outcomes of this research study (Chapter 7 p127).

### **The development of professional behaviour**

Scientists progress in their competence and learn how to become better in their work. There have been many studies of how people in professions progress generally. A useful model was designed by the Dreyfus brothers (1986). They defined 5 stages from novice to expert. The descriptions of the characteristics of each stage have been shown to be helpful in, for example, how nurses develop in their professionalism. There are some aspects of the Dreyfus model which may be of particular interest in studying the work of scientists.

There are three main dimensions of professional practice which the Dreyfus brothers believe develop over time. The first is the dependence on rules and protocols. The novice needs a framework, the expert works independently of such frameworks, possibly because they have become internalised or, more likely with an expert, because specific rules and protocols are in fact being established through their work. A second aspect of progression is the extent to which the scientist sees what they are doing as context specific. The expert has probably seen work applied to many contexts and has internalised the types of variables that matter. This means the expert shows a deep internalisation of the general procedure and the application to a specific situation comes easily and naturally. This leads to a third dimension of development - the way the scientist sees a project. In the novice the vision is one of parts which (mysteriously or possibly vaguely) come together as a project. Each part is essential for the whole project but no aspect can be understood as more or less important than others. The expert has some general rules which allows a whole project to be manipulated. Action on one part will be understood to have consequences elsewhere. At its peak this awareness allows the scientist to have a deep and sensitive overview, a vision, of the project and its implications. These three dimensions, the rules and procedures, the situational and the vision of the whole could be used to analyse the work of scientists at different levels of employment.

### **Models for describing scientific practice**

All of the research reported so far could serve as a framework for analysing the data gathered as part of this research; it would be possible to use each one the descriptions, or indeed a combination of different models, a hybrid model. Whilst using established models would be helpful in judging the validity of any conclusions reached in this study, it could have a formative influence on the outcomes of the research. Therefore I have used the models described above to evaluate the generalisations arising from this research study rather than to explicitly structure the analysis of data.

In this chapter we have seen that breaking down science into disciplines is not a useful way to consider the question "how do scientists work?". A more helpful system is to generalise from the activities scientists engage in. The concept of professional knowledge may be useful and this will include propositional knowledge and process knowledge. We have seen that the latter can take many forms which might be useful in evaluating the generalisations which emerge from the data gathered through interview.

Having reviewed some of the theoretical and empirical perspectives on scientific work it is appropriate to examine the setting for such work. The economic and social influence on work in businesses has an impact on investment (in projects, laboratories and equipment), work practices, time-scales, staffing levels and staff expertise. It is therefore a dimension that needs to be reviewed. This is the focus of the next chapter.

## Chapter 3: Scientists in the economy

Before the scientific requirements of employment are discussed in detail it is necessary to consider the context of working in a science-based private or public organisation. In this chapter I review the potential influences on career prospects for scientists, the numbers of scientists needed and quality of recruits to scientific jobs. All of these can have a bearing on the ways people work on scientific tasks.

### Careers in science

In the UK there are four trade unions<sup>5</sup> which have a significant membership drawn from people who work in science-based organisations. In a recent review of careers in science these four unions published a joint report (Science Alliance, 1996) which describes the UK Research and Development (R&D) employment market as one which is characterised by:

- job insecurity (of contract researchers);
- relatively low pay (within the UK and particularly so outside);
- dependence on short-term funding (mainly from Government);
- fragmentation (due to the above and poor career structure);
- poor transfer from pure to applied science (good on ideas - weak on enterprise to develop them).

A personnel officer (interviewed as part of this research study) stated there were now fewer applicants for research posts; he concluded:

*....so I think that's part and parcel of the downtrend in science, people are getting out because there's no decent career structure, no tenure, the salaries are poor and you've got to move so much because of short-term contracts...*

**Personnel Officer, large research institute**

A House of Lords Select Committee report, Academic Research Careers for Graduate Scientists, (1993) and the Cabinet Office, OPSS and OST paper Forward Look - Government-funded Science, Engineering and Technology, (1995a) confirms these observations. Whilst the UK is top of a table of countries in terms of science graduates per 100,000 persons (aged 25 -34) in the labour force (OECD, 1995) it is also near the bottom of a table of countries in terms of the percentage of workers (aged 35 - 54) employed as professional scientists<sup>6</sup>. The UK does not entice its science graduates into science-based

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<sup>5</sup> These are: The Association of University Teachers (AUT), the Institution of Professional Managers and Specialists (IPMS), the National Association of Teachers in further and Higher Education (NATFHE), and Manufacturing Science Finance (MSF).

<sup>6</sup> The difference in age range is probably not significant since it is the number of job positions which is being compared.

employment as efficiently as many other countries. A conclusion that could be made is that the UK does not fund its R&D as well as it might. This situation is likely to constrain scientific workers in terms of long term planning of projects and careers, the availability of non-specific funding, and weaker support (technicians and equipment) for project staff.

There is however a different perspective on the way science R&D is working. This suggests contract scientists will be the norm in the business climate of the future. The UK Government in its White Paper entitled Competitiveness - Forging Ahead, (HMSO, 1995) described the many influences on business practices and how they might change to make the UK economy thrive in an increasingly competitive and deregulated world market. These influences include more flexible approaches to employment to which companies operating in the world market had already responded.

### **Changes in the way organisations work**

There have been many projections about the ways in which businesses will change in the future. Some projections specific to technical businesses which come from significant sources follow in this chapter but a good general description of the way business is changing can be found in A Learning Nation, (CIHE, 1996, p1). Whilst there may be differences in how major employers see the future, they all share the view that change will continue into the 21st century and that the pace will quicken. The forces behind business change include opportunities offered by information technology, the need to be more responsive to customers and the need to secure wider, international markets.

The Industrial Research and Development Advisory Committee of the European Union summarised the changes in job patterns in their report Quality and Relevance (IRDAC, 1994). The committee pinpointed the likelihood of an increasing number of broader project type tasks often with a multidisciplinary dimension. This will require flexible and changing employment with higher levels of teamwork. The work will be increasingly dependent on information technology. The committee believe that the key qualities of workers will need to be intellectual and abstract in nature, requiring speedier perception, reaction and intelligent coordination.

The Ford Motor Company have responded to the new business environment (Ford, 1996) and in particular the power and potential of high technology by operating a flatter management structure with empowerment of staff at local level. They have reduced their work force dramatically in the last 10 years. The use of high technology requires that they put greater emphasis on the quality of staff inputs, needing proportionately more high level thinkers. To do this they have improved the staff selection processes, employed more women (particularly able women not in employment because they were raising young

children), and begun to develop the concept of a worker willing to adapt and learn through a commitment to lifelong learning.

Hoechst, a German company operating across the World, described (in Table 2) how research has changed over the last few years.

**Table 2: Changes in research in recent years**

1970's	1990's
• researcher centred ( personal and specialised)	• researcher able to work in a multi-disciplinary team
• national research	• international research
• less competition	• more competition
• long product life cycles	• short product life cycles
• economy only	• economy and ecology
• less bureaucracy	• more bureaucracy

Hoechst (1995) - private communication

Scientific research in universities has also changed. The use of IT networks has accelerated team working. Collaboration with businesses is being encouraged and made a key factor for public funding<sup>7</sup> The aim of the Government funded Technology Foresight scheme (Office for Science and Technology, 1995) is to give a more economic focus to areas of research.

The research review carried out by Parsons and Marshall (1996) confirmed these examples as more general and not applying to only technical areas. They reported reduced functional fragmentation, a merging of traditional functions and increasing cross-functional collaboration. They also reported a general upskilling in many jobs and new mixes of skills (multiskilling) across functions and across academic levels.

These findings signal a deep change in the way business operates today. Other changes such as the dramatic increase in the number of people working to short-term contracts (40% of full time and secure self employed, 30% casual and part-time, 30% unemployed or on non-survival wages), the increase in output related pay, the expansion of consultancy and teleworking with the consequent development of a smaller number of "core" staff (centrally employed, full-time, permanent administrative and strategic managers) further illustrates how companies are adapting to the business environment.

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<sup>7</sup>For example, the UK Government LINK scheme which encourages collaborations between industry and the science research base in over 30 priority areas of research.

People who use science in their work are affected by all these changes. Lovering, in a study of social processes determining the development of the European scientific labour market (1995), writes

*The relative insulation of the scientific labour market is coming to an end... employers are looking for a wider range of skills and abilities. They are increasingly concerned to secure recruits with the ability to work in teams, the discipline to work to time horizons and 'milestones', the social skills required to communicate research issues to customers/clients and marketing skills. These amount to a historic shift in the character of British scientific workers, the demise of the boffin.*

**Lovering, 1995, p10**

### **The importance of the scientist**

Many countries have shown interest in monitoring and improving the number of scientists in training. The focus is usually on the number of science, technology and mathematics graduates in universities. Recently in the UK the focus has fallen on 16 -19 year olds since a proportion of the places in the university system have remained unfilled (Dearing, 1996).

The number of people working in science and technology is critical to the future economic prospects of a country. There are many endorsements of this view, for example in the UK the Competitiveness White Papers (HMSO, 1995 and 1996), and Dearing's Review of 16 to 19 Education and Training (1996), where he had consultations with employers. The Labour Party statement on education and training (Labour party, 1997) includes reference to the serious implications of the 40% fall in the number of students electing to study science and mathematics in the UK since 1983. In the European Union, the Industrial Research and Development Advisory Committee of the European Communities (1991) has written of the economic importance of sound training in science and technology. From further afield in India (Jain, 1997) and in Africa (Tiagha, 1997), commentators confirm that economic progress is dependent on critical skills and competencies which centre on the scientific and technical. Major companies are conscious of the critical nature of recruitment of able people into science and technology:

*As a company we are concerned about the declining interest in Science, Maths and Technology subjects in schools.*

**British Steel plc in its evidence to Dearing, 1996**

### How many scientists are needed?

Extrapolations from figures in the Quarterly Labour Force Survey produces estimates of the number of people employed in the UK as scientists, technologists or mathematicians (ST&M). Using the three CSTI categorisations (see Chapter note A) of:

- i) people who are employed in ST&M as their *main* function;
- ii) people who use ST&M as a *critical* part of their job; and
- iii) people who's jobs are *enhanced* by use of ST&M;

we can compare 1992 figures with those of 1996 (see Table 3).

**Table 3: The number of scientists, technologists and mathematicians in the UK**

Level of ST&M	1992 (1000's)	1996 <sup>8</sup> (1000's)
Main	598	677
Critical	1747	2014
Enhanced	972	1051

Quarterly Labour Force Surveys, 1992, 1996

The figures show a trend towards a greater focus on scientific, technological and mathematical in jobs. This might be expected as computer controlled machines carry out routine operations and displace manual work. Technicians are needed to design, make, install and maintain such machines. Another factor which might contribute to the increase is the need to use technological equipment in more and more jobs - this requires training. As reported earlier, the motor manufacturers Ford have had a policy which builds on the premise that to compete effectively it needs to require higher level skills in its employees and proportionately less routine work. If replicated across other companies, the Ford policy of recruitment and training of ST&M trained people and the training of other key workers in ST&M skills, would account for the trends shown in Table 3.

### Quality of recruits to science jobs

Recruiting students into an area where there is a decline in interest produces tensions, especially for the professional bodies. How far should standards of entry be lowered to enable universities to recruit reasonable numbers of students to keep courses viable? The UK has seen a prolonged and serious downturn in interest in physics which has resulted in the closing of university departments. In the case of physics the quality of those people choosing to do physics is still very high despite there being fewer of them. In other areas questions have been raised about quality of intake. Mathematics (and/or numeracy) standards are continuing to fall according to many recruiters and analysts (for example the

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<sup>8</sup> Some estimation is necessary in calculating these figures. The methods used for the Spring Quarter of 1996 are consistent with those used in the CSTI report.

Joint Mathematical Council, 1997). This was a common complaint from those participating in this research.

*One of the major basics is numeracy and I must admit that I am somewhat concerned with the quality of maths that some of these young guys are coming into the lab with, you take away a calculator and they can't do simple maths.*

**Personnel officer, major public research organisation**

The Engineering Council has published a report (Sutherland R. and Pozzi S., 1995) on some research into mathematics in higher education engineering courses. Over half the higher education tutors interviewed said that the weak mathematical background of students was undermining the quality of their courses. Those interviewed confirmed a lowering of entrance requirements and identified increasing specific weakness in areas such as algebra, trigonometry, differential calculus and integration.

Neville Reed, as education officer for the Royal Society of Chemistry speaking at an International education-industry conference (Chemical Industries Education Centre, p88, 1995) was well aware of the issue of quality:

*The shortage of chemists is illusory - the real issue is quality, not quantity. We need to raise the quality of students and teaching to produce chemists with greater skills in team-working, communication and problem solving.*

In a report commissioned by the Laboratory of the Government Chemist (Murray, 1993) into the supply of analytical chemists there was criticism of the preparation of the graduate entry into chemistry jobs. There is concern about quality at the doctorate level too. The RSC report The chemistry Ph.D. - the enhancement of its quality, (RSC, 1995) includes reference to the poor quality of some doctoral graduates. Connor H. et.al., (1994) confirm this and go on to report that the key concern of employers is the need for better interpersonal skills training and increased business awareness. Employers believe formal training has squeezed creative thought, recruits are sought who have breadth of view.

One of the factors controlling the quality of scientific recruits is the numbers and abilities of young students opting to study science in schools and follow science as a career.

#### **Factors affecting the choice of science as a career**

There are many factors which influence a student's choice of science, technology or mathematics as a career. These are analysed in detail in a review of research in this area



undertaken by a team from King's College, London<sup>9</sup> (Osborne, 1997). In summary they found that (for science) the significant factor affecting choice over the long term was likely to be the quality of the teaching and learning of science in schools, and especially the teaching and learning of physics. The research team proposed (for England, Wales and Northern Ireland<sup>10</sup>):

- a less theoretical curriculum which allowed more time to be spent on relevant applications and issues which arise in science;
- further research into which aspects of teaching motivate students (especially girls);
- more teaching by teachers who are science specialists and have enthusiasm for their subject;
- easing of the difficulty of science studies relative to other subjects;
- broadening the range of subjects which can be taken after age 16.

People training to become scientists or technologists assume they require specialist education and training. This is in contrast to other areas of employment where a general education to degree level is seen as at least sufficient and probably advantageous, for example in post-graduate law degrees.

Over the last ten years there has been a dramatic increase in the number of students who study a mix of science and arts subjects at advanced level. In 1988/89 the proportion of students following mixed programmes i.e. a science or maths subject studied with an arts or humanities subject, was 33.2%. Five years later this figure had risen to 37.9%<sup>11</sup>. These students are choosing a broad curriculum and keeping their career options open. On applying for a higher education place to study a science based course such as engineering or medicine they can find the breadth of their studies has put them at a disadvantage to students who have specialised in the sciences and mathematics. This is an interesting point since one prestigious UK university department has found a strong correlation between good degree outcome and the grade a student achieved in their third A level, which was often not scientific.

There is also a sense that once students are in training for a scientific or technical career they are disqualified from jobs not requiring a scientific training (see Chapter note B). This may deter some students from entering scientific and technical careers because many might feel they have to make a large, long term commitment to science technology.

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<sup>9</sup> The research was carried out on behalf of the Association of Science Education, The Schools Assessment and Curriculum Authority and the National Council for Vocational Qualifications.

<sup>10</sup> The recruitment of students into science subjects in Scotland is less problematic.

<sup>11</sup> National Council for Education and Training Targets (NACETT), Report on progress towards national targets, 1995

### **Do qualifications really matter?**

In a study across 17 countries Oxenham (1985) reported that educational qualifications were not the primary factor in determining the person needed for a particular job. Often a salary level is specified and based on an internal scale. The qualification level of applicants becomes a response to the salary offered. Oxenham goes on to report that in the early 1980s the bulk of employers did not have any well tested means of relating job requirements to educational qualifications; determining educational requirements was particular to each employer. A study of British employers by a team from Brunel University in 1984 concluded that there was no such thing as an employer's view of their requirements of education (Kogan, 1984). Oxenham comes to the same conclusion and suggests employers will always find ways of testing for what they want and it is best for schools and colleges to 'get on with good education'. In the UK things have changed since the mid 1980s. We now have well-tested means of securing knowledge about what employers want from education. For example through employer organisations like the Confederation of British Industry, employer (Lead) bodies for occupational areas and through focused research such as the Fitness for Purpose study (Coles and Matthews, 1996). The need for changes in work practices has also encouraged employers to contribute to the debate about effective educational practice.

Employers recruiting scientists have to deal with the shortage of science graduates and the quality issue at the same time. They have to strike a balance. Companies are engaging in recruitment procedures more systematically than previously and many are developing training programmes which compensate for quality shortfall (Zeneca, 1993). Some companies have made it clear that relevant work experience is required for certain jobs. In this way they are recruiting from a bigger pool of people (those leaving education and those in their first job). For some years companies have been improving their communications systems with schools and colleges (leaflets, posters, careers fairs, schools liaison officers, industry-education links initiatives) in order to create clarity about what they expect of recruits to scientific jobs.

### **What of the future?**

With the exception of people carrying out some fairly low-level routine services in testing laboratories, scientists are well-trained intelligent people, operating with significant responsibilities for equipment, peoples' time, and the financial investment of others. In Robert Reich's (1991) analysis of the economics of the next century, jobs can be classified into three types

- routine production services
- in-person services
- symbolic-analytic services

The last category will encompass the work of scientists working at higher levels (usually graduate work). It is a category which is expanding and being more highly rewarded (relatively) as the 20th century closes. These people are brain workers, analysts, decision makers who find themselves operating, often through electronic communication, across the world. These *symbolic-analysts* are useful in law, in systems analysis and in finance. Science offers scope for developing abstract constructs and developing the attributes of a symbolic-analytic thinker. How many trained scientists - perhaps the best in their fields - be left to do science? If Reich is right and these people are in short supply, the quantity and perhaps the quality of scientists at work may decline.

We have seen that scientists are vulnerable to economic pressures. Changes in business organisations have had a direct effect on the work practices of individual scientists. Whilst technology may push up the demand for highly trained scientists there are doubts about the quality of current recruits into science and technology work.

Having considered the evidence about the broad setting for scientists work in the next chapter I build on this with a more detailed analysis of evidence about the knowledge and skills scientists need.

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## **Chapter notes**

**A** The three functional categories which can be used to assess the role of the scientific, mathematical and technological in a person's work are as follows.

The **MAIN** function of the work is scientific, technological or mathematical - the person is at the leading edge of their field.

A **CRITICAL** function of the work is scientific, technological or mathematical - it is not the only function of the person in the job, nor is it the main function but without the scientific, mathematical or technological occupational competence would be in doubt.

The work is **ENHANCED** by the scientific, mathematical or technological - performance of a competent person is aided by scientific, mathematical or technological knowledge, understanding or practical competence.

**B** The notion that a scientific training is a firm requirement for scientific work, and that those undertaking such training are disqualified from other non scientific jobs, was

expressed by a large group (24) of undergraduates on science degree courses. The group was convened as part of research conducted by the School Curriculum and Assessment Authority and the National Council for Vocational Qualifications. The students involved advised that younger students should be told that opting for a science based training would not preclude them from choosing non-science careers later (after graduating) as so many do. The report of this work is not published.

## Chapter 4: Knowledge and skills

What is it that scientists know and can do? In this chapter I report research evidence from major organisations about the knowledge and skills used by scientists.

Although the view of a working scientist as a laboratory-bound lone male conducting unique earth shattering experiments is hopelessly stereotypical, many people have no awareness of how scientists really work. In fact it is almost always a very broad function. The American National Academy of Sciences confirm this multifaceted nature of scientific work in their publication On being a scientist, (NAS et. al., 1996). They describe how scientific researchers...

*collect and analyse data, develop hypotheses, replicate and extend earlier work, communicate their work with others, review and critique the results of their peers, train and supervise associates and students, and otherwise engage in the life of the scientific community.*

National Academy of Sciences, 1995, p3

The Royal Society of Chemistry, looking at scientific work a little more closely (RSC, 1992) describe analytical chemists as...

*Well organised, methodical, reliable, honest, able to follow instructions, questioning of what they are doing, able to spot problems, flexible, prepared to do repetitive work, able to accept the support role for other scientists, having pride in their work, able to think logically, show initiative, knowing when to ask for help, paying attention to detail, persevering, seeing an analysis through to conclusion, being adaptable, having good presentational skills, a critical approach to their work and the ability to work in a team and learn for themselves.*

Royal Society of Chemistry, 1992, p1

These extracts give a feel for the breadth of the knowledge and skills of scientists. These need to be classified into groups to facilitate logical discussion. I begin this chapter with a discussion of the general skills used by scientists since these are afforded high priority by analysts in this area of work and form a significant part of professional knowledge. I will go on to review knowledge and skills which is more obviously part of scientific work, beginning with knowledge of explanatory concepts and moving on to skills and techniques, the scientific approach to problems and finally knowledge of the context within which scientific work takes place. The discussion is based on statements of employers, researchers and other commentators in terms of the scientific knowledge and scientific skills needed by those who use science in their work.

### **General skills and attributes**

Writers use the terms 'skills', 'attributes' and 'attitudes' interchangeably. Is creativity a skill or an attribute? Is it an ability which has been developed and is developing (a skill), or something which is in-built into a person's character and seems unchanging (an attribute)? Writers also find many words to describe general skills, for example life skills, key skills, core skills, common skills. There may be some semantic differences in these phrases but for the purposes of this study they will be taken to mean the skills which are non-scientific which are often needed to be able to work with science at a range of levels.

### **Employers' views on general skills**

Large science-based organisations are well placed to provide a broad perspective on the desirable features of the education of people employed as scientists. In the UK the Chemical Industries Association (CIA) works with a large industry which generates about £4.4 billion annually in sales of its products. The CIA sees an attractive new recruit as:

- *having an understanding of the world of work;*
- *being able to work in teams;*
- *having the skills of*
  - *- communication;*
  - *- use of number;*
  - *- information technology;*
- *being flexible, innovative, creative;*
- *being able to solve problems;*
- *having broad based knowledge (e.g. science);*
- *having the ability to learn, develop and progress;*
- *having an understanding of the benefits of science.*

**CIA public statement, 1995**

The Association for the British Pharmaceutical Industry (ABPI, 1995) carried out a survey of its member companies about what they valued in the 16 - 19 phase of general education. The qualities valued in a job applicant were:

- *motivation;*
- *communication;*
- *writing skills;*
- *team working;*
- *intellectual skills;*
- *numeracy;*
- *analytical skills;*

- *problem solving;*
- *self confidence;*
- *creative thinking;*
- *study skills;*
- *business awareness.*

APBI survey report, 1996, p2

The Ford Motor Company has the following list of qualities sought at selection of staff:

- *intellectual;*
- *team working;*
- *problem solving;*
- *planning and organising;*
- *results orientation;*
- *business/political awareness;*
- *technical competence;*
- *professional integrity/ambition.*

Ford public statement, 1996

I have found that these lists are typical of many which state the requirements for science recruits to business and public services. It is not surprising that when asked about the characteristics of a good scientific worker (or student of science) that most experts point first to a set of general skills and attributes. One reason is simply the fact that they are general, it is easier to focus on something which is likely to be relevant to a wide audience when publishing a report on something which is quite specific. Science practice is not singular - scientists practice over a wide range of specialisms - to make statements in terms of specific knowledge and skills would leave most readers with a feeling this was too specific for them and therefore mostly irrelevant.

Another reason for stating general skills and attributes ahead of scientific knowledge and skills is that scientists may well take some of the most basic scientific aspects for granted. A microbiologist will often use a vague general term such as *underpinning knowledge* to cover the many facts, principles and procedures which are vital to the practice of microbiology. Coles and Matthews (1996) tested a methodology which was effective in eliciting more precisely the knowledge and skills specific to a type of scientific work. This work was designed to overcome the well-known problem of experts finding it difficult to state knowledge and skills that they use regularly and often take for granted. However the same study showed that general skills were often not identified simply because they were general. Employers and higher education tutors set great store by them.

### General skills and social practice

When any worker joins a new team to do science there is a lot to learn. In scientific practice there will be a need to know about the team's aims in terms of, for example, their current and previous research inquiries and in particular the team's successes, hopes and recent failings. The new entrant will need to become familiar with standard operating procedures, company policies on quality, the specialist interests of co-workers and many more things. It is a steep, and often exciting, learning curve. They will, in Lave and Wegner's (1991) terms, be engaging in *legitimate peripheral participation*. The new worker begins to participate in the community of practitioners and the development of their knowledge and skills moves them towards full participation in the socio-cultural practices of a community. Learning is geared to becoming a full participant in a socio-cultural practice. Lave and Wegner would claim that the socio-cultural practice is dominant and subsumes the specialist knowledge and understanding which is learned on the way. In other words, learning is an integral and inseparable part of social practice. For this legitimate peripheral practice to grow - and even an expert senior manager is in some senses peripheral at the start of their work - there needs to be some practice of strong general abilities, such as communication, adoption of team roles, problem solving, self management. In a sense work teams are always adapting and individuals are using general skills to enhance their learning and position within the team. Specialist knowledge and skills are being developed at the same time as these general competencies. This was summarised by a scientist interviewed in this study.

*If you have communication skills and you're able to use them then you'll ask the right questions and you'll make friends and you'll fit in and you'll be a so much better pleasure to supervise and everyone would get more out of it. For example, if I give someone something to do which they are not sure of, they won't get upset and try to avoid doing it, they'll say OK, but I'm not really sure about this bit; they'll know the reason why they're feeling a bit afraid of what I've asked them to do and they'll explore it.*

Senior scientist, pharmaceutical company

There has been much discussion (Spurling, 1993; CBI, 1994; Harvey et al., 1997; RSC/CIHE, 1998) of the poor general skills of new graduates. This may be particularly evident in science graduates because the predominant view of learning science in universities (and before) is based on cognitive structures which the learner must develop and use. This is constructed in isolation from practice through text, classroom interaction and theoretical application. Learning which is more focused on the features of social practice, where effective learning takes place using real work contexts and draws on the knowledge and skills (including general skills) of experts, is seen as a valuable function of work experience or 'sandwich'<sup>12</sup> year

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<sup>12</sup> Undergraduate students who work in a business or service for up to a year as part of their degree course.



placements in degree courses. Some of the scientists (interviewed in this research project) who supervise sandwich course students commented on the students' lack of general skills at the beginning of placement and later acknowledge the speedy learning of these skills. The students themselves claim the development of their general skills (such as writing reports and working in a team) as a major personal achievement during a work experience placement (see Chapter note A).

There is another more pragmatic reason why general skills feature so strongly. Many commentators believe that someone with strong general skills is likely to be more adaptable in a changing job market. The strength of these skills which might include time-management or problem solving, indicates that these people capable of learning about new work quickly and will be up-to-speed and productive with a minimum of training.

### **Important general skills**

We can now consider which skills are considered general skills. The review of what commentators have said about scientific capability has yielded a great deal of data about each skill. This is not reported in full here since this research is more concerned with *scientific* capability. However such is the importance attached to these skills that a summary is necessary to create a balanced view of what scientific work involves. In Table 4 on the next page the general skills are identified and a short commentary on each of them is provided. Authoritative sources (n =138) (including reports from the European Union, the UK Government, business organisations and agencies specialising in employment research) have been analysed and references to each of these skills logged. The skills are presented in order of the number of sources in which they are mentioned. These skills are not mutually exclusive, therefore care needs to be taken in assigning importance to a one skill over another simply because it is mentioned in more sources. For example good teamwork is sometimes taken to imply effective communication skills. Care should also be taken in using the rankings in the table because a mention in a document could be a significant review of the skill or simply a passing mention.

**Table 4: A summary of the range and importance of general skills**

Generic skill or attribute	No. of sources (max. = 138)	Observations
Communication	58	This is a broad field - Coles and Matthews (1996) identified 52 different types of communication identified by employers and higher education tutors. There are often comments from employers on poor levels of communication skills.
Team work	49	Everything which signals good team-working potential is highly valued (see management below). Seen as a weakness in science graduates
Mathematics including number skills	40	Critical for most scientific work. Concerns about weak algebra and the effect of calculators on feel for numbers, estimating etc. Particular worries over maths abilities of physics and engineering undergraduates.
Self motivation, commitment	36	See personal skills below. Training to degree level seen as indicator of commitment to subject area. Needed for person to learn, develop and progress. Ambition is valued.
Business awareness	33	Usually about adjusting to business environment (opportunities and constraints)
Information technology skills	32	Increasing dependence on IT in research and management
Adaptability and flexibility	26	Needed in teamwork and in work environment

**Table 4: continued**

<b>Generic skill or attribute</b>	<b>No. of sources (max. = 138)</b>	<b>Observations</b>
Management	23	Commonly project management, people (team) management and sometimes time management
Creativity	22	Linked to progress and gaining commercial advantages
Problem solving	21	Some would regard this as a scientific skill. Seen as a composite by many, may include the management of problems
Initiative	17	Often limited to managing one's own work programme. Other times about taking opportunities for development.
Leadership	16	Links with teamwork
Planning	15	Varies considerably between different types and levels of work
Legal awareness	12	Arising more frequently because of health and safety responsibilities but also because some areas are becoming subject to increasing regulation.
Personal effectiveness	10	Often used as an overarching phrase to cover communication, team working, time management.
Decision making	8	Some would regard this as a scientific skill. Good decisions based on evaluation of data is seen as crucial. A key skill in managers
Foreign language skills	7	Often rated as an advantage rather than crucial

This review of general skills has shown that they play a role in the work of scientists. There are a wide range of these skills which intersect with one another and, in different combinations, are likely to form a significant part of the repertoire of abilities which scientists need to do their jobs effectively. Having discussed these general skills I now turn to knowledge and skills which are more recognisable as scientific.

### Scientific knowledge and skills

Before discussing the nature of scientific knowledge and skills it is necessary to limit the meaning of these words through definition. This area is immensely complex. From the philosopher's perspective we can *know things* (by accepting that they can be proven to be true), we can *know how* to do things and we can *know about* contexts and situations.

Applying this categorisation in the field of science we have a body of *knowledge* of facts, principles, laws and theories. Scientists are particularly *skillful* (they have *know-how*) in carrying out procedures which have been constructed using these facts, principles, laws and theories. Equally we can *know of* the world of science, how people view it, how it is used and abused.

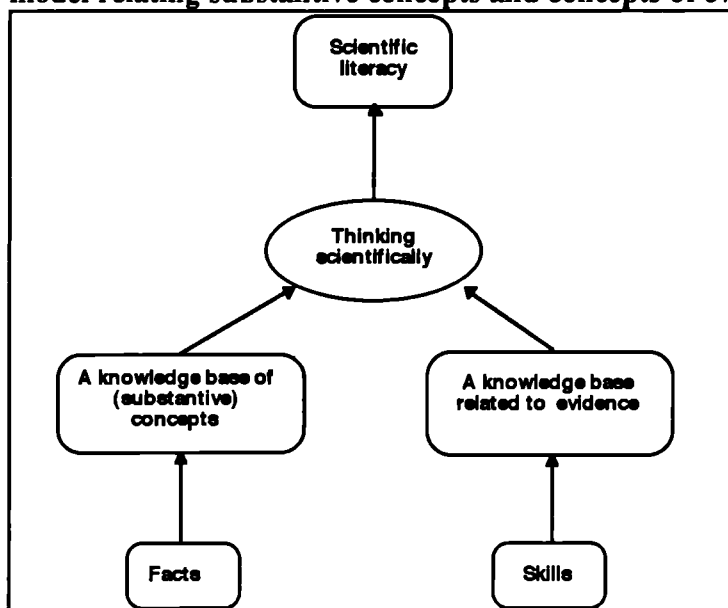
In the discussion which follows I will place limits on the interpretation of the word *knowledge*; it will be taken to refer to formal scientific facts, principles, laws and theories rather than any broader definition which might include knowledge of skills and procedures. To maintain clarity the phrase *knowledge of explanatory concepts* will be used when it is necessary to emphasise this narrower meaning of the word knowledge. The word *skill* will be taken to have a cognitive nature, a physical nature or to have both characteristics (see Chapter note B).

Gott and Duggan (1994) has attempted to clarify the relationship between knowledge, facts and skills in a different way. See Gott's model in chart 1. He has termed scientific principles, laws and theories as *substantive* concepts which has allowed him to go on to develop another field of knowledge which is concerned with the way evidence is generated, analysed, presented and used in science. Gott refers to this area of knowledge as *concepts of evidence*. Gott's *knowledge of substantive concepts* is similar in meaning to *knowledge of explanatory concepts* which is used in this thesis, but it differs significantly in two ways. Firstly the latter includes scientific facts and secondly it allows for the use of skills in using the substantive concepts in a purely theoretical way, that is without recourse to experiment or data<sup>13</sup>. As can be seen in chart 1, Gott draws experimental work and data into what he terms *thinking scientifically*.

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<sup>13</sup> These are clearly a set of skills used by high level (mainly theoretical) scientists.

**Chart 2: Gott's model relating substantive concepts and concepts of evidence**



Gott R. and Duggan S., 1996, p793

Gott goes on to elaborate the distinction between substantive concepts and concepts of evidence through use of taxonomy.

**Table 5: Comparison of taxonomies for substantive concepts and concepts of evidence**

Conceptual Taxonomy	A Taxonomy Linked To Evidence
Knowledge and recall of facts	Knowledge and recall of skills
Understanding of concepts	Understanding of concepts of evidence
Application of concepts (in unfamiliar situations)	Application of concepts of evidence (in unfamiliar situations)
Synthesis of concepts (in problem-solving)	Synthesis of skills and concepts of evidence (in problem-solving).

Gott R. and Duggan S., 1996, p797

Gott's approach is helpful in clarifying of the meaning of knowledge and skill. It shows, through the taxonomy linked to evidence, the complex interaction of skills and knowledge in performing tasks - yet it offers clarity in the distinction between the commonly accepted body of scientific knowledge (substantive knowledge), which is significant in science curricula, and knowledge associated with experiment and , which is often a small and ill-defined part of science curricula. This makes the model useful from the viewpoint of this

study - it offers a means to analyse the knowledge associated with experiment and data a little more closely.

In summary the following definitions will be used in this thesis.

**Knowledge (of explanatory concepts)** will include the commonly accepted body of scientific facts, principles, laws and theories. It will not include any knowledge of skills of using ideas, equipment or data.

**Skills** will include any physical process where any protocol is followed, where measurements and observations are made. It will also include the application of explanatory concepts to practical situations or synthesis brought about by linking one explanatory concept with another.

Further definitions of related ideas are included later in this chapter and in the glossary.

This definition of knowledge as limited to explanatory ideas does not help with the specification of knowledge scientists need. Employers in particular have not made specific statements about their knowledge requirements of scientists.

#### **Employers and the specification of skills and knowledge**

Specific scientific knowledge and skills rarely feature in public documents describing capabilities for technical work. Professional bodies sometimes publish accounts of general cores of knowledge and skills which are important (for example, Royal Society of Chemistry, 1991). More common is a process of professional body approval of syllabuses or training schemes which are produced independently of the professional body (for example Engineering Council accreditation of first degree courses). It has also proved difficult for researchers to ascertain employers requirements of the science education system in clear and specific terms<sup>14</sup>. Employers have expressed their requirements in general terms or they have produced specifications which include long, highly specific lists with no hint of priority.

There are many reasons why employers' requirements have been difficult to apply in education and training programmes. Employers are not a homogenous group. They all have different needs and priorities. Recognising this, they tend to take what the education and training systems provide and then supplement it with on-the-job training. They see this on-the-job training as effective, possibly because it will focus on *action* knowledge and therefore be more efficient in concentrating on what really matters from a company perspective. Some of the (on-the-job) training would be necessary regardless of the level of education of the

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<sup>14</sup> See Kogan 1984 and Oxenham 1988 for a fuller discussion of the problems. Both authors conclude that there is no consistent view from employers on what they want from education.

worker because the work carried out in a company is often highly specific. Some larger companies tend to establish links with educational institutions and achieve some of their requirements through 'compact' arrangements. This reduces the need for gaining wider (national) acceptance for what they see as important to them.

The specificity of work within companies can also obscure what it is that employers require from education and training programmes. In just the same way as Argyris and Schon (1974) recognised the difficulties of translating tacit knowledge into a more formal specification of knowledge, it seems possible that people who carry out routine tasks can lack the words (and possibly understanding) to describe what they do (Gott, 1997).

Even when a problem with education and training seems general and deep-seated many employers express a continuing respect for the professionals in the education and training system and do not generally wish to interfere with educational and training programmes. This may stem from employers' awareness of a wariness on the part of educationalists, particularly those involved with school education, to be too functional in the preparation of their students for work. The preparation of students for life beyond work is seen as the higher priority and can appear to employers as a blindness to the need for an equilibrium to be established between the broader needs of students and the needs related to effectiveness at work and employability more generally. The concerns of educationalists in this respect is summarised effectively by Sultana (1997, p55). In the UK, the Department for Education and Employment have begun a programme to increase awareness of teachers to the needs of employers (DfEE, 1996).

As part of a review of 16-19 education and training in England, Wales and Northern Ireland, Coles and Matthews (1996) devised a method of eliciting the components of (scientific) knowledge and skills which both employers and tutors in higher education considered essential in 16 - 19 education. It provided a means for employers and higher education tutors (n = 68) to describe what they considered important parts of science education. The project team analysed over 2000 distinct aspects of knowledge and skill covering the breadth of science and including general, technical and mathematical knowledge and skills. Table 5 summarises the knowledge and skills identified as essential by employers and tutors in higher education by grouping components under general headings. No attempt was made in the study to measure the priority associated with each aspect of knowledge and skill. All were judged to be essential to at least one type of scientific work. In the aggregation of the individual aspects of knowledge and skill no account was taken of the number of aspects under any one heading in Table 5. Hence Table 5 offers an opportunity to judge the scope of scientific work at this level rather than to conclude that one aspect is more important than another.

**Table 6: Topics considered important for 16 -19 science education by employers and tutors in higher education**

<b>Biology</b>	<b>chemistry</b>	<b>physics</b>
<ul style="list-style-type: none"> <li>• biological materials</li> <li>• biological structure</li> <li>• ecology</li> <li>• genetics</li> <li>• microbiology</li> <li>• osmosis</li> <li>• physiology</li> <li>• plant growth &amp; nutrition</li> <li>• social biology (inc. food supply)</li> </ul>	<ul style="list-style-type: none"> <li>• analytical chemistry</li> <li>• atomic structure and bonding</li> <li>• biochemistry</li> <li>• catalysts</li> <li>• chemical names</li> <li>• chemical properties</li> <li>• chemical reactions</li> <li>• environmental conservation</li> <li>• extraction of materials</li> <li>• physical chemistry (inc. solubility)</li> <li>• quantitative chemistry</li> <li>• structures of solids</li>   <li>• geology</li> </ul>	<ul style="list-style-type: none"> <li>• control</li> <li>• electricity</li> <li>• electronics</li> <li>• electrostatics</li> <li>• energy transfer</li> <li>• fields</li> <li>• fluid flow</li> <li>• forces and motion</li> <li>• kinetic theory</li> <li>• light and sound</li> <li>• materials</li> <li>• mechanics</li> <li>• network theory</li> <li>• physical properties</li> <li>• physics of measurement</li> <li>• properties of matter</li> <li>• quantum mechanics</li> <li>• radioactivity</li> <li>• structures</li> <li>• thermodynamics</li> <li>• waves</li> </ul>
<b>scientific method and practice</b>	<b>general skills</b>	<b>mathematics and numeracy</b>
<ul style="list-style-type: none"> <li>• fieldwork</li> <li>• measurements and observations</li> <li>• science in society</li> <li>• scientific method</li> <li>• techniques</li> <li>• health &amp; safety</li> </ul>	<ul style="list-style-type: none"> <li>• comprehension</li> <li>• cultural awareness</li> <li>• data skills</li> <li>• economic awareness</li> <li>• environment</li> <li>• ethics</li> <li>• evaluation</li> <li>• history of science</li> <li>• information handling</li> <li>• information technology</li> <li>• language (foreign)</li> <li>• oral communication</li> <li>• personal skills</li> <li>• phil. of science</li> <li>• planning</li> <li>• problem solving</li> <li>• social skills</li> <li>• social, economic and environmental issues,</li> <li>• standards</li> <li>• surveying</li> <li>• team working</li> <li>• written communication</li> </ul>	<ul style="list-style-type: none"> <li>• accuracy and precision</li> <li>• algebra</li> <li>• calculus</li> <li>• geometry</li> <li>• interpretation of relationships</li> <li>• logarithms</li> <li>• matrices</li> <li>• modeling</li> <li>• numeracy</li> <li>• presentation of relationships</li> <li>• statistics</li> <li>• trigonometry</li> <li>• units</li> <li>• vectors</li> </ul>



Coles and Matthews found that much of the current scientific content (facts and principles) of UK advanced science qualifications was relevant to employers and tutors in higher education. In terms of the science data analysed it is possible to identify a core of ideas which should be covered in advanced science qualifications. The match between the content of examination syllabuses (and courses based on them) and employer needs identified in the Coles and Matthews study indicates a general satisfaction with the content of qualifications for 16 to 19 year old students of science in the UK. There is potential in the methodology for extension to a wider analysis of scientific knowledge and skills required from science-based higher education courses. Indeed the approach has been extended and refined by Wake and Jervis (1997) so that it can be used to identify the mathematical and scientific aspects delivered by a range of technical qualifications.

The Coles and Matthews research identified two points of discord between some advanced science courses and the needs of employers and tutors in higher education. The first is that, in science examinations, employers and tutors in higher education, whilst generally satisfied with content, want practical capability and application of ideas to dominate these qualifications rather than simple recall of knowledge. This is a challenge to the specification of aims, assessment objectives and the means of assessment of many science courses. The second aspect of the discord is that the development of certain general skills needs to be more prominent in science courses at this level.

### **Underpinning knowledge**

Knowledge of scientific facts, principles and theories is clearly central to scientific activity. Indeed the use of such knowledge often allows an activity to be classified as science. Notwithstanding the fact that reports on science education from employers and their organisations rarely identify specific aspects of scientific propositional knowledge, when such reports call for propositional knowledge it is seen as a basic requirement, an underpinning to everything else - even as a context for the development of general skills, deliberative processes and meta-processes. Scientists themselves are often classified into types which are characterised by the area of science they work in (physicist, microbiologist, organic chemist). They are expert in the knowledge-base of their area and able to work with the different ideas in their specialism, make practicable plans to try out ideas and anticipate the outcome of planned (inter)actions.

Expert knowledge is also used in a different way by employers. It is sometimes treated as a 'proving' ground for people to show a genuine interest in an area - a student graduating in chemistry has shown a commitment and interest in chemistry which is likely to be continued in employment.

*Degree courses at universities are primarily intended to provide information, I think they are also intended to filter out people who aren't really interested in the subject, that is to say if you embark on a 3 year course in chemistry and survive that 3 years by being interested in the subject, it shows commitment and interest which will shape their career for the future....*

Senior manager, large private company

It is also a proving ground in another sense. Some of the sciences are regarded as intellectually challenging - a student successful in physics has shown a capability of deep thinking in a difficult area. Employers show confidence that such a student has the potential to show such deep thinking in another context.

### **The breadth of knowledge in education and training**

The knowledge-base of first degree courses is likely to encompass a broader range of knowledge than that which will be required at work. At the same time such courses are unlikely to be so specific that they deal with every area of science that employers are likely to be concerned with. Some knowledge will be directly relevant to the work itself (part of action knowledge), much of it will not. The new recruit may have a broad grasp of a subject area and relationships within it. Greater detail may become clearer and more important later as the recruit engages with research papers, the work of colleagues and pressing commercial or academic objectives. This was confirmed in a study by Harvey et. al., (1997) of the characteristics required of graduates entering employment across a range of disciplines.

*In essence employers expect a degree to provide a profound broad education rather than train someone for a specific job. In some cases particular knowledge and understanding of a subject area is a bonus as are specific technical skills.*

Harvey et. al., 1997, p2

There is support for education to do more than develop knowledge of explanatory concepts from the Royal Society of Chemistry. A report (RSC, 1995) on the chemistry Ph.D., concludes that studies can become too specialised and that students need to be more broadly familiar with their subject. The students need to pay more attention to the development of professional skills such as communication skills, oral skills (particularly non technical), writing skills, teamwork, and the ability to conduct independent research.

One area where a breadth of knowledge across the sciences is seen as important is environmental science (Court, Jagger and Moralee; 1995, Coles and Matthews, 1996). In the Court et al study interviews with 47 employers revealed that even Ph.D. students working in this field were not regarded as sufficiently knowledgeable about developments outside their field. Employers wanted people who could communicate with others working in different

specialisms. They needed people who were capable of linking knowledge across disciplines and who were able, as a result of the work, to develop multiple specialisms. Skill requirements of these employers varied a great deal but there was consistency in the need for mathematical, computing, data interpretation and modeling skills. The latter reflect the increasing emphasis on predictive work. Evidence from interviews conducted as part of the work reported in this thesis (see p116) suggests multidisciplinary work is on the increase. Several interviewees remarked on the need for cross-discipline awareness and suggested that the exciting areas of scientific development were often at the boundaries of traditional disciplines (e.g. biochemistry, genetics).

It seems a lot to expect of those in training to master the background knowledge to work across more than one discipline. The key to achieving this high level of capability seems to hinge on three factors. The first is a broad education in the sciences up to the appropriate pre-university standard (see Chapter note C). This is often a requirement of broad courses such as environmental science and health related degrees. The second factor is a degree level programme which starts as a broad study and gradually becomes more tightly focused - often with necessary post-graduate studies. A third factor is the need for work experience and on-the-job training. This is increasingly important in the preparation of students for technical occupations.

The centrality of a broad science knowledge-base has been recognised by agencies responsible for curricula and qualifications. In England, Wales and Northern Ireland the National Curriculum (DfEE/WO, 1995) is a good example of the importance attached to explanatory concepts. Atkin and Helms (1993) provide a summary of the centrality of knowledge in curricula in use across the world. It has also been recognised by employers, see Harvey et.al. (1997, p58). Part of the breadth described in these reports is derived from the inclusion of skills and techniques. I now move on to discuss this aspect of scientific ability.

### **Scientific skills and techniques**

The area of skills and techniques is bedevilled by not merely a lack of precise definition, but more seriously, by a whole variety of definitions which are implicit and at variance one with another. Industrialists are likely to use the terms in an attempt to describe the sort of creative, analytical and logical thinking that characterises the problem solver. Science teachers tend to view the terms as related to more basic practical attributes such as the use of a thermometer or the setting up of apparatus. Clearly there is a common thread here, but equally clearly there is more to the issue than either of these definitions allow.

The skills and techniques of science are considered in this thesis under three categories.

1) *Application and synthesis associated with explanatory concepts* - where ideas (facts, principles, laws, theories) about materials, devices and phenomena are interacted to synthesise new perspectives and ideas.

2) *Applying concepts of evidence* - the skills of setting up effective experiments such as developing hypotheses, ensuring practical processes yield reliable data, analysing such data to develop valid conclusions.

3) *Practical manipulations* which measure and create observations.

None of these categories can be divorced entirely from scientific facts, principles and theories. The careful construction of an hypothesis and analysis of evidence arising from, say, an artifact or an old document will be considered an *historical* process rather than scientific by many people. The link between these skills/techniques with scientific knowledge and the quest to create new, reliable scientific knowledge, makes them scientific in nature. Scientists can use all three categories as part of their work. Sparkes (1994) describes the technical ability of “know how” as a problem solving capability based on experience - a combination of knowledge, skills and intuition.

The first category of skill (*application and synthesis associated with explanatory concepts*) is inextricably linked to the scientific knowledge-base and has been considered earlier in this chapter; a discussion of the second and third categories follows.

### Applying concepts of evidence

*"The main skill of the working scientist is not the bench manipulation but in experimental design, in research strategy and tactics."*

Richard Whitely, 1984, p42

Considerable philosophical effort has been applied to the area of scientific method. Across civilisations philosophers have attempted to improve our methods of eliciting more and more reliable information through scientific means. But for present purposes a basic model of scientific work will suffice. This could take the form:

- making an observation;
- making a prediction/hypothesis;
- testing the prediction/hypothesis by;
  - identifying key variables
  - designing an experiment
  - observing objects and phenomena/measuring change

- analysing data;
- drawing conclusions;
- estimating reliability of results/validity of conclusions.

This process of scientific method becomes more complex when the role of imagination and creativity is considered. It would be further complicated by incorporating the various ways a scientist's ( team's) results and conclusions are verified and consolidated into the established scientific knowledge. A third complication can arise when technological processes are included. Nevertheless the six main features listed above are a useful starting point for the purposes of this research.

Atkin and Helms (1993), expressing an educational viewpoint, claim that practical reasoning is a prominent characteristic of human thought and action. Other educationalists, for example Gott and his research team at Durham University (Gott and Duggan, 1994), have argued that there is a basis of knowledge and understanding which underpins skills and problem solving. They reason that this type of underpinning knowledge needs to be defined and introduced explicitly into the curriculum otherwise it may fall "*between the cracks of a curriculum dominated by traditional science concepts*"<sup>15</sup>. Gott's team refer to this base in knowledge and understanding as 'procedural understanding'. They have attempted to define the underpinning knowledge required for procedural understanding. These "concepts of evidence" are summarised in Table 7 on the next page. In a research study of student performance in science investigations Millar et al, (1995) showed that the ideas which underpin the quality of empirical data have a positive influence on outcome of student investigations.

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<sup>15</sup> This quote from Gott and Duggan is included in a paper in press at the time of submission of this thesis.

**Table 7: Concepts of evidence and their definition**

<p><b>Associated with design</b></p> <p>variable identification</p> <p>fair test</p> <p>sample size</p> <p>variable types</p>	<p>Understanding the idea of a variable and identifying the relevant variable to change (the independent variable) and to measure, or assess if qualitative (the dependent variable).</p> <p>Understanding the structure of the fair test in terms of controlling the necessary variables and the importance that the control of variables has in relation to the validity of any resulting evidence.</p> <p>Understanding the significance of an appropriate sampling procedure to allow, for instance, for random or biological variation.</p> <p>Understanding the distinction between categoric, discrete, continuous and derived variables and how they link to different graph types. For example, a categoric independent variable, such as type of surface, cannot be displayed sensibly in a line graph. the behaviour of a continuous variable on the other hand is best shown in a line graph.</p>
<p><b>Associated with measurement</b></p> <p>relative scale</p> <p>range and interval</p> <p>choice of instrument</p> <p>repeatability</p> <p>accuracy</p>	<p>Understanding the need to choose sensible values for quantities so that resulting measurements of the dependent variable be meaningful. For instance, a large quantity chemical in a small quantity of water, causing saturation, will lead to difficulty in differentiating the dissolving times of different chemicals.</p> <p>Understanding the need to select a sensible range of values for the variables within the task so that the resulting line graph consists of values which are spread sufficiently widely and reasonably spaced out so that the 'whole' pattern can be seen; a suitable number of readings is therefore also subsumed this concept.</p> <p>Understanding the relationship between the choice of the instrument and the required scale, range, interval and accuracy.</p> <p>Understanding that the inherent variability in any physical measurement requires consideration of the need for repeats if necessary , to give reliable data.</p> <p>Understanding the appropriate degree of accuracy that required to provide reliable data which will allow a meaningful interpretation.</p>
<p><b>Associated with data handling</b></p> <p>tables</p> <p>graph types</p> <p>patterns</p> <p>multivariate data</p>	<p>Understanding that tables are more than ways of presenting data after it has been collected.. This can be used as ways of organising the design and subsequent data collection and analysis in advance of the whole experiment.</p> <p>Understanding that there is a close link between graphical representations and the type of variable they are to represent.</p> <p>Understanding that patterns represent the behaviour of the variables and that they can be seen in patterns in tables and graphs.</p> <p>Understanding the nature of multivariate data and how particular variables within those data can be held constant to discover the effect of one variable on another.</p>

Gott R. And Duggan S., 1994, p31

A key aspect of scientific skills and techniques is that of physical manipulation of materials and equipment.

### **Practical manipulation**

Most scientific work involves the observation of materials and systems under different conditions. Practical work is usually a critical part of scientific enquiry, as is care in design and reporting of practical procedures so that they might be replicated elsewhere. Also of critical importance is that the practical procedures used are carried out safely, correctly, consistently, observations made accurately, data recorded accurately and processing of the data conducted correctly. Even with well reported procedures there is a surprising amount of room for the introduction of variation through untrained practice.

Standard operating procedures (SOPs) - sometimes referred to as *protocols* - are critically important in many laboratories. They are also important (in research, analysis and production) because they eliminate inconsistency and encourage replicability. Some laboratory managers claim to be able to identify scientific workers who have aptitude for operating SOPs well.

It is surprising therefore that there is so little information from employers on practical manipulation. The Coles and Matthews study failed to elicit any detailed practical requirements from employers and higher education tutors (see Table 6, p41). The reasons for the paucity of information are similar to those which have been given for the poor specification of scientific knowledge (see p39). Employers may consider that the equipment and procedures they use in their work are so specific to their operation and sophisticated in nature that the practical skills required are best learned on-the-job.

A typical example of the general nature of requirements for practical skills comes from a job profile for a technician in a laboratory in a large chemical company.

*To be the custodian of specific scientific skills and knowledge and to apply them in order to provide data and information in support of agreed research programmes and projects.*

**Source: ICI job profile**

The use of practical techniques is implicit and not specific.

Employers are also aware that procedures are becoming more automated and instrumentation in laboratories is increasingly complex and versatile. This can mean that training programmes are required for existing staff as well as new recruits.

*We've recently acquired a couple of very fancy pieces of equipment, both on the (DNA) sequencing front. Some of the post-doctoral fellows have learnt the technique of using these machines, they help other people and develop protocols. They have become experts and trainers with that facility.*

**Research director, large public research institute**

Charlesworth (1989) noticed in his in-depth study of scientists at work that the equipment to which laboratory staff has access can drastically change the sort of work that can be done.

It is clear that practical manipulation is an important part of scientific work but it is rarely articulated as a job requirement in any detail.

### **Scientific 'habits of mind'**

Atkin and Helms (1993) identify developing certain 'habits of mind' as among the most important outcomes of science education. This educational thrust is supported by reports on scientific work (see below), and interviews with working scientists (see chapter 6) contain references to analytical thinking, logical thought, open mindedness and other scientific attributes such as aptitude for problem solving. The results of the employer surveys reported earlier in this chapter (CIA, ABPI, Ford UK) reveal a heavy weighting for intellectual/analytical/problem solving abilities. There is evidence that scientific training develops these abilities well. For example the Conference Board of Canada (an employer group) states one of the reasons why science education needs extra emphasis is because it develops *critical thinking skills - being logical - the ability to differentiate cause and effect*. A group of employers in the Wirral<sup>16</sup> identify the ability to listen, analyse and think critically as key characteristic of a good employee. This type of ability has been recognised in military training too.

*Diagnostic testing, problem solving and being able to see and solve a problem - I call these analytical skills. They can come across a vehicle and they can - either by hands on, or by thinking, or by looking and listening - analyse the situation. These people make good engineers.*

**Senior instructor, Mechanical Engineering School**

Some employers (see Harvey et. al. (1997), p3) have recognised a threat to the development of analytical thinking in students through broader, modular degree programmes. They appreciate the power of these broader courses to deliver more flexible and adaptable workers

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<sup>16</sup> The group of employers included this statement in their submission to the Dearing review of 16 - 19 Education and Training in England and Wales (Dearing, 1996)



but claim that such courses can be “*insufficiently academically rigorous, failing to provide critical, analytic and reflective thinkers*”.

Of course it is not possible to describe analytical thinking as solely a scientific skill and many non scientific jobs require such an ability. Michael Fowle - of management consultants KPMG<sup>17</sup> includes *analytical and proactive thinking* as one of the six key abilities for graduates entering any business. On a broader canvass still, Robert Reich (1991) in his analysis of work in USA, which was outlined earlier (p27), characterises symbolic analysts (which include scientists) as people who manipulate symbols - data, words, oral and visual representations - in their work. They are people who solve problems and engage in strategic brokering activities. It is interesting that Reich quickly dismisses the notion that symbolic analysts are professionals - at least in the sense that they are masters of a domain of knowledge - he pursues the notion that these analysts know how to get to the knowledge and use it.

The interaction of knowledge and skills, and having certain habits of mind does not represent the whole picture of scientific capability as it emerges from literature. As pointed out in chapter 3 the context in which people work is also significant.

### **Knowledge of the context of scientific work**

When employing organisations write about the context of scientific work they are usually point out the importance of business awareness. (Spurling, 1993; see the statements from the CIA, Ford and the ABPI on p31/32). Clearly scientists in most areas of work need to be aware of the costs of R&D and the economic impact of new processes and products. Another area which receives much attention is teamwork (see table 4 p35); the social dimension of scientists work will demand personal and interpersonal skills.

Much has been written of the relationship between science and society. By far the most significant of recent work is that of Kuhn (1970). Until Kuhn produced a model of scientific work which encompassed the social viewpoint, science was characterised as the epitome of positivism, an almost mechanical process which leads to incontestable and reliable knowledge. Human intervention was minimalised and facts were believed to be the basis of all knowledge constructs. Scientific reasoning was neutral in its interaction with values. Kuhn proposed that the scientific enterprise works within a commonly accepted framework. Scientists promote their work (and interpret their findings) so that acceptance by fellow scientists is more likely to follow. They compete with each other according to rules - the commonly accepted social scientific framework. Kuhn called this *normal science*. He proposed that occasionally a theory was propounded which challenges the accepted

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<sup>17</sup> Included in a presentation to a Council for Industry and Higher Education conference, Sept. 1997, Institute of Education, London

framework for scientific knowledge and work. If it was a powerful new theory, that is if it convinced the powerful scientists of the day, a *revolution* would take place. Scientists would use this new conception of science knowledge and work as the basis of a new form of *normal* science. Kuhn made it clear that personal, social and professional dispositions of scientists (and others) were part of the process of revolution and therefore of scientific advancement. Millar and Driver (1987) extended this notion (of science set in a social context) to the educational setting and suggested that every individual constructs meaning according to their experiences, a view which gains support from cognitive psychology (Resnick, 1987).

### **In summary**

In this review of the field of knowledge and skills which could provide insight into the work of scientists, we have seen how it is important to consider all aspects of professional knowledge - particularly general skills. The definition of scientific knowledge and skill emerges as an important tool in preparing for the fieldwork and in analysing the outcomes of fieldwork. Problems of identifying the requirements of employers in terms of scientific knowledge and skills have been highlighted. These problems must be overcome since knowledge is seen as critically important in most areas of scientific work. The scientific knowledge-base has to be supplemented with the thinking processes which draw on concepts of evidence, the skills of practical manipulation and certain 'habits of mind' if the area of scientific work is to be explored comprehensively. The important components of scientific knowledge and skills which emerge from the analysis in this chapter can be summarised as:

- General skills
- Knowledge of explanatory concepts
- Scientific Skills
  - application of explanatory concepts
  - concepts of evidence
  - manipulation of equipment
- Habits of mind
  - analytical thinking
- Knowledge of the context of scientific work (how scientific work progresses)

These components are complementary to the categorisation of the ways scientists work which emerged in chapter 2. The research and theoretical constructions outlined in chapters 2, 3 and 4 will be used to evaluate the model which I have developed from empirical data. This evaluation is reported in chapter 8.

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## **Chapter notes**

**A** Sandwich students proved to be a useful vehicle for focusing the attention of those interviewed in this study on the qualities needed in their work. The skills of these students and what they learned during their placement year was often a topic of discussion during the interview process. It was also possible to meet some sandwich students and talk with them as they carried out their work. A common theme of the discussions was the way the student became more aware of work practices and a maturing of attitude to work during the placement. Students regarded the placement as a very important part of their courses and many thought that their attitude to study would also be better on return to college.

Work in Leeds University, where students were given an extended research project in their final year, has also revealed a growth in general skills as a result of students working with research teams.

**B** The interaction between knowledge and skills is complex. Consider the discovery of an anomalous result by a technician after many “normal” routine measurements of, for example, pH. After the technician has concluded that he or she has not simply deviated from a protocol they may consider several questions - Is something different about the substrate? Is it changing? Is there a problem with the treatment of the substrate? Is there a problem with pH probe? Physical damage? Electronic fault? Does the meter need recalibrating? All these questions require a degree of knowledge, experience (of the processes) and skill in pinning down the problem.

**C** Research by Solomon (1997) into the science required in health and social care qualifications underlines the importance attached to underpinning knowledge of scientific explanatory concepts. She found that some tutors of health-related courses in higher education wanted to see a strong underpinning of basic science taught in schools and colleges. This they seemed to value more highly than the teaching of vocational material related to (health-based) occupations.

## Chapter 5: Methodology, structure and techniques

The fieldwork aspect of this research seeks to answer the question:

*what are the main features of the work of scientists?*

The question requires interaction with working scientists in a way which produces evidence of how they act in order to do their job. This evidence can then be analysed so that some generalisations can be made about the work of scientists.

I begin this chapter by discussing the methodological basis of the research study. Following this discussion is a description of the research techniques I have used, including those for sampling the field of science employment, devising the interview structure, processing the data gathered and analysis of the data.

### **The methodological basis**

It is not automatically the case that there are common features to the work of most scientists which can be discovered. The field of science is so vast and the types and levels of work so numerous that it could be the case that it is impossible to generalise about the work of scientists with any confidence. There may be nothing to know about the commonality of scientists' work. The only significant theoretical perspective which indicates that there is something to know is the work of philosophers (for example Kuhn, 1970 and Popper, 1959) on the nature of science itself. However this is tangential to the study here. It is not *science* which is the subject of the study, it is the *activities* of people who are called scientists. These people may (or may not) use science in different ways and may (or may not) understand science in different ways. Therefore the study is essentially sociological, it concerns itself with behaviours of a group of people called scientists. The terms *scientist* and *work* have been defined earlier (p1).

The literature which relates to working scientists (summarised in chapters 2,3 and 4) provides some empirical evidence and some theoretical constructs about components of the work of professionals that together suggest some general pattern of scientific work is likely to exist. The fact that people are called scientists and that many are trained as scientists suggests the existence of some general understanding of what these people do. The results of this study will indicate, within the limitations of the reliability of the data and the validity of conclusions, the extent to which there are common features in the work activities of scientists.

The purpose of the study is to inform a discussion about the nature of general science education. For the outcome of the fieldwork to be useful the activities of scientists must have

a firm basis in the evidence. In other words they can be seen across the different types of scientific work. The activities must also be well-defined and be distinct from one another. Usefulness will therefore depend on selecting methods of enquiry which are appropriate, carrying them through in ways which optimise reliability and validity, and finally analysing data with skill, insight and honesty. Whilst there may be limited theoretical underpinning for the work of scientists, there is a vast theoretical literature on methods of inquiry and analysis, which can optimise the potential contribution a study such as this can make to improving our understanding (see for example, Bulmer, 1984; Cohen and Manion, 1989; and in a practical vein - Miles and Huberman, 1994).

### **The characteristics of the study**

The setting for this research study has characteristics which influence the choice of methods which could be used; in this study the following features are significant.

- The vast size of the field of science and the fact that many diverse organisations employ scientists. This leads to the need for a sampling mechanism which will maintain reasonable generalisability.
- The broad nature of the work of scientists. This requires an exploration of the nature of work prior to the main data gathering phase. It is also a key factor in requiring a method of inquiry which uses a researcher familiar with the field.
- The many different ways people describe what they do (vocabulary, traditions, personal interpretations). This requires expert interaction with scientists.
- The data collected will be extensive. This requires the planning of a system for storage, retrieval and analysis of the data.
- The need to produce a generalisable description of scientific work. It is not necessary to generate a theory which is predictive. It is hoped that the outcome of the study will be explanatory in a retrospective sense (Hammersley, 1985).

I discuss these features, and the response to them in terms of research design, in a later section of this chapter.

### **Grounded theory**

A particular feature of this study is that it was never the intention to support, prove or extend an existing generalisation or theoretical construct. There was too little (empirical) evidence for this. The nature of scientific work needed to be explored by gathering data and formulating conclusions which could build into generalisations. The approach adopted therefore draws extensively on grounded theory methodology, first conceptualised in the now classic text by Glaser and Strauss, The Discovery of Grounded Theory: Strategies for Qualitative Research in 1967. It also uses the more sophisticated structure for grounded theory research which was developed later (Glaser, 1978; and Strauss and Corbin, 1994). This makes clearer the methodological position with regard to the researcher's expertise and

how this makes him or her sensitive to existing theoretical constructions. Prior to these modifications the emphasis in grounded theory was on the need for, at most, a neutral research perspective at the outset of a study.

Grounded theories start with the research question. The original approach to grounded theory methodology avoids 'shaping' the research with existing theories, hypotheses and existing research data. The concept is that the researcher begins to explore the territory of the research with the research question in mind and gradually begins to use the data collected to reformulate the approach to gathering more data.

Before considering why grounded theory development is appropriate (or otherwise) for this research study I review the nature of grounded theory development. I think this discussion is important for two reasons. Firstly, parts of grounded theory are often used by researchers to complement other methodologies, however in this study it is used in its full form including some more recent refinements to the original description. The second reason for discussing grounded theory here is that it will provide a helpful methodological overview of the whole of this research study. Grounded Theory methodology involves the following components, each of which is described below in the context of this research study.

#### *1. Data collection*

All forms of evidence are acceptable; the aim is to gather as realistic a description of the focus of research as possible. The researcher needs to get close to the information sources whilst taking care not to exert an influence which could distort the data gathered. In this study this process involved semi-structured interviews. In the pilot phase the interviews were almost unstructured (a series of headings was used to ensure coverage of the areas which were believed to be relevant). The interviewer was to some degree sensitised to the field (through personal and professional experience) and was developing greater sensitisation through the process of literature review. This notion of being theoretically sensitive is one of the later developments of grounded theory methodology referred to earlier. Clearly the more familiar a researcher is with the field under investigation, the greater the tendency for the research to take the form of deductive testing of ideas or verification rather than theory development.

#### *2. Transcription*

Strauss and Corbin (1990) advise that the researcher be selective in what is transcribed early in the process of the research. This is intended to allow for efficient use of time during a period when the researcher is seeking ideas and patterns in the data which could be the building blocks of theory. In this study all interviews were transcribed whilst accepting that some interviews were rather raw (reflecting the early stages of interview design and the

inexperience of the interviewer) and were unlikely to be typical of interviews in the whole data-set.

All the interviews were entered into software designed to organise and allow analysis of qualitative data.

**3. *Develop categories***

The categorisation of the data took place in two stages. The first set of categories were developed by reading the interview responses and adding codes which reflected the parts of the interviews and the literature on this subject. These eventually took the form of a coding list which is included at annex D.

The second form of categorisation was developed by using a series of on-line searches of the maturing data-set. After reading transcriptions, certain themes occurred more frequently than others. Investigation of these themes resulted in an additional set of categorisations which were more detailed than the first set. It was at this stage that patterns which developed into the main findings of the research began to appear.

**4. *Saturate categories***

This involves reaching the point when new interviews do not seem to advance the thinking on each area of categorisation. This point was reached about three quarters of the way through a sequence of interviews which was designed to sample the field of scientific work. Nevertheless the interview schedule was completed in an attempt to increase the generalisability of the emerging model. Interviews later in the process became a check on the generalisability of the model.

**5. *Abstract definitions***

This process begins to 'tighten' the emerging model by seeking to define each aspect of the model in ways which distinguish it from other aspects and facilitate identification of occurrences of each aspect of the model in new primary data. The development of definitions was of particular importance in this research study as the model, in effect, forms the criteria for analysis of general science education provision.

**6. *Theoretical sampling***

Theoretical sampling is a discrete part of grounded theory methodology but is conducted at different stages in the process of research. Theoretical sampling involves the selection of the sources of information and the sampling of questions which are asked (to optimise theoretical relevance and generalisability). In this study theoretical sampling began with the construction of the map of the scientific domain and thence permeated the rest of the study.

7. *Axial coding*

This refers to the process by which relationships between aspects of data and emerging theory are identified, corroborated and characterised. It is the point at which the proximity of data and theory is articulated. Axial coding makes connections between different parts of the emerging model. In this study axial coding was most prominent during the stages of analysing transcripts and assigning segments to more generalised headings. The process of checking the emerging theory against the interview data (see 9 below) involved axial coding. Because each interviewee worked in a different context and had different experience it was necessary to analyse carefully the meaning of their viewpoint and assign it to a category. Thus there was a continuous process of checking one segment of data against another and against the emerging model.

8. *Theoretical integration*

This stage involves description of the emerging model. It is characterised by a bringing together of data segments under a single code into a condensed statement. Table 15, p122 exemplifies the outcome of theoretical integration in this study.

9. *Grounding the theory*

The theory (or in this case - the model) is now compared to the whole of the data-set and checked for internal validity by identifying its strengths and weaknesses in explaining (or in this case - describing) data segments (see table 15, p122).

10. *Filling in gaps*

This process involves a review of the data-set in the light of the grounded theory. The data-set may need expansion of a relatively weak area of data or a development of the sampling process. The aim is to ensure the data-set and the sampling are well developed so that they do not reduce confidence in the grounded theory. In this study some additional interviews were conducted where evidence from one type of scientific work was considered not sufficient.

This review of grounded theory has provided an overview of the research process used in this study. Whilst the theory is clear in its structure there are issues which have emerged during the process of applying it to the study of scientists' work. I now turn to these issues.

### **Methodological issues**

There are potentially many factors, both practical and theoretical, which challenge the emergence of a model from empirical data. Such a model may easily become influenced by such factors as the preconceptions of the researcher or by inadvertent use of existing



models<sup>18</sup> of scientific practice or as a result of practical limitations arising from the sampling process. The emerging model could also receive too much emphasis from the most senior interviewees or the largest, most reputable organisations. I describe how these influences were minimised later in this chapter.

### **Reactivity**

Chapters 2, 3 and 4 provide perspective for this study. In these chapters I have attempted to indicate where the results of this study could contribute to what we know of the work of scientists. However this evidence, coupled with the researcher's knowledge and experience of science, both in business and of science education, there is clearly potential for unhelpful influence during the data gathering stage and during the analysis of the data. Influences could take the form of a 'closed' mind to points made by interviewees which the researcher is not familiar, or points with which the researcher disagrees. The opposite of these two influences is also possible. This issue has been the subject of discussions of research methods for some time (see Denzin, 1989). The total independence of the researcher from the data and its analysis parallels one model (dominant until earlier this century) of scientific or naturalist method. The diversity of methods is now better appreciated and some philosophers call for a unification of the different traditions in sociological research (Bhaskar, 1979).

Thus there are clearly dangers of reactivity and in this study steps were therefore taken to reduce the possibility of the researcher inadvertently influencing the analysis of data. I give a full explanation of this process later in this chapter (p83). However there are advantages in getting close to the interviewees' position and these can outweigh the disadvantages. Indeed the most serious influence on the data gathering and analysis may arise from the lack of awareness of the setting of scientist's work, their technical task and its relative importance. These aspects are less likely to occur with an expert researcher - as Hammersley (1992) points out a setting can be unrepresentative and can lead to *ecological invalidity*. The fact that a researcher takes a low profile will not, in itself, make the situation more valid.

### **The starting point**

The earliest forms of grounded theory methodology avoid 'shaping' the research with existing theories, hypotheses and existing research data. It would be difficult to claim that this study starts with a clean sheet: the work in the early chapters concludes with a 'model' of scientific activity at the end of chapter 4. Additionally the semi-structured interview has a shape which is based on the reality of interviewing a busy person for about an hour during their working day. Certain questions were inevitable (How long have you worked here? What is the purpose of your work?). Most importantly the research began with a clear intention that the outcome would be formulated in a way which would be useful in general science

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<sup>18</sup> This area has been explored in chapters 2,3 and 4.

education. In other words the process of structuring the data collection had begun before the first visit to an organisation. Problems such as these have already been recognised by theorists (see Bulmer, 1979; Harris, 1979). The methods used in this study attempted to capitalise on the prior knowledge and experience of the researcher in the sense that the data collected may have been generated through questioning, listening and prompting which was informed by the researcher's previous experience.

### **Access and ethics**

In this study an open autocratic approach was used: the researcher negotiated access to information and promised full confidentiality.

The purpose of the research was explained to potential interviewees when they were invited to participate in the research. From a methodological point of view this posed problems. Access had to be negotiated and information about purposes of the research was critical to gaining access. Many of the companies had working methods and areas of research which were commercially sensitive. They had to know why the research was taking place, what types of data would be collected and who would have access to that data. Hammersley and Atkinson (1983) have described some of the issues which need to be weighed against each other in this way. They warn of the dangers of losing a participant's confidence (and access to data) when being open at the outset of a study and, at some later date, being unable to be so open.

Confidentiality was a key factor in the interview process. All those involved were given written and oral assurance that their need for confidentiality would be respected throughout the research process. There were three dimensions to this confidentiality. The first was the common respect for each person's experience, careers, ambitions and performance. The second was a guarantee that information about the work performance of fellow workers would be secure. The third area concerned commercial security. This was often a significant issue. The researcher was asked on occasions to sign declarations about non-disclosure of sensitive information.

Participants were not invited to review a transcription of their interview since interviews had the potential to include personal information about the participant and their working colleagues (subordinates and superiors). If, during negotiation of access, a promise had been made to return transcripts for checking this might have caused interviewees to suppress some views (interviewees may have anticipated that colleagues may have asked to see the transcript and refusal might have become difficult). Furthermore (i) interviews were recorded and a simple transcription was made of what was said during interview, (ii) the number of interviews was large and the process of checking transcripts would have added considerably to the research task, and (iii) the participants were all busy working scientists and it was felt

that most would have balked at the prospect of having to read through and amend an extensive interview transcript. No interviewee asked to see the transcript; had they done so transcripts would have been sent; there was no sense in which the methodology itself ruled this out.

### **Sampling**

The sampling process was designed to generate evidence across the breadth of scientific work; as many of the different types of scientific work as possible were sampled within the time constraints of the study. It was important to sample in this way so that the model of scientific practice would take into account the major forms of work. Any definition of scientific capability which does not take into account an important work area, or gives higher priority to a type of work which is less frequently practised than another, may adversely affect the validity of outcomes. This type of sample is aimed at securing a sound basis for theorising about the work scientists do and is termed theoretical sampling (Mitchell, 1983). The criterion which is important for determining the sample is that each scientist interviewed has the potential to illuminate a part of a generalised image of scientists' work. But the choice of the sample is built upon an a priori theory about what the range of scientific work might be.

The data sources for this study were sampled in ways which were likely to lead to confidence in the final model of scientific work as a means for judging the quality or relevance of general science courses. The main types of scientific work, the levels of work and the activities of scientists were sampled. This study has used *purposive* sampling rather than random sampling (Kuzel 1992; Morse 1989). In addition to the practical problems of randomly sampling across several large fields and the consequential access problems, the study requires certain main fields to be explored. The reduction in validity which might be associated with use of a weaker form of statistical sampling is compensated by the gains involved in sampling all of the main fields at least once.

The research study sets out to gather data from a defined field, from particular individuals, and about specific types of activity. In a sense therefore it is *stratified* since attempts are made to cover categories of scientific fields, workers, experience, and contexts. As stated above these strata are sampled to give a general outcome and not to create a means of comparison. Further research using larger samples could be carried out in order to make such comparisons.

### **Quantitative approaches**

It would be useful to know something of the frequency with which certain activities are present in the work of scientists. Attempts were made to analyse data quantitatively but this approach is severely limited by the design of the study. The field of science is so broad, and

the variation within fields so wide, that to analyse quantitatively much of the data gathered in this research study would beg questions about the validity of any conclusions. The study therefore analyses the data qualitatively to create a model of scientific activity which can be the starting point for more specific studies which could be quantitative. Some theorists have held strong positions on the need for as quantitative an approach as possible (Smith, 1984) but there are some strong advocates for a less dichotomous view of these two approaches (Hammersley, 1992). The advantage of a quantitative approach for future investigations is that it might give clearer indications of how common a particular activity is in the work of scientists or it might allow some sort of prioritisation of activities (e.g. is one activity more important than another).

Having considered the methodological basis of the study I now move on to describe the techniques which were used to sample the field, gather data and analyse the data.

### **Methods**

The research reported here explores an extremely wide and complex field. There are many interesting and potentially useful research inquiries which can be made using the data gathered in this study. Throughout the design, implementation and analysis it has been necessary to restrict approaches to those which are most relevant to the task of developing a *general* description of the work of scientists in organisations and those that are most likely to be useful in informing a discussion of the ways education and training might develop in the light of this general description. This limitation is important since the evidence assembled here could inform answers to questions of a comparative kind. For example, what is the difference in practices between scientists working in each of the main disciplines of science? What are the differences in practices for scientists working at different levels of seniority in organisations? These comparative lines of inquiry are powerful distractors and have been reserved for later research.

### **Alternative methods**

As with many research studies a combination of several methods was considered likely to lead to more reliable data, although the dangers of mixing methods have been well articulated (see Morse, 1992, Baker et al, 1992). The method of using in-depth semi-structured interviewing was used in preference to two other well known techniques, namely case study and questionnaire-survey. A discussion of the advantages and disadvantages of each of these methods follows and is used to justify the decision to use in-depth semi-structured interviewing as the main method of gathering data in this study.

### *Using extended case studies*

It is possible to develop a model of scientific work through extended case study (Walker, 1984). A limited number of organisations could be involved in an in-depth study of the

organisation's scientific activities. Staff working at a range of levels could be interviewed and observed at work. A case study approach would probably reveal greater detail about the work carried out by individuals and lead to a better appreciation of the context for the scientific work being carried out in the organisation. However there are disadvantages such as the poorer coverage of the field of science since each case study would require a larger time commitment from the researcher. Limiting the number of scientific organisations involved in the research would weaken the potential generalisability of the outcomes of the work. A smaller number of interactions with scientists would increase the chances that atypical working methods would influence the outcome: this could reduce generalisability. Another drawback of case study methods is that only large organisations could offer the range of science work which needed to be sampled; therefore small and medium sized organisations would be ignored and this could also have a deleterious effect on generalisability.

One advantage of using a larger number of smaller interview studies is that it can allow a development of research instruments in line with developing theory. This is particularly important in studies such as this which are based on grounded theory methodology. Fewer case studies would mean fewer opportunities to develop instruments.

Other potential consequences of using large-scale case studies concerns the ethics of deeper researcher involvement with scientist's work, and limits to access because of the commercial sensitivity of much scientific work. A large scale study might give participating organisations a sense that the more extensive data gathered during the research might include something of commercial interest.

However it is possible that the extended case study method could be used as a validation mechanism for the research reported in this thesis - the advantages of case study work would then be available without incurring many of the disadvantages (see Chapter note A).

#### *Questionnaire-survey method*

A second, more quantitative, approach to this research might have been possible. This could have drawn on questionnaire-survey method. Once again the method has much to offer, for example:

- a wider coverage of the domains of science. This would have advantages in allowing a model to emerge from a wider sample of scientists in work and potentially greater generalisability. These advantages can only be gained if the quality of data is good (see below).
- larger scale sampling, perhaps even random sampling, with resulting improvements in the reliability of the data;
- a quantitative interpretation which could allow prioritisation of the key aspects of scientific work. Currently the sample size is small, and selected purposefully rather than

randomly. It is not possible to decide, for example, whether practical work takes up more of a scientist's time than analytical thinking.

On the other hand survey methods suffer some drawbacks when used on research topics such as that reported here. The most serious of these is that the data gathered on work practices may be very difficult to condense into a form which is meaningful as a question or as an answer to a question. The technique does not match the purpose of the research - that is to gather data (which may be in extended prose) which cannot be anticipated - in a way which lends itself to classification.

The questionnaire would need to be constructed prior to the main enquiry. It would be limited by the need to be written in a way which requires no further interpretation and, because it must be used across a range of settings, is mostly independent of the respondent's situation. This could lead to misinterpretation, incomplete returns and frustration on behalf of the respondent. There may have been a reluctance to participate in the research if an impersonal and relatively unsupportive questionnaire was used.

Data gathered through questionnaire would be likely to lead to much weaker theory development since questions could not easily be modified in response to early feedback; nor could a questionnaire probe potentially useful areas raised by a response to an earlier question.

Another serious drawback to use of a questionnaire concerns semantics. People often have personalised interpretations of words and phrases (Argyris and Schon, 1974). Many words and phrases, even technical ones, can be interpreted in different ways. Questionnaires leave the researcher no opportunity to seek clarification of meaning. This can seriously weaken the reliability of data gathered through questionnaire.

For these reasons a questionnaire style survey was considered inappropriate for a survey of this type. However, like extended case study, a questionnaire survey has great potential for validating the data gathered in this research. Certainly the evidence gathered in this study would inform the generation of a well-focused questionnaire which would test certain of the findings.

### **Fieldwork**

Before a detailed consideration of the fieldwork a brief overview of the process follows; this may help the reader appreciate the role of each part of the study. In outline the fieldwork involved:

- developing a 'map' of the scientific domain;
- establishing links with science-based organisations;

- analysing published information about these organisations and their work;
- matching working scientists to the types of scientific work in the domain;
- matching working scientists to the different levels of scientific work;
- interviewing working scientists from those domains across a range of levels;
- observation of work in a sample of those domains.

The data gathering process began with small pilot studies which, through iteration, allowed the reconstruction of the interview instrument. Firstly four interviews were conducted (two in university research and two in private business) using only a series of headings for questions. During this phase of the study a more robust and sensitive semi-structured interview schedule was developed. In a second phase, 12 interviews were conducted with scientists; these covered the following three groups:

- university researchers - two people at different levels of experience/work;
- scientists in private businesses - seven people, at three different levels of experience/work);
- scientists in public service - three people, at three different levels of experience/work.

During this phase the interview framework was further refined and the breadth of the science domain was clarified through contact with personnel officers and by use of the experience of those interviewed. The domain map was reconstructed and a third round of interviews arranged with scientists representing areas of science not so far covered. During these interviews the interview schedule became further refined. After this third round of trials, the domain map and the interview framework remained unchanged.

The first major task which needed to be undertaken in preparation for the research was the development of a categorisation of possible areas of work for scientists.

### **The development of a description of the domain of science**

About 2.7 million people in the UK work force use science and technology (inc. mathematics) to do their jobs effectively (CSTI, 1993). Over 1.25 million of these people use science as a critical part of their work. The types of scientific work that these people engage in needs to be identified and categorised so that any sampling procedure reflects the range of important areas of work.

The field of science is vast. Almost everything we do is touched by some scientific practice. To complicate things further the areas of technology, mathematics and engineering all relate in some (poorly defined) way to the area of science. Criteria were developed to aid the definition of the domain of science and various levels of sub-domains within it.

The domains and sub-domains need to:

- span the main areas of science;
- cover the main economic and employment areas;
- include higher education areas which produce large numbers of graduates to main science employment areas.

**What are the main areas of scientific work?**

There are many ways of describing the structure of scientific employment. Boundaries between areas of science are often vague and arbitrarily determined. Important considerations are such things as occupational indices (e.g. the basis of standard occupational codes), economic indicators (e.g. employment figures), academic scientific disciplines, and higher education provision (e.g. range of courses, course population statistics). The range of potentially useful sources of information about areas of scientific work is provided in Table 8 on the next page, together with commentary on their strengths and weaknesses. A full description of each source is given in annex E.



**Table 8: Sources of information about areas of scientific work**

Source	Commentary
<b>An economic focus</b>	
(i) Occupational indices	Up to date information is available and the work focus is important.
(ii) Economic data	Figures based on economic performance necessarily exclude publicly-funded areas which are significant employers of scientists. This list might also under-represent those scientists involved in analytical services and production.
<b>An education and training focus</b>	
(iii) Traditional sub-disciplines of science	Scientists working as engineers or technologists may be difficult to classify - these groups would, to some extent, be regarded as multi-disciplinary. These groupings are also broad and are not sensitive to small but significant sub-groupings.
(iv) Student populations in higher education courses	Good for general capability in science but may be insensitive to employment opportunities.
(v) Based on vocational qualifications	This list might give weight to larger companies and trading areas since these are more likely to develop NVQs. The smaller companies and services may be under-represented.
<b>A research and development (R&amp;D) focus</b>	
(vi) EU Venture Economics Industry codes	This categorisation was developed some years ago and may not reflect the R&D field today. Most scientists will be employed in R&D. The European dimension may be important.
(vii) COST (the European Co-operation in the field of Scientific and Technical Research)	These groupings are old but are still in use. The European dimension may be important. The list needs to be rationalised with list (vi).
(viii) Technology Foresight	Up to date and may contain the main areas of R&D expenditure in the future.

**Selecting final description of areas of scientific work**

There are clearly common groupings in the eight sets described above, but the final description must achieve a balance between the sets. The process of deciding a final description involves arbitration between the sets, to decide where differences in names of groups actually represents a diversity between them and where it is merely an alternative descriptor.

By eliminating overlap between the listings and merging areas where there is unlikely to be a distinct difference in the ways science is used, the following composite list is generated.

- Biochemistry, molecular biology
- Biology
- Chemistry, preparing pharmaceuticals
- Education
- Engineering (civil, mechanical, chemical, electrical, electronic)
- Environmental science
- Agriculture and food science
- Geology
- Maintaining health
- Materials science, materials extraction and processing
- Meteorology
- Physics inc. astronomy

There is another perspective on scientific work which might affect the balance of opinion gathered at interview. Scientists in companies work in the following areas which may not spring naturally from the consolidated listing above. They are in fact included in several of the other headings and care was taken to set up interviews with scientists working in these businesses.

- Consumer related, retail and distribution
- Communications
- Energy and fuels
- Leisure
- Manufacturing
- Transport

Another dimension which was taken into account when setting up the interviews was to ensure a sampling across public service and private business.

The consolidated list can be rationalised into a smaller number of areas of science which will be referred to as *primary domains*. Each of these can be subdivided into a further set of constituent *secondary domains*. It would be expected that groupings within the primary domains would have similar perspectives on the science practised in the domain. It would be expected that movement between primary domains would result in a significant shift in the science used by those employed.

After consulting the wide range of sources of categorisation decisions were made in order to create a map of the domain scientific work which was used in the study (see Table 9 on the next page). To some extent the decisions which were made about the structure of this map are bound to be arbitrary, however the sources of information used were extensive and the mapping can now form the basis of discussion about how this domain is best described.

**Table 9: The map of scientific domains**

primary domains	secondary domains	examples include
Biology	pure research molecular biology, zoology anatomy/physiology	doctoral students, academics
Chemical production	pharmaceutical bulk chemicals biotechnology	plant managers, research managers, laboratory technicians
Chemistry	pure research biochemistry	doctoral students, academics, technicians
Education	Secondary, FE, HE	teachers, lecturers, trainers
Engineering	mechanical electrical and electronic civil chemical	project managers, academics, technicians
Environmental science	marine science meteorology	project managers, doctoral students, academics
Food production	agriculture processing	process engineers, farmers, production unit managers
Maintenance of health	medicine  occupations supplementary to medicine	dentists, doctors, opticians, veterinarians, psychologists, academics, technicians nurses, radiographers, midwives, occupational therapists, physiotherapists, technicians
Materials extraction and processing	geology oil refining forestry marine science	project managers, academics, doctoral students, technicians
Physics	pure research astronomy	doctoral students, academics, technicians
Public analysis	health and safety quality control environmental monitoring forensic	laboratory managers, field officers, technicians

Behavioural science was eliminated as a domain because there are very few personnel officers in businesses with a training in behavioural science and most occupational psychologists were employed in management consultancy rather than science-based work. It was difficult to gain access to the psychiatric aspect of science-based work and this group is relatively small. This area will be included in the next phase of the research.

The domain map is extremely wide ranging and some areas are yet to receive in-depth study, for example forensic science, astronomy and forestry.

### **The level of scientific work**

At one level of scientific work a junior technician may make up standard solutions for general laboratory use, at another level a research scientist will manage a team of people as they produce a strategy for the development of a product, process or manufacturing unit. In order to sample across these levels of scientific work it was necessary to use a framework describing the different levels of work. The framework selected was the five level classification devised by NCVQ for determining standards within National Vocational Qualifications (NCVQ, 1996a, see Annex E). The framework has the advantages of being a national system which was developed by employers. However the fact that the framework has to work within a wide range of occupations can cause problems for any single occupation. This is the case with scientific workers. The five level framework gives strong emphasis to the person management dimension. Whilst person management responsibility increases with level of work in scientific occupations, so does the level of professional knowledge and the latter may be overshadowed by the person management focus. There is a danger that sampling based on the five level system would not take account of the extremely high level of scientific knowledge and skills used by many scientists. In fact this problem proved not to be serious as the categorisation of jobs to a single level was never possible. People worked across two and three levels at different times and many senior scientists were also senior managers. The framework served its purpose by allocating a notional level to a person's job, in this way it ensured that the sampling process took in jobs across the range of levels. Not all levels were sampled to the same extent; this was a consequence of the fact that most science trained people are generally recruited to companies at level three and four. I decided to sample the higher level jobs (3,4 and 5) more frequently whilst ensuring some coverage of all the levels.

Table 10 shows the job titles that were used in the organisations involved in the study. These are assigned to the five level framework referred to above. Each organisation developed its own job titles. Therefore some names are common to more than one level of work.

**Table 10: Levels and job titles**

Level	A Sample of Job titles
1	Laboratory Assistant
2	Laboratory Technician, Assistant Experimentalist
3	Trainee Scientist, Laboratory Technician, Experimentalist, Senior Laboratory Technician, Scientist
4	Doctoral Student, Analytical Chemist, Senior Laboratory Technician, Research Associate, teacher/lecturer, Senior/experienced Experimentalist, Project Leader, Technical Manager, Technical Officer, Research Officer, Higher Technical Officer, Higher Research Officer, Scientific Officer, Senior Technologist, Senior Lecturer, Group Technical Manager
5	Professor, Director of Research, Director of Laboratories, Manager of Blood Services Unit, Project Manager, Laboratory Manager, Senior Technical Officer, Head of department, Higher Scientific Officer, Senior Research Officer, Principal Technical Officer, Principal Research Officer, Senior Technologist

### Selecting scientists for interview

The selection of scientists for interview is an important process. The generalisability of any outcome based on analysis of the interview sample depends on this selection. In the discussion which follows the aim is to show how the sample relates to the population of scientific workers as a whole (see Honigman, 1973, for a theoretical perspective of this type of sampling).

The concept of a *user* of science is helpful: a user is a person who is employed in a large business or significant academic area who, from time to time, uses scientific knowledge and skills in their work. As the research itself is aiming to define the nature of the science they use, this definition may, at first, appear to be unhelpful as the outcome may only reflect the science selected for inclusion in the research study at the outset. To overcome this problem a sharper focus on science was achieved by applying three criteria to individuals and their work at the point of selection for interview.

- i) Scientific knowledge is critical to a successful outcome at some point in the work.
- ii) Some of the skills associated with scientific enquiry such as experimental design, use of equipment which is designed to produce reliable data, recording of operating procedures and results, making decisions based on data were essential parts of the work.

iii) Those carrying out the activity have a scientific qualification as a prerequisite for working in the area.

Selection of scientists for interview was also complicated by the fact that there is no clear division between scientific roles and technological roles; this has been raised as an issue in Chapter 2 p10 and is discussed further in Chapter 8 p147. Many jobs which depend on scientific knowledge are, in fact, technological in nature - they are about optimising a process or producing a product. Some technicians could do their jobs effectively with little scientific knowledge.

A further complication was that most people used science for only part of the work time. Some senior managers were more involved with financial matters and strategic planning than the process of science carried out in their laboratories. Five such senior managers were interviewed but most of the interviewees spent the largest portion of their time on science/technology based activities.

Most of those interviewed had been nominated by a personnel officer or a senior colleague. In order to achieve coverage of the scientific domains and levels of work it was necessary, when approaching organisations, to be quite specific about persons who would be suitable for interview. The following extract from an invitation for organisations to participate illustrates this specificity.

*..... Ideally the visit would include an introduction to the range of technical work in [your operation] and some idea of the level and type of recruitment of people into technical jobs. Then I would need between 30 and 45 minutes with a recent recruit into a laboratory based job as a non graduate and then the same time with someone who supervises a project, laboratory or work team. It would be helpful if I could spend some time more informally, say another 30 minutes, with these people as they get on with their work. I realise this is not always possible. At some stage I would like to discuss the science related to the work you do in the field of ....*

Only four organisations did not wish to participate in the research. Two of these were in the process of restructuring and making employees redundant; it was felt inquiries about work practices could lead to industrial relations problems. The remaining two organisations failed to respond to letters and telephone calls.

### **The interviews**

The fieldwork was based on a set of semi-structured interviews. This style of interview was used to optimise coverage of the main areas of questioning which were likely to elicit information about work practices and also to allow the interviewee to cover the activities

which they perceived as important. The quality of the data is largely determined by how well it reflects the reality in the particular work situation. Semi-structured approaches allow the interviewer to respond to contexts and seek clarification of points made in context.

Interviews were used in place of full-scale workplace observation for five reasons.

- i. The perceptions of the scientists form an important context for the work activities they undertake.
- ii. Interviews allow some description of previous practice. This includes recent practices and those that took place days, weeks or months previously.
- iii. Interview accounts condense the time spent data-gathering.
- iv. Interviews allow a description of situations which would not be accessible to the researcher, e.g. safety, ethics.
- v. Interviews allow a prediction of future changes to work practices to be included in the data-set.

Interviews were conducted in the place of work. This was to allow the interviewer to see the context for the work and to allow for some cross-checking of data by reference to other sources for example the accounts of colleagues or observed work practices. It is important for the researcher to witness the context of work so that an appreciation of the structures within which the scientists works can develop. This working environment can influence the interviewees perception of what they do (Burgess, 1984).

### **The interview schedule**

The interviews were carried out using a semi structured interview schedule (see Annex C). The design of the interview schedule was carried out by treading the fine line between a prescribed sequenced list of specific questions which would aid analysis and an “open” style which might be more difficult to analyse. A more closed question set would lead to ‘blindness’ to meaning or significance of responses and the outcome of the interview could suffer from the *knowledgeable informant* effect. The more open style is not helpful when used on a small scale as interpretation becomes necessary and generalisability becomes questionable. Interviews are also longer and omissions more likely.

The semi-structured approach was also likely to increase the validity of the interview process relative to the more closed interview schedule since the interviewer could be, at least to a degree, responsive to the points made by the interviewee. It was important to gather



information about the work carried out by the interviewee through their own perception of the work. Validity depended on the accuracy of the interviewee's perceptions and the interviewer's interpretation of what was said. Increased interaction through semi-structured questioning allows checking and clarification to be part of the interview process.

The need for internal validity of the instrument, that is that the instrument should measure what it is intended to measure, together with an interview period which was manageable, were factors which determined the use of a semi-structured approach.

The purpose of the interviews was to:

- get a clear idea of the work domain;
- ascertain the scientific "status" of the interviewee including educational experience and qualifications gained;
- obtain full details of the roles the person plays in his/her work and prioritise these where possible;
- obtain a view on the key abilities of people doing similar/related jobs in the organisation;
- determine the scientific knowledge and skills required for different jobs;
- determine the generic knowledge and skills required for different jobs;
- find out about changes in work practices.

There was no attempt to develop a data-set which could be used for internal comparison. The reasons for this restriction have been explained earlier (p61). But inevitably internal comparisons between the views of different respondents were made, some of these are reported in the next chapter. This happens because of the need to attempt to understand conflicting responses.

All the interviews included the features shown in the left hand column of Table 11. The rationale for making enquiries in each area is given in the right hand column. The purpose of the research was raised as early as possible after meeting the interviewee. The letter of invitation to participate also made the purpose clear.

**Table11: An outline description of the semi-structured interviews**

<b>Area of questioning</b>	<b>Rationale</b>
<b>Preliminaries:</b> such as confidentiality, the time required, permission to record the interview, the outline structure of the interview, inviting issues from the interviewee.	Good research practice and allowing interviewee to judge the pace, relevance and line of questioning.
<b>Professional Standing:</b> judged by experience, qualifications, current work, membership of professional groups.	Establishes the interview, clarifies domains and levels of work. Sets up later questions about education and training systems.
<b>Education and training:</b> description, evaluation of relevance, opinion on forms of general education.	Helps make judgements (later) about the effectiveness of education and training in the light of the emerging model of scientific work.
<b>Work:</b> job description, description of work setting, description of a typical day.	Key enquiry to generate model. Provides contexts for next two areas of questioning.
<b>Knowledge:</b> that which underpins or is the subject of work.	Clarifies domain, provides an idea of the significance of scientific knowledge.
<b>Skills:</b> those used often in work.	Key enquiry allowing practice to be discussed in detail.
<b>General knowledge and skills:</b> those used often in work.	Used when not raised in two previous areas of questioning. Validity check on work practice.
<b>Professional development:</b> ways of enhancing the quality of work.	Provides a second way of getting to relevant knowledge and skills through practice. Elicits information on changes in working practice
<b>Feedback:</b> anything overlooked, observations and suggestions, willingness to participate further.	Good practice. Safety net for context specific information which may have been overlooked.

There was a problem in eliciting from interviewees the knowledge and understanding which underpinned their work. Theories may be taught but learners may well personalise them; there is evidence for this from a study of a range of professional behaviours that they do (Argyris and Schon, 1974). It was clear on several occasions that the interviewee had created their own mental model of how a material, a reaction or a device was behaving. The problem of eliciting how people personalise established theories or ideas is difficult since, when

people are challenged about the ideas they have used, the established theories are often expounded. This is a very important aspect of professional practice and deserves more research. The problem can be stated as follows: is there a formal, established knowledge and skills base which is used in training and in inter-scientist communications, but quite another, personalised, practical one used in work? This research study seeks to obtain as much data as possible on science in practice and does not seek to probe the extent to which those interviewed said what they believe to be the formal description of knowledge and skills rather than a statement of knowledge and skills in a form they actually use. There was no time for this level of detail in the interview sessions.

All of those interviewed, although mostly nominees rather than volunteers, involved themselves thoroughly in the interview process and were willing to explain quite sensitive matters about their work, their career to date and their prospects for the future. Many of them said they had found the interview interesting and thought provoking.

### **The data collected**

Sixty three interviews were conducted with people from twenty eight organisations covering the main domains of science; eight of these interviews were with pairs of people or small groups. In all eighty six people contributed information through interview. A list of all the organisations involved in the research is included as Annex A. A codified list of those interviewed is given in Table 12 below. The number for each interviewee refers to their employing organisation, the letter identifies them as an individual. The codes are not appended to quotes in this thesis (particularly in chapter 6) as this would allow the identification of the individual making the quote; this would infringe confidentiality promised at the outset of the research.

**Table 12: A coded list of interviewees**

1A	Analytical Chemist, large production plant
2A	Environmental Health Officer, local government
2B	Environmental Health Officer, local government
3A	YTS student, private research organisation
3B	Scientist, private research organisation
3C	Medicinal Chemist - student, private research organisation
3D	Quality Control Supervisor, private research organisation
3E	YTS student, private research organisation
3F	Research Scientist, private research organisation
3G	Primary Research Scientist, private research organisation

**Table 12: continued**

3H	Protein Chemist, private research organisation
4A	Research Director, large private company
4B	Chemist, large private company
4C	Senior chemist, large private company
4D	Senior technologist, large private company
5A	Senior research officer, private research organisation
5B	Laboratory scientist, private research organisation
5C	Junior laboratory technician, private research organisation
6A	Technician trainees (6), large production company
6B	Director of Company Training, large production company
6C	Senior chemist, large production company
7A	Director of analytical laboratory, large production company
8A	Trainee nurses (2), university
8B	Senior nursing tutor, university
9A	Senior Laboratory Technician, public laboratory
9B	Laboratory Technician, public laboratory
9C	Public Analyst, public laboratory
10A	Technical Directors (3), private food production unit
10B	Technical Sales, private food production unit
10C	Senior Laboratory Technician, private food production unit
11A	Engineering Projects manager, energy production
12A	Head Technician, public research institution
12B	Immunologist, public research institution
12C	Personnel Manager, public research institution
12D	Senior Scientist, public research institution
12E	Scientific Officer, public research institution
12F	Animal Technician, public research institution
13A	Physiotherapy tutors (10), university
13B	Physiotherapy tutor, university
14A	Electrical and Electronic Engineering Tutor, university
15A	Head of Therapy - Radiology, university
16A	Higher instructional officers (2) - mech. eng., military college

**Table 12: continued**

16B	Trainee mechanical engineers (6), military college
17A	Electrical Engineer, military college
17B	Trainee electrical engineers (2), military college
18A	Blood scientist, hospital
18B	Laboratory technician, hospital
18C	Sandwich student (applied biology), hospital
19A	Director, private training organisation
20A	Biotechnology post graduate students (9), university
21A	Director - New Technologies, large private company
21B	Director - Fish and Poultry Innovation, large private company
21C	Instrument Engineer, large private company
22A	Chemistry lecturer, university
23A	Research Chemist, university
24A	Industry Liaison Officer, private organisation
25A	Engineering Manager, medium private company
25B	Trainee Engineer, medium private company
25C	Sandwich Students (2) (IT Innovation), university
26A	Research Chemist, university
26B	Ph.D. Student, university
27A	Admissions tutor
28A	Physics teacher

**The work people do**

It is possible to categorise the work carried out by interviewees. The following list forms one such categorisation. Two examples of work are provided for each category.

- Analysing biological samples: *from post-mortem, biopsy from patient*
- Analysing chemical samples: *from a continuous production process, from a food product*
- Culturing biological material: *for testing purposes, for medical application*
- Developing physical devices: *for monitoring telecommunications, for managing inputs to chemical plant*
- Direct health services to people: *nursing, physiotherapy*
- Maintaining a laboratory: *dealing with routine samples, ordering supplies, maintaining safety equipment*
- Maintaining physical devices: *to make vehicles reliable, for conducting analyses*

- Maintaining supplies of living material: *for laboratory testing, as a substrate for a product*
- Management of scientific functions: *a project group, company R&D*
- Monitoring the environment: *water pollution, living conditions*
- Monitoring the safety of materials and devices: *toys for children, foodstuffs*
- Optimising agricultural production: *by reducing disease, by genetic means*
- Preparation of chemical materials: *small samples of pharmaceuticals for test purposes, bulk chemicals such as PVC*
- Providing education and training: *in universities, in company training schemes*
- Recruitment of scientific personnel: *into a company, into a research organisation*
- Refining biological samples: *blood products, sub-cellular components*
- Researching the properties of sub-cellular matter: *for cancer treatment, for AIDS treatment*
- Researching the nature of substances: *for development into a useful product, to develop a production process*
- Strategic management of research: *to optimise chances of a breakthrough, to reach prescribed targets*

The list provides the reader with an overview of the range of activities covered in this study.

#### **Coverage of domains**

The tables which follow summarise the extent and nature of the interview sample.

Interviews were arranged to cover as many of the secondary science domains as possible. Table 13 on the next page shows the extent of the coverage.

**Table 13: Coverage of the domains of science**

Primary employment domain	Secondary employment domains	Number of Interviews*	Primary domain total
Biology	pure research	16	19
	microbiology	3	
	zoology	0	
	anatomy/physiology	11	
Chemical production	pharmaceutical	22	52
	bulk chemicals	7	
	biotechnology	17	
	chemical engineering	6	
Chemistry	pure research	18	32
	biochemistry	14	
Education	Secondary	1	3
	FE	0	
	HE	2	
Engineering	mechanical	3	21
	electrical	8	
	electronic	10	
	civil	0	
Environmental science	environmental health	2	2
	meteorology	0	
Food production	agriculture	3	8
	processing	5	
Maintenance of health	medicine	1	9
	Occupations supp. to medicine	8	
Materials extraction and processing	geology	0	5
	oil refining	5	
Physics	pure research	1	0
	astronomy	0	
Public analysis	health and safety	16	36
	quality control	15	
	environmental monitoring	5	
	forensic	0	

\* Note - many people work across two or more of these secondary domains, hence the coverage of interviews exceeds the number of people interviewed.

**Job level**

The 5 level system developed by NCVQ was used to analyse the type of work undertaken by interviewees. Table 14 below includes detail of how the interviews covered the range of levels and the characteristic job titles for each level.

**Table 14: Coverage of levels of scientific work**

<b>Level</b>	<b>Number of interviews*</b>	<b>Samples of job title</b>
<b>1</b>	<b>6</b>	Laboratory Assistant,
<b>2</b>	<b>10</b>	Laboratory Technician, Assistant Experimentalist,
<b>3</b>	<b>15</b>	Trainee Scientist, Laboratory Technician, Experimentalist, Senior Laboratory Technician, Scientist
<b>4</b>	<b>42</b>	Doctoral Student, Analytical Chemist, Senior Laboratory Technician, Research Associate, Senior/experienced Experimentalist, Project Leader, Teacher, Technical Manager, Technical Officer, Research Officer, Higher Technical Officer, Higher Research Officer, Scientific Officer, Senior Technologist, Senior Lecturer, Group Technical Manager,
<b>5</b>	<b>32</b>	Professor, Director of Research, Director of Laboratories, Manager of Blood Services Unit, Project Manager, Laboratory Manager, Head of department, Senior Technical Officer, Senior Research Officer, Higher Scientific Officer, Principal Technical Officer, Principal Research Officer, Senior Technologist

\* note: some individuals often work across two or even three levels, hence the number of interviews in the Table will exceed the number of people interviewed.



### **Other relevant data**

- Of the 28 organisations sampled 12 were private enterprises, 7 were public service organisations and 9 were university departments. Most of the organisations were large, employing more than 100 people in scientific work.
- Of the 88 people interviewed 32 were female.
- In 7 of the 28 organisations interview data was supplemented by observing scientific work in progress.
- Of those interviewed 8 were engaged in general laboratory technician work.

### **Observation of work activity**

Early in the research study, in fact mainly during the process of refining the interview schedule, some informal observations of work activity were made. About a quarter of all of those interviewed were observed at work with colleagues. These observations provided information about:

- the context of the work described in the interview;
- the ways in which work groups operate;
- the conditions under which work was done; and
- the equipment used.

The work observation was undertaken to provide background information on scientific work which could enhance the relevance of the interview questions for the interviewee. It also allowed a degree of checking of meaning of some points made during the interviews.

The framework developed during the mapping of the science, technology and mathematics domain by the Consortium of Scientific Institutes in 1993 was used as the basis of work observation. The checklist for work observation is included at Annex F.

### **Analysing the interview data**

Interviews were recorded and transcribed. A software package<sup>19</sup> was used to store and index the data.

A list of 'keywords' was compiled; these words are those that could be useful in analysing the data. They were identified during the literature review and during the interviews. Each document was searched for these keywords and occurrences of the words were tagged to a node. A list of the nodes used to collate all of the data is given at Annex D.

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<sup>19</sup> The software was NUD\*IST (non numerical unstructured data - indexing, searching and theorising), Qualitative Solutions and Research Pty Ltd., Melbourne, Australia

The data collected was analysed from the earliest stages. At first the analysis aided the development of the interview structure and later analysis was used to detect themes and patterns in the data. The central aim was to allow generalisations to flow from the data. Problems arise for the following reasons.

- The statements from such a group of interviewees are rarely congruent. Diverse opinion needs to be reviewed for both the frequency with which a point is made and the weight given to a point by an interviewee.
- The interview schedule was developed through iteration and, despite the researchers' intention to follow the leads given by interviewees, the schedule itself, and time constraints, inevitably guide the responses from interviewees.
- The points made by interviewees were not always clear and a certain lack of clarity of meaning is bound to remain when analysing what was said at a later stage (sometimes up to a year later).

Steps were taken in the design stage of the project to reduce these effects, for example by interviewing more than one person from a domain, by using a semi-structured approach, by seeking as much clarification as possible during interview and taking away from the interview site potentially useful written materials about the organisation. During the analysis further measures were used to make the analysis of responses as true a reflection of the general response to the research question as possible. These were as follows.

(i) No form was imposed on the output from interviews other than that of the semi-structured interview. The raw transcript data was entered into the project database.

(ii) As many "keywords" or "phrases" as possible were listed for analysis of the raw data by software. Through statistical analysis of the "finds" of these key words or phrases it is possible to get an idea of the general form of the data and the strength of feeling on certain points.

(iii) Every transcript was read again over a short time scale (within a few days of each other). This was done to gain an overview of the data. Indeed by the time the analyses were written up the transcripts had been read many times. The researcher had become very familiar with them.

(iv) The data was inspected using software according to the headings in the interview schedule. Points made by interviewees were allocated to each of the headings in the schedule. Sometimes a single point made by an interviewee was allocated to more than one heading.

(v) Summaries were made of the points collected under the headings in the interview schedule. It was here that the patterns and themes began to emerge. The list of summary

points were read and collated into groups of related points; these groups included opposing points of view where such positions were taken. The data was then summarised using representative quotes wherever possible. Whilst the data set is extensive it was not possible to quantify responses to produce reliable data (see p60).

(vi) On completion of the analysis the interview transcripts were skimmed again to check that the balance of what was written in the summary was in line with the general feel in the transcripts. A few minor amendments were made to the summaries at this stage.

(vii) After the summaries were written and themes were identified, a check on the consensus in the data on these themes was carried out. The level of support for the model was assessed *from each interview*. Where themes were not adequately supported the data were reviewed again.

(viii) Finally a random sampling of the interview transcripts was carried out and these were checked against the summaries by a third party.

### **In summary**

The use of grounded theory methodology has enabled analysis of primary data. The primary data were especially rich as interviewees were generally keen to articulate the features of their jobs. The mapping of the scientific domains has produced a workable sampling of the types and levels of scientific work. For a research study of this limited scale, covering ground which is relatively under-researched, the theoretical sampling has proven to be useful. It would need to be reviewed and possibly revised before it was used on any larger scale research work. The design of the study (its ethnographic nature and working within constraints of time and access to people) has produced a model of scientific work which may prove to be useful. This model is described and discussed in the remaining chapters of the thesis. The first area to be discussed is the primary data itself, chapter 6 serves as a summary of the data-set as a whole.

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### **Chapter notes**

A The author is aware of the potential of such in-depth case studies. A research team based at Durham University have recently conducted a pilot study of scientific work in one company. The Durham team have described<sup>20</sup> some types of scientific work which match those identified in this thesis. However the greater depth of analysis they have carried out allows another (more detailed) level of description to be added to the description of the types of work reported here. For example the practical manipulation of equipment reported

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<sup>20</sup> This remains unpublished as this thesis is finalised.

later in this thesis includes reference to protocols or standard operating procedures. The Durham team have analysed one of these in great detail and have begun the task of identifying the key components of practical manipulative work. There is likely to be some benefit in terms of a better understanding of scientific practice in relating the work reported here and the on-going work at Durham. The Durham team have as their principal aim the development of a better structure for understanding of procedural aspects of science.

## Chapter 6: The results of the study

A research review of skills, qualifications and their utilisation in the engineering industry reported that there is:

*...substantial evidence of employer deficiencies in the match between knowledge, skills and other attributes they require and the education and, to a much lesser extent, training (since the latter is more within employers' control) which may lead to engineering qualifications. The research evidence for this mismatch is fragmented. Empirical evidence is limited.*

Parsons and Marshall, 1995, p21

The data base which is summarised in this chapter is substantial and makes a significant contribution to the empirical evidence of the knowledge, skills and attributes required of scientists in work.

In this chapter the data gathered through interview are summarised under the headings in the semi-structured interview pro-forma (see Annex C). Each section is written in a form which allows the reader to gain an overview of the primary data.

Section A covers the **scientific training and career** of the scientists.

Section B summarises views on the **strengths and weakness of the training** of scientists.

Section C describes the **working environment** for scientific workers.

Section D discusses views on **scientific knowledge** requirements.

Section E discusses views on **scientific skills** requirements.

Section F reviews the types of **general skills** which are valued in scientific workers.

Section G summarises discussion of **changes in work practices** over a notional 10 year period.

## **A - Scientific training and career**

Working scientists are generally highly qualified. Almost all interviewees had a degree in a science subject. Even people in relatively low level scientific jobs in laboratories (technicians at levels 2 and 3) were sometimes graduates. Almost all trainee technicians at levels 2 and 3 were studying part-time for an HNC in an area related to their work, (for example Laboratory Management) or for a degree (for example Microbiology). Companies did not require a degree for some jobs but had recruited graduates when application for these jobs were received from graduates.

Some interviewees had Ph.D.s; they had been recruited to their first post because they had developed their specialism to such an advanced level. The people working at level 5 were about evenly split between those who had joined their organisation with a doctorate and those that had a distinguished research record but had not submitted a doctoral thesis. The Ph.D. was looked on most favourably in universities and research organisations. The key advantage of recruiting someone with a Ph.D., in addition to an advanced scientific knowledge and skills base, was project management experience.

*They can stand on their own feet, they are more independent than those coming straight from a degree. Their intellectual powers are higher.*

**Senior scientist, large production company**

*Most people have a Ph.D. before they join us because we would regard it as important that they have demonstrated a commitment to do research. The only way you can do that is to carry it out in a university. We don't really like to take on board people who say 'well I might be interested in research'.*

**Research Director, large research organisation**

People were almost always working within the subject area of their degree and using the knowledge-base the degree provided. Many spoke of now being much more diverse in their scientific work.

*My degree was modular and it enabled me to do much more in the way of other disciplines - I did biotechnology and fermentation technology which is something I come into contact with now and I've got a bit of understanding. A pure microbiology degree wouldn't have that.*

**Senior Research Officer, large research group**

Experience of work at a particular level in another organisation was seen as a very important feature of a person's background.

*... these people are bringing their expertise from the working environment with them. They know what is necessary in the working environment so they have expertise which gives them some idea of priorities. You can easily divide competencies into competence in chemistry and general competence. That means the competence in the working environment, with the unions, or with safety issues etc. People coming from university usually lack this knowledge.*

**Research Director, large production company**

The younger recruits interviewed were well aware of this. Almost all had completed degrees with an industrial placement. Some had taken temporary jobs to gain this crucial edge in the competition for good jobs.

*I actually worked for 2 months for no pay ( in a Laboratory at London Zoo) because I wanted to get some molecular biology experience. To be honest, as a graduate with a reasonable degree (a 2.2), I didn't think I stood much chance of standing out in a crowd, so I thought if I had this 2 months' experience it would help.*

**Scientific officer, large public research organisation**

When asked about keeping up to date with developments the most common answers referred to reading journals and talking with colleagues. Most were members of professional bodies (e.g. Royal Society of Chemistry, European Society for Animal Cell Technology) which they found useful because these bodies provide specialist journals and arrange meetings of specialists in a scientific field.

The people interviewed, who were nominees rather than volunteers, were generally positive about their work. Through their words and other means it was clear that most found satisfaction in scientific work. These two statements illustrate this satisfaction and also show how it varies between levels of work.

*I'm not exactly sure what turns me on as such but I suppose I just like the field of science it's interesting and I like being involved with it, even if it's not at a great level.*

**Technician, private company**

*I enjoy the challenge of it, I've always felt that as a practising organic chemist that if you don't get a reaction to work or you don't get the molecule in the bottle, then you're exposed to criticism, so you have to continue to deliver. The pull if you like, the inspiration, comes from the hope and expectation that you will one day come up with a product that will be a success in the market place, that will make money and will change the course of mankind as we know it.*

*Such naive ideas tend to get wrung out of you the older you get, but basically I get a kick out of it, I get a kick out of patents, I get a kick out of the intellectual stimulation of thinking, this is new, this is something that has not been thought of, this is an improvement.*

**Team leader, private research company**

Interviewees were pleased to discuss their background. The topic of their experience was therefore a useful introduction to the interview. In the next section the responses to inquiries about training are summarised.



## **B - Strengths and weaknesses of training**

All interviewees were asked to comment on how well their training prepared them for their current role. Having been asked about their education earlier in the interview most interpreted the question in terms of their initial education rather than subsequent training programmes. On-the-job training was also something which had to be elicited through prompting. In order to get as broad a perspective on training as possible interviewees were asked their opinion on the preparedness of new recruits and sandwich students for work in their organisation.

The breadth and depth of science education and training was the most common issue raised. The comments were evenly balanced - some people believing the current preparation to be strong and other people seeing specific weaknesses. Firstly the strong points. The development of theoretical knowledge, particularly at A level and in degree and HND programmes was often cited as a strength of the current system.

*I think your training gives you very good background knowledge of various things. I think I must have done 30 subjects when I was doing my degree, so it's a huge field and gives you a vast background. It's very general when you're doing your degree, and to be honest it's not until you start working that you realise that there's an awful lot you don't know, but things that you've learnt at college actually now make sense.*

**Scientific Officer, local government**

And in terms of sandwich students on year-long placement in organisations:

*The students we get are all quite intelligent in terms of their theoretical background.*

**Scientific officer, private research company**

The greatest weaknesses identified were training in practical skills and awareness of the ways laboratories function. These weaknesses was identified across the spectrum of levels and types of work. School, college and university courses were criticised for perceived low levels of relevant practical experience.

*Most of it at university is theory work. We got set amounts of practicals but they were artificial.*

**Technician, private research company**

*College practicals are nothing like how you would carry out the same things here; I mean I know from doing them at college that they bear no relevance to what you would do in an industrial lab.*

**Ph.D. student**

And again in terms of sandwich students:

*I wish they were a bit better at looking at more than one aspect of a problem before they start to tackle it.*

**Team leader, large private company**

*They seem to have done little or no practical work, and what practical work they've experienced seems to have been done by a teacher in front of them, so they haven't had any hands on experience- they are all thumbs.*

**Research scientist, private company**

There were some positive comments about the practical skills of new recruits from one laboratory manager (private research organisation) who set out during recruitment to identify students with potential for practical work.

*I think some people we have recruited have a great feeling for working in labs. They're just more practically orientated.*

**Laboratory manager, private research organisation**

There was a mixed response to the question whether practical skills, whilst generally poor, were in decline or improving. The majority of interviewees considered standards were still falling. These were concentrated in work groups where analysis of one form or another was prominent in the work load. For example the two statements which follow are from two analytical chemists in different private companies.

*I believe the standard of practical skills is falling - they ought to be much higher.*

*I think practical aspects are getting weaker , there is far too much emphasis on theory.*

On the other hand, from an electrical engineering perspective:

*I think the level of practical skills actually is probably slightly better than it used to be.*

**Electrical and Electronic Engineering Tutor, university**

Finally there was recognition that restrictions in time, space, money and equipment in educational institutions make it difficult to give a realistic experience of working in science.

*To heat something up something at college you get a Bunsen Burner and a water bath and shove your flask in it, but you would never do that here, we have devices like hairdryers (heat guns) and stirrers with a heating mantle on. I've never seen one at any college I've been at. You're always trying to find equipment at college, there's never enough of it and it's all very ancient. The equipment here is so much more advanced that it becomes completely different to what you encounter in an academic way I think.*

**Technician, large public research organisation**

Comments were made about the lack of relevance of school, college and university science to “real” world science<sup>21</sup>. Starting with a general point about academic examinations.

*I think they're (A levels) very difficult exams. I don't think they're a brilliant exam to show what someone's going to be like in the future.*

**Research manager, large private company**

The two main improvements sought in education and training programmes were the introduction of more application of knowledge and business awareness. Interviewees also stated that some student recruits have a poor notion of science and scientists. They said there was a need to improve the accuracy of the image of science that is created by the media. Some interviewees wanted to see more learning by doing rather than through theory.

The following statements from a range of interviewees illustrate these points.

*It would make things much easier for whoever's training students if they have practical knowledge.*

**Technician, Public Analysts Laboratory**

*The preparation of basic knowledge in schools sometimes deprives people of a chance to use the knowledge-base. This brings excitement. They should be looking at practical application.*

**Instrument Engineer, large private company**

*Basic commercial awareness needs improvement because we get people coming in and I don't believe they really understand how the world works commercially.*

**Executive, food company**

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<sup>21</sup> See the report *Change and diversity: the challenges facing higher education*, (RSC/CIHE, 1998, p46) for a fuller discussion of this point. The research reported in this publication confirms much of the evidence reported in this section of chapter 6.

*At school all it's geared towards is going to university, that's all. They don't care if you get the job or not, it's all, "go to university", "study this and that". But if they could do it slightly more practically, slightly more towards what you might be aiming to work as, it would be much better. It's the practical that builds up the confidence, you do all the theory and you come out of it and think, I think I understand that, then you go and see a motor and you think, I don't know where to start, but someone shows you how to do it and you carry it on from there.*

**Trainee electrical engineer, military college**

*An appreciation of scientific method is much better taught and learned through doing it. It's just not efficient to try to teach it as you would scientific factors.*

**Research chemist, university**

Once again there was acceptance that science education experts had a difficult task.

*They need teachers who have actually had real contact, so many teachers go straight from university to teaching and they haven't a notion of what the real world is like out there. They work incredibly hard and do a good job but they really do need to be seconded or given an opportunity to work in the real world.*

**Technical manager, private company**

There were suggestions for improving education and training programmes by focusing more on general skills, for example training in foreign language skills, report writing and how to manage upward relationships.

The extracts exemplify the range of comments interviewees wanted to make about their training. We now move on to consider the working environment.

### C - The working environment

There is insufficient data to provide a summary of the ways whole organisations structure scientific work. In most cases only one or two individuals were interviewed from one department. However it is possible to generalise about the immediate work structure for these individuals.

Almost all interviewees were working in teams. The teams varied in size from three to ten people. In most cases they were working as a fixed group dedicated to exploring one main problem. Typical of a team is this description of a group exploring thermal processing of food products.

*We have two research officers who are junior to me, then all the technicians, who are graded one to five, so there is a hierarchy.*

Senior research officer, private research organisation

Some organisations, chiefly research organisations, operated a structure of highly specialist teams. Companies involved in production generally operated a broader team structure using people with different specialist knowledge and skills.

There were exchanges between teams in the form of data, reports and meetings. There was always a director controlling the ways teams interacted (reasons for this are discussed in section E). In some cases there was a larger work group (up to 30 people). Individuals in work groups of this size were assigned to smaller teams each working on a specific aspect of a common problem. In this arrangement people changed teams regularly.

In organisations where the work group was small the individuals were regarded as specialists working on problems which were specific to them. This was particularly the case where the research function (as opposed to another function such as routine testing) was less important, for example in an analytical laboratory. In these small teams, where people worked on problems and tasks as individuals, there was often a high level of informal mutual support for team members, for example covering for absence or helping a colleague out when the work load was particularly high. This situation may arise as a result of reductions in staffing levels. A technician in a small work group summarised his working day and begins to illuminate this area of support for colleagues when he discusses doing analyses.

*Possibly the first two hours are devoted to opening mail and dealing with orders for chemicals and equipment. Then possibly another half hour going around doing a lot of calibration of refrigerators, ovens, balances. That's done daily for legal reasons to check that they're working OK. Then possibly there's the repair of equipment, glassware, electronics. Although there's only a small staff, the amount of technical work is still high. On paper I'm also in*

*charge of the two laboratory attendants. I do quite a lot of analysis now. More and more. Chemical and mechanical analysis. Testing of toys, flammability on clothing. It's extremely varied.*

**Senior Laboratory Technician, Public laboratory**

Where teams operated on one problem there was a hierarchy of positions which was based on experience and qualifications. Three of the larger organisations were in the process of creating a flatter structure with fewer levels of responsibility. Sometimes technicians (or administration assistants) were shared between teams. In some organisations there were common support services for a range of teams, for example information services, analytical services or supplies.

No interviews were held with scientists working alone on a problem<sup>22</sup>, nor was any such arrangement mentioned in any of the organisations visited. That said, some of the projects were extremely sophisticated and it was clear from interviewees that, whilst their own role was clear to them and the overall purpose of the project was understood, the ways the different lines of enquiry related to one another was not. The specialised work undertaken meant that the work of one individual was often not understood by others in the team.

It was clear from interviews and observations that the formal seniority structures in teams did not inhibit many junior staff from making informal suggestions for potentially useful investigations. Several junior staff stated that they were doing work which was usually reserved for more senior team members.

It is difficult to overstate the perceived importance of team working. Managers and personnel officers stressed it was increasingly important that the dynamics of team working was understood so that effectiveness could be optimised.

#### **How much work was scientific?**

Whilst all interviewees were involved in scientific work, this was accompanied by work on administrative tasks and in some cases managerial work. At higher levels the scientific work was less likely to be practical and more likely to involve analytical and creative thought about evidence and possibilities.

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<sup>22</sup> Ph.D. students had their own unique perspective on a problem but the problem itself was shared by a team in the case of those involved in this kind of research.

Junior staff have the highest proportion of time spent on practical scientific enquiry. This is often routine.

*I'd say 90 percent of my time is spent on practical work. The only time I don't do practical work is when I'm writing up what I've done. It's our boss who's office based. He would be planning work for the whole project, he's got 7 people of my grade working for him, all working on different aspects.*

**Protein Chemist, private company**

**A project manager with a large private company** illustrates how the level of practical work declines with middle management responsibilities.

*My work consists of some laboratory work, interaction with legal people in terms of patents, with engineers, with business people. If I realistically split up my job I suppose I spend about 30% or 40% of the time actually engaged in practical work.*

**And from a more senior manager:**

*I don't do any lab work, it's all desk work. The technicians do this (lab. work) and you've got to help them do it, offer advice or if there are problems, help them a bit. Make sure they're doing it on time, help them interpret the results and then help them report the work. We could have between 8 and 15 projects running at any one time. A couple of those would be large projects, the rest would be smaller contracts.*

This spread of commitment to “bench practical work” is typical of responses across all the domains.

Those staff working in quality control functions (mostly analysis) have the highest proportion of bench science. Those in managerial positions have to make a high commitment to communication and managerial roles. They are the contact point and voice of their working group. On average they may spend between 20 and 40% of their time at the bench.

In most interviews discussion about the work context progressed to a discussion of knowledge and skills associated with scientific work. These discussions are summarised in the next three sections.

## D - Scientific knowledge

In every interview people were asked about the scientific nature of their job, in particular about the knowledge and skills they needed. In order to aid thinking about this enquiry, which was about things which interviewees sometimes took for granted, the questions were framed in terms of the scientific knowledge and skill that would be sought if a new recruit was being appointed to stand in for them for a year.

Before presenting the findings it is important to remind the reader of a point made earlier; questioning people about the knowledge and skills they use is problematic. It is not a simple matter of breaking down the scientific part of what people do into categories of scientific knowledge and skills. In response to the question "What science do you use in your work?" they often requested (explicitly or implicitly) clarification. The reply "What scientific knowledge (facts, ideas or principles and theories) and skills and techniques do you use?" seemed to do little to help. The working scientist may not need to classify the aspects of scientific behaviour as educationalists do. If they want to find out about a particular protocol, they do an electronic search for it. If they want to get some background on a new product, they use research papers. They see their colleagues as key resources for solving problems with scientific work. Another way interviewees responded to this line of questioning was to attempt to broaden the question for example:

*I need to have a good knowledge of microbiology because I use that, but also experience of the way we work in the team. When you are confident you can do things quicker and not hang back in practicals. You can go on and get the whole thing finished and reference the work. You need to be a very good communicator. A lot of our contact with customers is on the telephone so verbal communication is important. Also you have to be good at people management. Microbiology is very slow so you've got to be able to push people to get things done but not put pressure on them.*

**Senior Research Officer, private company**

In chapter 4 the ways in which people personalise theories and principles were discussed. Argyris and Schon (1974) have suggested that, when challenged about these personal constructions, people tend to articulate the standard theory or principle rather than their personal construction. It might be the case that interviewees in this study were unwilling either to articulate the way they thought about something, or to try to give the standardised (accepted) version. Those people who did try to respond before prompting, tended to give a general reply rather than a specific one.

The analyses of other researchers, for example Erault (1994) and Norman (1985), have resulted in the definition of more general processes as typical of professional behaviour, rather than processes specific to any one profession. For example each of these analyses also



includes problem solving as a key activity. The flexible nature of the problem solving process, depending on resources such as equipment, people, time and on iteration between different aspects of the problem, means that it is more difficult for the worker to pin down exactly what is required of themselves to solve the problem. This is discussed further in the next chapter.

In this section the emphasis will be on reporting patterns of what people said rather than trying to organise it into some framework of knowledge, skills and techniques.

Interviewees who were practitioners in educational settings were able to be clear about the scientific knowledge-base required to do their job. They were able to provide syllabuses for trainees which specified in some detail the facts, principles and theories which would be used in practice. The fact that these people were practising scientists gave added validity to the knowledge requirements. In one prestigious university department the focus in the first two years of a degree course is (almost) exclusively on developing a sound understanding of principles. In the remaining year (for a B.Sc.) or two years (for an M.Sci.) the course broadens considerably to offer opportunities for the development of scientific skills, project management skills and general skills such as presentational skills, business awareness and problem solving.

*We find employers saying to us "concentrate on the physics. We want bright young people who know their stuff - we can offer on-the-job training for other things". We tend to steer away from applications in our courses and concentrate on pure physics for this reason.<sup>23</sup>*

**Admissions tutor, university**

Most interviewees stated a need for a basic scientific knowledge for example:

*A knowledge of basic chemistry is very important. The whole fundamentals of the work here is chemical analysis. We do so many different things that it all comes down to chemical analysis.*

**Laboratory Technician, public laboratory**

In some interviews the question of scientific knowledge was interpreted more broadly in another sense. Phrases like "to have a feel for (electronics)", or "to be able to think like a (physicist)" were used. Probing these responses revealed a more precise interpretation of underpinning knowledge - underpinning knowledge that enables the conceptualisation of what is happening in a situation and the use theoretical thinking to analyse problems and solve them. For example:

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<sup>23</sup> Students wanting application are steered towards engineering or courses such as medical physics.

*If a signal that you're measuring is fluctuating, you'll know that the only place in the circuit that could cause the fluctuation. It's an intuitive feeling. In an electronics circuit you can't see the changes occurring, so therefore the only way that you perceive what is going on is a strong underpinning knowledge of mathematics. This is because a component stays the same colour, the same temperature, the same shape at all times.*

**Electronics engineer and trainer**

At the lower levels of scientific work there was much less emphasis on scientific knowledge.

*I'm not saying that no background knowledge and theory is needed at all, that is important, but I think there's too much emphasis on it and not enough on the practical side. I think you need both.*

**Laboratory Technician, public laboratory**

*As far as knowledge and skills at this stage a new recruit wouldn't need that much, I mean obviously I'd like them to hold a personal licence in order to do procedure work, that would be an advantage, so obviously someone at least would have to have the grounding of animal technology and animal husbandry.*

**Animal Technician, research organisation**

It is possible to work on a problem and appreciate very little of the underpinning science. However there is an expressed link between underpinning knowledge, interest and commitment to the project and the possibility of enhanced contributions to the task.

*In some ways you are just being thrown samples and it can be monotonous, I've only been here 7 or 8 months so I'm fine at the moment but it is very routine. You have to understand what DNA is and understand the nature of DNA and what it's all about, you couldn't join in the discussions otherwise (but I'm not that encouraged to anyway). I wouldn't see the point of someone not fully understanding that, because they would show lack of interest or lack of concern for the problems you can come across.*

**Scientific officer, Large public research organisation**

There was much evidence of individuals using an extensive body of knowledge gathered over many years and adapted to fit the circumstances of the projects being undertaken. They had adapted practical procedures in the same way. The major ideas are seen as tools of the job. Fluency in the use of these ideas seem to be a characteristic of the more experienced workers.

### **Learning on-the-job**

Many of the scientists interviewed referred to the effectiveness and the speed with which learning on-the-job takes place.

*I learned as much in that one year as they learn in their whole 3 years of being at college.*

**Scientist, private research organisation**

*I started in here knowing nothing and I've managed to pick up an enormous amount of information since I started.*

**Laboratory Technician, public laboratory**

One supervisor commented on how a new recruit to his department had benefited from on-the-job learning:

*She felt her previous job was excellent training, she feels you have to learn so much on-the-job and there is no better way to do it. In her first job she picked up such things as setting up equipment, modifying things, managing time, thinking on her feet.*

**Analytical Chemist, large production plant**

Most often this learning was quite specific to the organisation and its processes and or products. The range of learning spanned basic techniques to advanced knowledge of explanatory concepts. The quotes which follow illustrate the range.

*At first there's ever such a lot (for students on placement) to learn ... how to weigh things out, how to work out calculations, but it becomes second nature, you know like, how to work out molarities and things like that.*

**Laboratory scientist, private research organisation**

*It's an ongoing learning thing (as well as work), you interpret results, you learn new things and you evolve in the sense that it's learning all the time, it doesn't stand still, you don't learn the same thing all the time.*

**Immunologist, public research institution**

Those scientists working with undergraduate students in universities spoke of the positive effects of work placements.

*They know what questions to ask when they come back from clinical placement. Before that they don't know what questions to ask, they listen to the theory and the only questions they ask are, do I or do I not understand this theory? But when they come back from a placement they say, well yes it's all*

*very well saying that theoretically, but this patient.... They can ask clinical questions which they couldn't before. It's a bit like learning a language in school and then going to the country where the language is used.*

**Physiotherapy tutor, university**

In addition to the learning specific to the work in an organisation, some scientists also referred to the way new team members developed general skills as they carried out their work.

*She's picked up the other (general) skills which shows that she's able to take things on board relatively quickly and as a person she's not afraid to ask questions, which is good, she appreciates her own shortcomings shall we say...*

**Personnel Manager, public research institution**

People working in most organisations had many opportunities, formal and informal, to learn through discussion of the work being undertaken in a team. The formal discussions were clearly structured to enable colleagues to critically appraise the work being undertaken and for junior members of staff to learn from the discussion.

## E - Scientific skills

In chapter 4 we saw how the skills and techniques of science can be considered in three categories.

- 1) *Application and synthesis associated with explanatory concepts* - where ideas (facts, principles, laws, theories) about materials, devices and phenomena are interacted to synthesise new perspectives and ideas.
- 2) *Applying concepts of evidence* - the skills of setting up effective experiments such as developing hypotheses, ensuring practical processes yield reliable data, analysing such data to develop valid conclusions.
- 3) *Practical manipulations* which measure and create observations.

There was evidence that all three aspects are a feature of the work of the scientists interviewed. The thinking processes where new perspectives are generated was regarded as extremely important in all the research and development laboratories visited. For the research scientist, it is the basis of their work; for the commercial R&D laboratory, the competitive edge of the business depends on the imaginative leaps in the scientist's mind. The senior laboratory group managers were expected to be able to pull ideas together to illuminate new lines of enquiry, and identify the moment when existing work was leading nowhere. From their scientific thinking they were able to build strategies for the next phase of work. The following extract from an interview with a laboratory manager (LM) in a pharmaceutical company illustrates the process.

*LM: my technician is currently finishing preparing and purifying a series of compounds which we think may have some interesting properties. The effectiveness of these compounds (as a drug) will then be tested. When the results come back the next stage of the process will come into play. We'll actually tabulate the results and try to draw conclusions and see if the structures we have made have a bearing on the potency of the compound.*

*Int. - That's your work?*

*LM - Well I'll involve her in that as well.*

*Int. - So that's part of some group meeting?*

*LM - Yes, very much so. After the meeting I'll be setting new targets based on those results and seeking approval from management to pursue the new line of enquiry.*

*Int. - So another set of compounds.....*

*LM - That's right.*

*Int. - And that cycle is what, every 3 months, every.....*

*LM - Yes, it depends, if you're learning new chemistry it may take you longer to sort out some of the synthetic steps.*

Similar approaches were used in all research organisations. The extract which follows is from a senior scientist (SS) investigating cellular immunology.

*SS - It's my job to work out a new course of action to take, and I do that in conjunction with my line manager. We discuss experimental results about once a month and decide on a new course of action for the subsequent month. I design experiments - it mainly involves thinking about the work in hand, what the objective is, and designing experiments to reach the objective. If that experiment gives us a result that is not the predicted result, the experiment is changed to investigate what's changed or what's not quite right and then we look at the overall picture and then maybe design some other experiments to fit in with.....*

*Int. - So there's quite a lot of strategic thinking then, you're evaluating the strategy, and every month you have a full-scale evaluation?*

*SS - Yes. We have a lab. meeting on Monday mornings when we all take turns to talk, and then I get together with my line manager and we look at results. She likes to look at everyone's results, even those from the Post Docs. and the Ph.D. students. She interacts with all those people, looks at their results and then she'll make constructive suggestions or criticisms depending on what we've done.*

This hierarchy (for strategic thinking) is well established and accepted as part of the system.

*My supervisor decides what direction the project is going to go, and which parts to pick up on or drop depending on the results or the way the project looks as if it might go. So I don't have any real control over decision making in the sense that I don't decide which direction the project is going or which project I work on.*

**Higher Scientific Officer, public research organisation**

This strategic approach allows all involved to keep objectives in mind and allows for 'cross-fertilisation' of ideas.

In education the *design* or *synthesis* component of courses was mentioned. It was seen as important that students were challenged to bring together the knowledge and skills they had learned in different phases of their courses.

*We use a weekly tutorial system where one member of staff meets four students to give them practice of dancing on their feet in response to questioning. Synthesis is an extremely important skill to us.*

**Admissions tutor, university**

The second category of skills relates to the cognitive skill associated with handling data. This is an extremely important area for almost all the interviewees. Many identified this as an aspect of their work which made them a key employee. There were three threads to this ability to understand the nature of data. The first is the purely mathematical and arithmetical skills needed to process and interpret the data. Almost all interviewees had a good grasp of these techniques. The second thread is the ability to see patterns and trends in data. The third strand is being able to make decisions based on the data. This involves conceptualising how reliable the data is and how far one might trust a conclusion based on the data. Asked about the skills of a project manager one such manager in a private company stated:

*Generally they have to be pretty good at taking data and analysing data, and handling it - making decisions.*

**Project manager, large private company**

And a beginning researcher summarised the skills in this way.

*You've got to be able to evaluate the data or else it's pointless doing the experiment. It's no use if you can't evaluate the results you've got. You can use help from the supervisors but you should really know yourself.*

**Ph.D. student**

A more experienced scientist gave a response which embodies many aspects stated by other interviewees.

*During my Post-Doctoral work, especially in (...) but also at(...), my use of scientific method and particularly my analytical skills really crystallised. My problem solving skills also became honed. As one of my major tasks is*

*analysis and problem solving, these skills are extremely valuable in my work group.*

**Senior technologist, large private company**

A typical response concerning strategy of experimentation was:

*... you can conduct an experiment that you have crafted such that it will, as far as is possible, give you an unambiguous result. That means you have identified all the controls. It also means that you understand the complications within the experiment so that you're not fooled into believing you've got the right result when you haven't.*

**Project Manager, large private company**

Research methods were prominent in syllabuses for the training of all of the health fields sampled. Interviewees considered this aspect of work a key feature of the work of future professionals. They believe that the observant worker, who through careful listening notices a pattern in the way patients describe something, or notices responses to certain treatments, can develop into an effective professional. These people were thought to be more likely to have something to contribute to the solution of a difficult or unusual clinical problem. The research outlook is also believed to contribute to an open mindedness when considering symptoms and facilitate more detailed enquiries of the patient and of proposed treatments. **A tutor in health care commented:**

*Students from here are said to be very good (at researching). The main comments that come back are positive about their inquiring minds and their questioning. Some clinicians find it threatening that the students want to know things like Why does this work? Why do we use this rather than this?*

This response of the clinicians to more research minded students was also reported by other health care professionals.

The ability to make decisions based on data is regarded as another key skill of scientists. The fact that this skill is needed at every level of work and that the most senior managers are required to think strategically using the data created by their teams, are clear indicators of its centrality and importance in scientific work. The absence of such skills in people who are otherwise well equipped for scientific work can be frustrating.

*I find it annoying and upsetting when people won't make decisions on the basis of their own practical abilities*

**Senior technician, medical laboratory**



The third category of skills identified in this section was the ability to manipulate equipment and materials. All interviewees saw these skills as an important part of their work. Many senior people implied they had been reluctant to reduce their own work on the bench when they were promoted to more senior positions. Most interviewees wanted to stress the importance of technique in obtaining good data. Scientists in the research laboratories were keen to express the importance of careful experimentation, especially the design of the experiments. Technicians involved in chemical analysis or patient care were particularly concerned with technique since they were often following protocols which have been accepted (by the scientific community) as reliable.

Some managers wanted to stress the need for careful practical experimentation.

*Research radiographers are people who can assimilate information quickly, who can be analytical. We wouldn't want all radiographers to be like that because we also need the 'bread and butter' radiographer working on the unit.*  
University tutor

*We put great store in hand skills here. The students are required to do a variety of courses during their main course down in the students' workshop. There they do bench fitting, then broaden that out to electronic techniques, producing circuit boards, soldering, building the mechanical frameworks for the components to go on, fitting the components, testing the components, physically just having the skills to be able to manipulate the tools and the components and equipment themselves, so we've always put great store in that, and then once of course they get out into the field, that is what's going to enable them to get to the item of equipment that they have to repair, which might be embedded several layers of equipment down. Clearly a mechanical knowledge, ability and a feel for this sort of work is essential.*

Trainer, military engineering school

Managers claimed they could sense potential for good experimental work in a new technician recruit. There were many examples, especially in the chemical and biological areas, where new materials were being prepared and tested against certain criteria. The preparation of the compounds was often complex and drew upon the latest preparative methods and methods of purification. Once the technician had been introduced to the technique they were required to repeat it again and again with small changes to say the substrate or the conditions of the process. In other words very skillful activity was tending toward the routine. A new recruit into a university department summed up how she felt going throughout his process.

*You have to be able to set up the experiments and synthesise something that's nice and clean and not full of black rubbish or anything. You've got to be able*

*to do standard experiments, check whether things are actually happening or whether you've missed something. You've got to be able to check everything so it's not some third party (chemical) that's taking part and actually causing the reaction. You've got to check everything to make sure the results you've got are true and be able to actually do the experiments yourself and not need too much help from other people more senior in the lab. It is necessary to be able to set up your own experiments and get on with it and not expect too much input from everybody else. When you first start you are shown what to do but then it's up to you really to carry on and increase your own practical skills.*

Training in the development of practical skills was invariably carried out in house. All organisations took care to induct their new recruits into the specific standard operating procedures (SOPs) and instrumentation used in the organisation. Schools and colleges would not have the facilities or time to familiarise students with the main techniques used in scientific work. The best that could be achieved is a familiarisation with some of the underpinning ideas and the general techniques of, say, analysis.

*We could have done with a lot more practical experience, just in simple things. Being familiar with laboratory equipment which is fairly standard in laboratories all over the world and just knowing how to use it. When I came in here I didn't have a clue.*

**Technician, public laboratory**

The interviewees appreciated the position of new recruits coming across highly specialised techniques. Even small changes to the context of such work (using HPLC with different substrates) would add complications which might 'throw' an inexperienced person. Generally they learn by watching and helping and gradually tune in to the demands of the tasks.

*I think I've picked up good practical skills from people, because it was people here that taught me. I've picked up the way they would like it done, because I didn't know any other way, so you learn exactly how they would like it done right from the beginning to the end. I've done quite well with my practical skills, I always get my targets done fairly well and high purity compounds and things, which they like.*

**New recruit, large private research company**

*In new recruits.... the practical skills are lacking, and they have to be looked after very carefully for several weeks if not months and every time you change the nature of the experiment that they're doing, you have to ensure that again they're taught.*

**Project manager, large private company**

Technicians were expected to maintain the cleanliness of the working environments. Sometimes this involved much more than cleaning equipment and wiping down surfaces. Special disposal techniques were required in several laboratories and procedures in one research centre required a doubling of the time allocated to tasks because safety procedures were so stringent.

Safe working practices had heavy emphasis in all organisations, and the topic of safety was raised in most interviews as something which impinged on the work practices.

*Safety is very important, you don't do very much safety at A Level because the substances you handle aren't particularly noxious. Then you come here and you're working with cyanide and you suddenly have to learn safety. That's important for industry because they're very, very strict.*

**Ph.D. Student**

The practical scientific work was, for most interviewees, providing good job satisfaction.

*I just love practical work, I loved it at A Level and even more when I came here. I really enjoy practical work instead of just sitting at a desk.*

**Ph.D. Student**

In cases where it was not providing satisfaction, the reasons given were a consequence of poor relationships or the absence of promotion opportunities. In two cases the reason was that people felt over qualified to carry out basic technician work.

Supervisors considered commitment to practical scientific work important because there were always likely to be set backs.

*They've got to be enthusiastic because so often things don't go well, or go so badly. If you're not enthusiastic you're just going to give up, so enthusiasm's really important.*

**University tutor**

**Being scientific**

Statements made about the knowledge and skills requirements for practising scientists were invariably supplemented by more general statements about the nature of "being scientific". Some interviewees said they recognised their ability to be scientific early in their career. When pressed on the signs of this ability the most common response was centred on analytical or logical thinking.

*When you're trained as a scientist, right at the beginning of a degree, you're trained to think analytically. You can break down problems into compartments and think. In other disciplines I don't think that the same sort of training is given.*

**Post - doctoral student**

*I think data analysis and experimental design are extremely important in the work that we do here. It would be very difficult to work here without having a good analytical mind.*

**Research chemist, large private company**

*Most of what I do I do in a fairly logical and analytical way so I tend to look at the problem, analyse it, find out what I need to know, get to know it, and then start addressing the solution. So I tend to approach things in a fairly scientific way.*

**Senior scientist, large private research laboratory**

Problem solving was often considered to be one of the key abilities of scientific staff. This **senior manager in a large private company** sums up the importance of problem solving abilities which he refers to as technical competence.

*By technical competence I don't mean just hands, I mean ability to solve technical problems and therefore mental ability within technical areas. That is essential for our people because they are supporting their client operations as well as identifying new opportunities and if a plant isn't running, or a plant has broken down, there's nobody who is going to solve it for us, it is our people that have to come up with the answers.*

It was clear that people interviewed had different understandings of what was involved in problem solving in their work. Technicians were more concerned with practical problems and overcoming mathematical and statistical problems within data. At higher levels a broader perspective becomes clear. For example:

*Problem solvers continually inquire, try something new, find information sources to check-out results. They evaluate where they are in a systematic way - it is essential that they are systematic. Signs of systematic behaviour are planning, manage time well, making time to report/write and monitoring of progress.*

**Project leader, large private company**

Some interviewees remarked on the relatively poor pay they received relative to, for example, “the city”. One interviewee saw the desirable feature of scientific training as the key quality sought in the better paid jobs.

*In accountancy they say that the training the scientists are given is excellent; they don't want pure mathematicians, they want analytical minds.*

Interviewees went on to identify thinking logically, thinking deeply and thinking differently (for example open-mindedness - “you're more available to different concepts and different ideas”).

*You have to be incredibly open minded because the decision that you make on the problem that's there, whether it's housing or commercial premises, will then lead you into making decisions on what action you're going to take, whether that be legal or informal.*

**Scientific officer, local government**

The scientific doctorate was identified as rigorous training. The important characteristics recognised in recruits with a Ph.D. were creativity, high standards of accuracy, and a keenness to improve work practices.

A **laboratory manager** who was responsible for recruitment into a large public research institution commented on weakness in the general skills of some applicants.

*A particular weakness is that they (new recruits - all levels) regard everything as starting in the lab and finishing in the lab. I find it very difficult with some people to get over the philosophy that science starts with an idea and works its way through proposals and getting funding, getting everything off the ground, then it's the lab. bit. Then at the end there's a lot more to do again in terms of getting the thing into practical use and writing it up and so on. So it's almost a philosophy or cultural thing if you like.*

This section of the interviews concerned with scientific skills and “being scientific” often formed a large part of interviews. This was an important part of work practice which many interviewees wanted to articulate as fully as possible.

The sections on scientific knowledge and skills provided much of the evidence about scientific aspects of work. In the next section data on broader (non-scientific) skills are discussed.

## F - General skills

Almost all interviewees wished to stress the importance of a range of more general attributes. A list of these is given on p35. These general capabilities are particularly important and were often mentioned ahead of any specific scientific knowledge, understanding or skills. This might reflect the emphasis scientists wish to give to them or the fact that the scientific skills were taken for granted. Managers were keen to stress that the changing working environment in many organisations requires people with good general capabilities to make them effective.

Sometimes these general skills seem to overlap with the skills or attitudes identified in the previous section. For example, one **team leader in a private research unit** said:

*It comes down to general skills actually, the skills that we need in the lab. I mean if you have general skills I think that we can use people like that. If you can ask good questions, you're not afraid to ask questions, and if you're fairly careful about what you do and have an ability to concentrate as well, we appreciate that.*

Some interviewees believed that their science base actually developed the broader range of skills which they considered important. A **manager from a private research laboratory** said:

*In many ways biology offers a way to develop general skills. For example biologists can be both literate and numerate, in that they have to handle words. You don't have to do that in chemistry and physics so much. At the same time you have to be able to handle data and interpret data. I certainly feel that one of the benefits that came out of my studying biology was an ability to express things in words but also to interpolate that with understanding and interpreting data and being able to put the two together. I feel comfortable doing that, and it's an important part of my job.*

However the skills were usually much less science-specific and less obviously related to scientific training. It is difficult to summarise the various ways interviewees saw these skills. Aside from the fact that they were almost always identified as important, and that communication, teamwork (personal) skills and, to a lesser extent numeracy<sup>24</sup> were important, there was not time during interview to make inquiries as to the way they saw the nature of these skills. This is particularly problematic since a skill such as problem solving might, or might not include inter-personal skills. Another example of this imprecision is that

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<sup>24</sup> The less frequent identification of numeracy as a general skill may be due to the fact that the people interviewed were scientists and likely to be highly skilled in arithmetic; they might also be taking for granted the number skills they use without articulating the need for them.

communication skills might or might not include oral presentations. A second area of difficulty is that skills and personal attributes were often not distinguished. This was often further compounded by the relative importance to the interviewee's work programme. The following statement seems to sum up all of these difficulties.

*Scientists need to have self-motivation, perseverance, indomitable spirit, tenacity, written communication skills and some oral skills. They'd have to be able to liaise and communicate with people on a professional level and an academic level. They have to understand what the project is and have a broad spectrum of technical skills as well. They have to be pleasant and be able to work well with people.*

**Higher scientific officer, public research laboratory**

In some scientific work the need for certain general skills is of particular importance.

*One of the key things for nurses is how well they communicate. Personality is a strong point. Nursing is a relationship, quite a complex thing to consider, Researchers have argued that the primary nature of nursing is the formation of a relationship that you can then build on and work with. If you cannot create that relationship with the team (colleagues) and also with the client and the relatives, then what you'll end with is an automaton, a robot. A nurse may have excellent technical skills and be the fastest catheteriser in the west, but I may not see her as a very good nurse. Nursing is complicated by the fact that if you look at any one specific task a nurse does, you may find that a health care assistant can do it as well.*

**Senior nurse trainer**

The ability to become detached from the personal angle in a situation was identified by several interviewees. The nurse has to learn to stand back from a patient's personal position.

*I did some research into nurses in their first year of work and their feelings of effectiveness and ability. What came out strongly was connectedness, how connected they were to the patient. When it got hard, they said they disconnected, did the technical job and then reconnected.*

**Senior nurse trainer**

An interviewee from higher education emphasised that after a reconstruction of their courses the staff had decided that a unit in the final year which aims to develop skills such as personal skills, presentation skills and business finance was needed. The interviewee went on to point out that students were often sceptical about the value of the unit but came to appreciate its importance after experiencing it.

The scientists interviewed often took time to emphasise the importance of general skills. This emphasis was often carried forward into the final section of interview which was concerned with discussion of recent changes in work practises and some articulation of what future changes might be. This discussion is summarised in the next section.



### **G - Changes in work practices**

All interviewees were asked about recent changes (over the last 5 years) and their thoughts on future changes (over the next 5 years) in the way they work.

The main theme which was raised was of cut-backs in staff and financial constraints generally. There were some areas where this was not the case (pharmaceuticals, electronic engineering). The effect of these pressures was to increase the need for teams to achieve objectives more quickly (e.g. more analyses per day, more environmental health cases covered per month, six month research projects being completed in four months, two research projects being conducted simultaneously). The knock-on effect of this pressure resulted in two related effects:

- more delegation of responsibility in teams - therefore more operations of different kinds being carried out by more junior staff; and,
- more junior staff doing more technical work than previously.

There were indications from interviewees that in the public sector the “customer care” philosophy had fallen victim to cut-backs. In the private sector no interviewee suggested that this was the case although there were indications that the ability to be pro-active in responding to clients had become more difficult. There was a general feeling across all areas that expansion of the scientific activities was not likely. During the fieldwork phase of this research a major food retailer closed its quality control and research facility just prior to some interviews. In a publicly funded research laboratory the cut-back process was making people redundant during the time of the interviews and this research work was curtailed. The following statements illustrate the effects of these changes.

*The most important thing that is no longer being done is that the time to deal with a problem in a user friendly way has been cut. The customer care approach is the first thing to disappear.*

**Scientific officer, local government**

*We have gone below the line on professional engineering expertise, we're cut back and cut back, so in some areas we don't have the resource actually on site and that's true of other (similar facilities). We haven't got anybody on site that's got civil engineering or structural engineering knowledge. We've just recruited a couple of ex-turbine engineers, because we didn't have that resource, too many chaps have moved away.*

**Engineer, private company**

The shifting of work to more junior levels or, phrasing it more positively, providing opportunities for more junior staff to do more technical work, had happened already and was considered to be likely to continue in many areas of work.

*Now nurses are being given so much more to do on the technical side, we feel more professional, but you can't just do it from nothing.*

**Student nurse**

*Some people in the profession have a problem with this (less qualified people working at a particular level) because it looks like people who haven't got a degree can come here and do the same job. There's going to be a change, in that you're going to get more people who haven't got our qualifications coming in doing virtually the same job as we are.*

**Scientific officer, local government**

The increased delegation, together with the fact that work is now being done by junior members of staff which was previously done by more highly qualified people, has already led to greater specialisation amongst the most qualified. These specialists monitor/manage the work of a (generally) less qualified workforce. For example:

*I think some people will specialise much earlier and there'll be a greater use of assistants. If you look at North America, that's the thing that they're really working on at the moment.*

**Health trainer**

*It's now changing much more by taking away the generalist (worker) and putting people into much more niche markets. You have professionals (in each aspect of the work) and it's taking away the generalist nature. Now you're getting a position where we have to be specialised in our role. The adversarial conflict in the commercial sector is so great now that you can't get away with knowing something about most things. You have to know more about one area.*

**Higher scientific officer, local government**

This sort of change means the less qualified “assistants” may have to be capable across a wider range of activities.

*It is no longer acceptable to have one skill or one job. So a chap that's a mechanical fitter will be doing things such as working without a foreman. He'll be empowered, making his own decisions, he'll be doing his own (electrical)*

*disconnections, he'll be writing his own job cards on a computer, he'll be IT literate, he'll be responsible for some aspects of financial management.*

Senior engineer, private company

Some interviewees suggested that the amount of contract work would increase, projects would be contracted out leaving a core (permanent) workforce.

*Certainly the trend in the USA seems to be to have a management core to a firm and a core of competent engineers and then, depending on the size of the projects you take on or not, you swell the size of your workforce and decrease it.*

Senior engineer, private company

This increased flexibility is one of the ways in which recent changes were likely to continue. However the need for flexible people seems to contrast with the trend toward more specialists.

*Flexibility is something that we always look for, we can't always get it. Sometimes we find it in a small number of individuals. There are some very attractive people who can do hardware and software even if they've got a bias one way or the other. People with a broad range of experience and skill in this type of work are very attractive because they've got a better understanding at the system level and as they progress they become good system architects; whereas somebody who sticks only with one discipline always finds it harder when it comes to looking at systems.*

Senior engineer, private company

Another way in which things had changed (and were expected to continue to change) is in terms of the legal regulation of work practices.

*Regulation is increasing all the time. Every time something new comes out there's more pressure on ourselves to do something about it. These days you need people who know a great deal about law because legislation's become more demanding.*

Scientific officer, local government

*In my particular area we just get more and more documentation, and it will lead to more and more protocols and legal requirements.*

Health trainer

The power of technological change was also considered to be an important agent in changing work practices. Besides making some jobs redundant it is also creating new jobs.

*I would say it's less hands on, more black box. For instance, I tell them we'll repair an item, we'll diagnose and switch over or replace, and that requires a higher level of knowledge, and less mechanical or hand skills.*

**Senior engineer, private company**

*It's a rapidly expanding field, it's actually creating new types of jobs, for example network managers. This is becoming quite a big employment area. They need knowledge of software/hardware and modern communication and protocols. It seems to me every graduate here gets a job.*

**Electronic engineer, higher education**

### **Analysing the primary data**

This concludes the summary of the primary data. The full set of primary data is held in an electronic indexing system which can be extended and be further analysed. In the next three chapters I analyse and discuss the full range of evidence gathered in the study. In chapter 7 the primary data is compared with what we already know through other research work. I outline the implications of this work for education and training in science in chapter 8. This is followed by a discussion of the ways science education and training could change in order to relate more closely to the practice of science in work (chapter 9).

## **Chapter 7: A model of scientific capability**

Having reviewed the interview data it is now possible to draw the data together and attempt to produce a model or a framework which will define the broad features of the work of practising scientists. At this stage it is timely to reflect on the goal of this research and the context to which it relates.

There are possibly three main reasons why we need to learn as much as possible about the way scientific work proceeds. Firstly, scientific activity provides a critical underpinning for manufacturing and technical public services (CSTI, 1993) in the UK. Secondly, the UK makes a substantial publicly funded commitment to pure research. Thirdly, and more generally, we are all faced with problems which could be better solved with the help of some scientific knowledge, including appreciating how data has been generated and what it can be relied on to tell.

In the research reported here the quest has been to use primary and secondary data about scientific work to describe scientific capability and then to begin the processes of using the findings to reflect on the relevance of science education and training. In this chapter all of the evidence is considered to produce answers to the question:

**On the basis of the evidence, what is the best general description of the work of scientists?**

### **The evidence base**

The primary data gathered in the research is substantial and provides a firm basis from which to generalise about the nature of the work of scientists. There are common themes which arise in the interviews which gives some confidence in asserting that certain activities are likely to be part of the work of most scientists.

### **Breadth of scientific work**

The main value claimed for of this study appears to lie in its breadth. The gathering of data across a range of fields using a consistent methodology and a relatively short time-scale provides a snap-shot of scientific work. This is likely remain useful for the next 5 - 10 years. It is an unusual situation, possibly a unique situation, for science educators to have a single model of science practice which has the potential to inform the curriculum and its assessment from a vocational or work-related perspective. The more common situation is that many perspectives are available, each providing only a partial view of the field of scientific work, these need to be combined to gain a perspective of scientific work. Most of these perspectives will have been developed with purposes other than the improvement of the science curriculum in mind, for example, to aid the development of general skills in new graduates.

### **The general education and training perspective**

The research here enhances our understanding of the work of scientists in another way. The scientific work which forms the base of this study was probed from a general science educational perspective. This perspective influenced all aspects of the study from the design of instruments to the sampling of the field. Other perspectives on scientific work such as the supply and demand of scientifically trained people or levels of staffing were of secondary importance. Therefore the evidence and analysis presented here extends the research findings described in chapter 2 (the work scientists do) and chapter 4 (knowledge and skills) in the sense that it is specific to the improvement of science education and training. In chapter 8 the evidence and analysis derived from this research study is evaluated against the work of other researchers in this field.

### **Some limitations on inferences**

The sampling which was necessary in order to cover the main domains of scientific work restricts the inferences which can be drawn to general points rather than specific points or comparative outcomes. The data is not sufficiently extensive in any one domain for interrogation to lead to valid comparative statements. For example it is not possible to describe with confidence the differences between scientific work in the private and public sectors, or compare the work in science education to that outside education.

Whilst the data gathered spans the main domains of science there has been no attempt to weight the data to reflect the numbers of people employed in certain fields. It would seem reasonable, for example, to give extra weight to data gathered from engineers and less weight to astronomers since there are many more people working as engineers. This is an important consideration for further work in this field.

The data is also not sufficiently extensive in any one field of scientific work to lead to conclusions about occupational training for that field. The content of courses and syllabuses in specific fields, such as electrical engineering, are best evaluated against industry standards or through occupationally specific research and development programmes.

### **Themes arising in the interview data**

Through analysis of the points made in interview, and the summaries of these in the previous chapter, certain common themes appear across the different domains of scientific work and from scientists working at different levels. These themes are form the basis of the features of scientific work which is the main research finding originating from this study.

### **The knowledge base**

The requirement to have a sound scientific knowledge-base for work was proposed by almost all interviewees. However the range of interpretation of what constitutes a knowledge-base was wide. Several sub-themes about knowledge emerged from the data. These are related to the issue of whether a breadth of scientific knowledge or deep knowledge of a scientific field is required. There were five main categories of response:

- the underpinning knowledge or basic knowledge of the central explanatory concepts of (school) science - this may not be an explicit part of work activities;
- a working knowledge of explanatory concepts in a specific area of science used in work activities;
- a working knowledge of procedures and techniques in a specific area of science used in work activities;
- an expert knowledge of explanatory concepts in an area of science which is the basis of work activities;
- an expert knowledge of procedures and techniques in an area of science which is the basis of work activities.

It is not possible, on the basis of the evidence gathered in this study, to generalise about the level of knowledge required for jobs except to say that some scientific knowledge is required in all jobs. It is possible to go on to say that this knowledge is often highly refined through the work undertaken and that people who work at a relatively low level, and who have modest qualifications, show a relatively detailed knowledge of ideas behind their work. There is evidence that junior staff are being asked to carry out higher level work than that they have previously been required to do. It seems likely that they will be expected to develop a knowledge-base which is at an appropriate level for their new work.

### **General skills**

A second theme which arises in many parts of the interviews is the importance of general skills such as communication skills and the ability to work well with others. These skills received strong emphasis when the qualities necessary to do scientific jobs were probed in interview. They emerge as a key component of scientific work. The interviews suggest that these skills are refined on-the-job and are learned quickly by successful workers.

### **Scientific skills**

The “doing” part of scientific work received much emphasis in the interviews and this area can become diffuse if it is aggregated into a single theme. Therefore the three main features of scientific skills which emerged are maintained as separate themes. Scientific practice was interpreted as “bench” or “hands-on” work by most people and as designing experiments by some people. These two features are key components of scientific work. The balance

between them depends on the level of seniority of the worker. Senior workers are more likely to be involved in designing experiments.

Another important “doing” part of scientific work was a rather more diffuse set of skills - a kind of fusion of general and scientific skills, for example problem solving and logical analysis of a situation or of a data-set. Middle ranking scientists often cited these skills as the most important parts of their work. During discussion senior managers referred to them in terms of how they made decisions or developed strategies for a work programme. Unfortunately the extent to which these abilities are developed on-the-job was not adequately probed during interviews. On reflection this would have proved to be a useful inquiry, though it is not certain that the interviewees would have been able to articulate the process by which such skills develop.

### **Work in context**

The final theme emerging from the interview data is concerned with the need for scientific workers to be able to see their work in relation to the work of colleagues, the work of other teams or of the organisation as a whole. The strongest indications of this theme comes through discussion of the nature of teamwork but it also emerges in the expressions of the need for new recruits to have a business awareness. Some interviewees were keen to criticise their own training because it lacked a “real world” perspective. The value attached to work experience by some interviewees also adds something to this theme.

### **The work scientists do**

In summary, analysis of the new evidence, arising from the interviews with practising scientists, leads to the following set of characteristics (Table 15 on the next page) for people carrying out scientific work.



**Table 15: The broad characteristics of scientific capability**

<b>Characteristics of scientific capability</b>	<b>Comment</b>
<b>A. Knowledge of facts, principles, laws and theories</b>	knowledge is needed at all levels of work. The knowledge required is often specialised and personalised.
<b>B. Generic (non scientific) skills</b>	Such as the ability to communicate well with individuals and groups, the ability to seek out relevant information, the ability to work well with others.
<b>C. The ability to manipulate skillfully equipment and materials</b>	Measurements and creating observations. Appropriate accuracy, good consistency and a knowledge of the underlying principles on which the measurement or observation is based is important.
<b>D. Understanding how to experiment</b>	The ability to solve a problem by analysing the nature of the problem, creating a hypothesis to test and constructing an experimental procedure which is well controlled and is likely to yield data of optimum value.
<b>E. The ability to analyse data</b>	Data arising from different sources and in different forms (words, numbers, graphical, images) to create statements which can be shown to have a basis in the data. Logical thought and open-minded consideration of evidence is part of this feature
<b>F. Appreciating the nature and structure of science work</b>	This includes appreciation of different approaches to creating new, reliable knowledge. On a local scale it includes such things as understanding how the parts of a science work group interact and the ways such groups contribute to more general purposes within companies and public services. On a wider scale it involves knowledge of how science makes progress.

In the discussion which follows the features in Table 15 are, at first, written in as they appear in the left hand column; however to aid the flow of the discussion, they are identified in letter form later in the discussion.

**A check on consensus**

In order to check the degree to which the interview data supports the areas of scientific work described in Table 15, a further analysis was carried out. Each interview transcript was read again to determine the level of support each interviewee would give to each of the features in Table 15. The results of this further analysis is presented in Table 16.

<b>Key</b>	
Each interviewee is represented by a unique code, 1A, 3B etc.	
✓	signals a weak but significant reference, for example the feature was raised by the interviewer and confirmed as important by the interviewee, or it was raised in passing by the interviewee.
✓✓	signals a strong reference, for example the interviewee took pains to stress the importance of the feature.
✓✓✓	signals a very strong reference, for example, the feature was a recurring theme for the interviewee.
The <b>b</b> or <b>s</b> under the knowledge heading indicates whether the interviewee identified broad or specialised knowledge respectively. No reference indicates no clear indication.	

**Table 16: The level of support for the six features of scientific practice**

Interviewee code	Knowledge-base (A)	General skills (B)	Manipulate skillfully (C)	Understand how to experiment (D)	Analyse data (E)	Nature of scientific work (F)
1A		✓	✓			✓
2A	✓✓b	✓✓✓			✓✓✓	✓✓
2B	✓✓b	✓✓			✓✓	✓
3A		✓	✓			✓
3B	✓b	✓✓	✓✓✓	✓	✓✓	✓
3C	✓✓s	✓	✓✓	✓?	✓✓	✓✓
3D	✓	✓	✓✓✓	✓✓	✓✓	✓✓
3E	✓s	✓✓✓	✓✓✓	✓	✓✓	✓
3F	✓s	✓	✓✓✓	✓	✓✓	✓
3G	✓	✓	✓	✓	✓✓✓	✓
3H	✓b	✓	✓✓✓	✓✓	✓✓	
4A	✓b	✓✓✓	✓		✓	✓✓
4B	✓✓s	✓✓	✓	✓✓✓	✓✓	✓
4C	✓✓s	✓		✓	✓	
4D	✓b	✓	✓	✓✓✓	✓✓✓	
5A	✓	✓✓	✓✓	✓✓	✓	
5B		✓	✓✓	✓✓	✓✓	✓✓
5C			✓			

Table 16: continued

Interviewee code	Knowledge-base (A)	General skills (B)	Manipulate skillfully (C)	Understand how to experiment (D)	Analyse data (E)	Nature of scientific work (F)
6A			///	✓	✓	
6B						✓
6C	///s	///	✓	///	✓	✓
7A	///	///	///		✓	✓
8A	✓b	///	///		✓	///
8B	///b	///	✓			///
9A	✓b	///	///		✓	✓
9B	///b	✓	///		✓	
9C	///	///	///	✓	///	///
10A	///	///	✓	✓	///	✓
10B	///	///	✓	✓	✓	
10C	✓	///	///		✓	
11A	///	///	✓		///	///
12A	✓b	✓	✓			✓
12B	///s	///	✓	///	///	
12C	///s	✓	✓	///	✓	
12D	///s	✓	///	///	///	✓
12E	///s	✓	///		///	✓
12F	✓b	✓	///			
13A	///b	///	///			✓
13B	///	///	///	///	///	
14A	✓	✓	✓			///
15A	✓b	///	///	✓	///	///
16A	✓		///			
16B	✓	✓	///		✓	///
17A	✓b	✓	///		///	✓
17B	✓	✓			✓	
18A	///s		///	///	///	✓
18B		///	///	✓	///	✓
18C	///		///		✓	
19A	///	///	///	✓	///	✓
20A	///s		✓	///	///	
21A	✓b	///	✓	✓	✓	
21B	✓b	///	✓	✓	✓	
21C	✓b	///	///	✓	✓	
22A	///	///	✓	✓	✓	
23A	///s	✓	✓	✓	✓	✓
24A	///s	✓	✓	✓	///	✓
25A	///	✓	///	✓	///	✓
25B	///b	///	///	///	///	///
25C	///b	✓	///	///	///	
26A	///s	✓	///	///	///	
26B	///s		///	///	///	

Table 16 shows that the six broad features of scientific work identified have a good grounding in the interview data. Support appears to be strongest for *manipulate skillfully* and *analyse data*. The weakest support is for *knowing how to experiment* and the *appreciating the nature of scientific work*. In the case of the former the gaps in Table 16 correspond with interviewees who work at lower levels. This confirms that the ability to experiment is usually regarded as a high level task. The gaps associated with the *appreciate the nature of scientific work* feature is likely to be a function of the diffuse nature of this characteristic. If there was any doubt that the interviewee intended to refer to *appreciating the nature of scientific work* then no check mark was made in column 7.

Table 16 also illustrates the even balance between those scientists who see specialist knowledge as important and those who see a broad base of scientific knowledge as desirable. It is generally the case that those who identified a specialist base are high-level research scientists.

### **A check against the literature on scientific work**

There is little literature which is specifically related to the focus of this study. Nevertheless there are some interesting issues which arise when the conclusions reached about the six characteristics of scientific work are compared to the conclusions of other researchers operating in related fields.

### **Science as a profession**

In his work of analysing professional activity across a range of professions Eraut (1994) identified five characteristics which were generally present. These characteristics are also broad in nature and it is possible to interpret them in a way which matches well the outcome from the interview data, (subsequently referred to as primary data) given in Table 15.

Eraut's first category is *acquiring information*. It could be argued that the primary quest for scientists is to obtain information. However a scientist's activity in this respect would have to be considered in two parts. Firstly it would involve the gathering of secondary data and would be no different to the way any researcher focuses on the information requirements of a problem. This is a general skill (see B in Table 15). The second aspect of a scientist's quest for information relates to the way scientists gain data and knowledge from experiments. The knowledge needs to be defensible and must stand up to practical and academic testing. In this sense it is acquiring reliable information and this has its place under C, D and E in Table 15 above.

Eraut's second aspect of professional activity is *skilled behaviour*. If we take this to mean skills which are more or less specific to a professional group then it corresponds with the skillful manipulation (C) and possibly the experimentation (D) which were derived from

primary data. It is also possible to consider a cognitive aspect to skilled behaviour when one considers scientists combining areas of knowledge to create new knowledge. This would lead to the inclusion of A within Eraut's *skilled behaviour* category.

There is also a good match between Eraut's *deliberative processes* and the ability to experiment (D) and analyse data (E). The broader aspect of appreciating the nature and working in science (F) will also have features which can be seen as *deliberative processes*. The achievement of a set of data and a conclusion at the end of an experiment is only one part of a larger scheme of work with which practising scientists engage. The setting up of projects, achieving support and funding, establishing a team and setting up equipment are all preliminary *deliberative processes*. After the data and conclusion have been established the *deliberative process* of dissemination begins which can be complex and extended in time.

Eraut also identifies *giving information* as part of the work of professionals. Scientists in analytical laboratories and other public services do this as a matter of primary duty, others such as research and development workers are expected to deliver high value information on a regular basis. Eraut's characteristic is covered under the general skills heading above (B) but this may not represent as substantial a *giving of information* as Eraut intended. The substance of the information to be communicated as a professional activity is captured in "analysing data" (E in Table 15). The professional behaviour of using scientific journals and peer appraisal is captured under the heading "appreciate the nature and structure of scientific work" (F in Table 15).

The last area of professional behaviour Eraut identifies is *metaprocesses for directing and controlling your own behaviour*. The outcome of the analysis of the primary data does not cover this area well. There is no doubt that senior managers and team leaders have the scope to control their own behaviour but there is much less for the junior technician or an analyst. The interviewees were not asked details of how much scope they had for decision making in this way. Neither was data from work observation of sufficient weight to allow conclusions to be drawn about the scope for this type of professional behaviour. Just three (of 35) managers mentioned initiative as a desirable feature of technicians or new recruits.

*Manager: The technicians still need quite a lot of help if they've got practical problems. You're still having to continually solve practical problems.*

*Int: If you could put your finger on one thing that technicians often don't do well enough, what would that be?*

*Manager: Showing some initiative.*

*Int: Even if they might be worried about getting off on the wrong track?*

*Manager: Yes.*

Although the primary data points away from *metaprocesses for directing and controlling your own behaviour*, it is likely that junior scientists do have an element of control over the way they do their work. Excepting the most basic of routine activities, there were two such cases in the interview process; the tasks and responsibilities of technicians were so complex that the route through the work was, to a degree, determined by the individual. Taking the primary and secondary data into account there is a case for including this capacity to think about and direct one's own behaviour as a characteristic activity of scientists. This characteristic is probably best incorporated into general skills, B in Table 15. However for the more senior strategists it probably demands its own distinctive place in the description of scientific capability. In Table 15 the characteristic has been included in the detail of B.

### **Science in medicine**

In chapter 4, work by Norman (1985) on the medical profession was reported. Norman concluded that the work of physicians has five aspects.

- Clinical skills: the ability to acquire information and interpret its significance.
- Knowledge and understanding: the ability to remember relevant knowledge about clinical conditions.
- Interpersonal attributes: the expression of personal and professional character.
- Problem solving and clinical judgement: The application of clinical skills, knowledge and interpersonal skills in the diagnosis, investigation and management of a clinical problem.
- Technical skills: the ability to use special procedures and techniques in investigation and management of clinical problems.

There is a close correspondence between the outcome of Norman's work and the analysis of primary data from a broader range of scientific work. Norman distinguishes *clinical skills* and *technical skills*. The former correspond to the ability to manipulate skillfully (C) in Table 15 although Norman may have intended the *clinical skills* to include a large component of applying knowledge. This feature is covered by the ability to experiment (D) in the analysis of primary data. Norman's *technical skills* certainly relates to this outcome. There is no equivalent in Norman's structure to the category 'appreciate the nature and structure of scientific work', F in Table 15, since only the area of clinical work was the focus of his study and it did not include general tasks such as management and administration.

### **Progression in scientific practice**

The progression in characteristics of work from junior to senior scientists described by the Dreyfus brothers (see p18) also bears a strong correspondence to evidence in the primary

data. There are several dimensions which the Dreyfus brothers believe develop with growing professionalism. The first is the *dependence on rules and protocols* which relates to C in Table 15. The novice needs a framework of rules and protocols, the expert works independently of them. The primary data reveals that protocols dominate the lower levels of work and increasing regulation seems to be leading to greater use of protocols. Protocols are devised, appraised and approved by senior scientists.

No direct questions were asked in interview which would confirm or challenge the Dreyfus brothers' second assertion - that *the extent to which scientists see what they are doing as context specific* decreases with seniority. Certainly high levels of teamwork tend to broaden all minds as to the general thrust of work. Perhaps the progression that the Dreyfus brothers have identified shows itself more clearly in more hierarchical structures than those encountered in this study.

The third dimension of development identified by the Dreyfus brothers is about *the way the scientist sees a project*, this relates to F in Table 15. In the novice the vision is one of parts which (somehow) come together as a project. The expert has a deep and sensitive overview, a vision of the whole project and its implications. This is supported in the primary data where many interviewees pointed out that senior staff were responsible for the strategic thinking about the direction of the work. This strategic thinking demands an overview. Once again the use of teamwork means that even junior staff become aware of overall goals even if they were not part of formulating them.

### **Studies of scientists work**

The major study of scientists, technologists and mathematicians conducted on behalf of the CSTI (1993) identified characteristics of the work of these people under three main headings - scientific, communication and managerial. These are described in detail in Table 1, p12.

Scientific aspects of this work included:

- generating ideas, hypotheses and theoretical models and using those postulated by others;
- designing investigations, experiments, trials, tests, simulations and operations;
- conducting investigations, experiments, trials, tests and operations;
- evaluating data and results from the processes and outcomes of investigations, experiments, trials, tests and operations.

There is strong support here for the analysis of primary data as reported in Table 15. The other two characteristics reported in the CSTI study, *communications* and *managerial aspects of work*, correspond with B and F in Table 15. The CSTI study (CSTI, 1993) reports 34 discrete activities which are part of the work of scientists, technologists and mathematicians. The correspondence of these discrete activities and the activities in Table 15

is included in Annex H. There is a good match, all the discrete activities correspond with one or more of the features in Table 15.

### **Managerial skills**

The emphasis on management in the CSTI study stretches the bounds of the “general skills” category in Table 15 in much the same way as Eraut’s study did (see above). Management skills are certainly important in the work of senior scientists. Charlesworth (1989) reports that, especially for the senior scientist who must coordinate and consult with technicians, students and post-doctoral fellows, there are a host of non-research commitments which are part of work - writing papers and grant applications, preparing reports on other scientists papers and grant applications; looking after visiting guests; attending meetings, seminars and major conferences; handling personnel and management issues. Inevitably Charlesworth concludes that the more senior the scientist, the less time they spend at the bench.

There is a sense in which the managerial skills of senior scientists can be considered as scientific rather than generic. Such skills will often be brought to bear on scientific problems and demand scientific knowledge and knowledge of scientific procedures. In this sense management skills should take their place as a separate category in Table 15. However these broad management skills may be better classified as generic rather than scientific because they will often carry only an administrative (non scientific) function. There is no clear solution to this issue. The creation of a new distinct part of feature B to cover *managing systems, equipment, people and personal work programme*, overcomes this difficulty. It ensures the scope of scientific practice is clear to scientists and other users.

General skills are seen as a key aspect of work by many organisations (see Table 4) and are often associated with good management. In a memorandum on higher education the European Community issued in 1991 the European Commission reported (p4) a shortage of important general skills which included quality assurance skills, problem solving skills, learning efficiency, flexibility and communication skills. The report went on to highlight a shortage of critical scientific and technological skills. There is little doubt that a selection of these skills should be considered part of scientific capability.

### **An higher education perspective**

During 1994 and 1995 a survey was conducted among tutors about the abilities of new students entering the faculty of Applied Sciences at the University of the West of England (UWE) (Croudace, 1995). They were asked to classify the abilities required in new students as *essential* or *desirable* or *helpful*. Accepting that the tutors want to have students with interest and motivation for study of their subject, and focusing attention only on the essential abilities, the list on the next page was developed.



- Background (underpinning) knowledge
- Experience of using laboratory equipment for preparing materials for experiment and analysis and for making measurements and systematic observations
- The ability to analyse, interpret and draw conclusions from experimental data
- Skills of analysis, synthesis and critical evaluation
- General skills such as
  - organise, present and communicate information
  - a solid foundation in numeracy
  - basic study skills e.g. information search and retrieval

The list of abilities produced by the faculty has a good correspondence with the outcome of the research reported in this thesis. The UWE survey is a helpful endorsement of the model which has emerged in this research since the faculty there has a tradition of strong links with local scientific businesses and services. However there are two important differences between the outcomes of the survey and this research study. Firstly, experimental design, which was identified in this study as a key part of scientific work, is only implied in the UWE list. This may be due to the rather restricted scope of practical work in many HE science departments (see Meester, 1994). It may also be an acknowledgment that higher level skills are a more significant part of the work of senior scientists. Secondly there is no statement about appreciating the way science works. However, in the next categorisation in the research report (what is *desirable* rather than *essential*), work experience is often identified. Work experience would be a key contributor to the process of allowing students to gain an impression of the ways science works in the 'real world'.

In addition to lending support to the outcomes of the present analysis, the UWE survey signals that some education providers have recognised the key elements in preparing students for scientific work. However there is no indication that these characteristics are developed in the courses the students follow or that they are assessed and reported so that employers can distinguish between students in terms of the extent to which they meet the requirements of the job.

Three categories in Table 15 (C, D and E) are associated with data generation and analysis. These may be the central part of the activities of scientists. Certainly other researchers have reported this perception, for example Mittroff (1974). Charlesworth reported in his study of a large research institution (Charlesworth, 1989, p 108):

*What impresses me more and more about a good deal of science at the Institute is the concentration on 'getting data'. Everything seems to be subordinated to the production or generation of data.*

The degree to which the findings of this study of scientific work match fields which other researchers found part of professional activity is summarised in Table 17.

**Table 17: Scientific work and broader professional activity**

Characteristics of scientific work	Characteristics of broader professional activity
A. Knowledge of facts, principles, laws and theories	<ul style="list-style-type: none"> <li>• skilled behaviour (Eraut)</li> <li>• knowledge and understanding (Norman)</li> <li>• background (underpinning) knowledge (UWE)</li> </ul>
B. Generic (non scientific) skills	<ul style="list-style-type: none"> <li>• acquiring information (Eraut)</li> <li>• skilled behaviour (Eraut)</li> <li>• giving information (Eraut)</li> <li>• meta processes for controlling your own behaviour (Eraut)</li> <li>• interpersonal skills (Norman)</li> <li>• communications (CSTI)</li> <li>• managerial aspects (CSTI)</li> <li>• organise, present and communicate information, a solid foundation in numeracy, basic study skills (UWE)</li> </ul>

**Table 17: continued**

<b>Characteristics of scientific work</b>	<b>Characteristics of broader professional activity</b>
C. The ability to manipulate skillfully equipment and materials	<ul style="list-style-type: none"> <li>• acquiring information (Eraut)</li> <li>• skilled behaviour (Eraut)</li> <li>• technical skills (Norman)</li> <li>• dependence on rules and protocols (Dreyfus brothers)</li> <li>• conducting investigations, experiments, trials, tests and operations (CSTI)</li> <li>• experience of using laboratory equipment for preparing materials for experiment and analysis and for making measurements and systematic observations (UWE)</li> </ul>
D. Understanding how to experiment	<ul style="list-style-type: none"> <li>• acquiring information (Eraut)</li> <li>• skilled behaviour (Eraut)</li> <li>• deliberative processes (Eraut)</li> <li>• clinical skills (Norman)</li> <li>• generating ideas, hypotheses and theoretical models (CSTI)</li> <li>• designing investigations, experiments, trials, tests, simulations &amp; operations (CSTI)</li> </ul>
E. The ability to analyse data	<ul style="list-style-type: none"> <li>• acquiring information (Eraut)</li> <li>• deliberative processes (Eraut)</li> <li>• clinical skills (Norman)</li> <li>• evaluating data &amp; results from the processes and outcomes of investigations, experiments, trials, tests &amp; operations (CSTI)</li> <li>• the ability to analyse, interpret and draw conclusions from experimental data (UWE)</li> <li>• skills of analysis, synthesis and critical evaluation (UWE)</li> </ul>
F. Appreciating the nature and structure of science work	<ul style="list-style-type: none"> <li>• deliberative processes (Eraut)</li> <li>• giving information (Eraut)</li> <li>• the way a scientist sees a project (Dreyfus brothers)</li> <li>• managerial aspects (CSTI)</li> </ul>

### **In conclusion**

Chapter 4 of this thesis summarises the theoretical perspectives on scientific knowledge and skills and gives a digest of the many reports, statements and conference proceedings which relate to technical work. The conclusion to chapter 4 includes the following statement (p51).

The scientific knowledge-base has to be supplemented with the thinking processes which draw on concepts of evidence, the skills of practical manipulation and certain 'habits of mind' if the area of scientific work is to be explored comprehensively. The important components of scientific knowledge and skills which emerges from the analysis in this chapter can be summarised as:

- General skills
- Knowledge of explanatory concepts
- Scientific Skills
  - application of explanatory concepts
  - concepts of evidence
  - manipulation of equipment
- Habits of mind
  - analytical thinking
- Knowledge of how scientific work progresses

These components are complementary to the categorisation of the ways scientists work which emerged in chapter 2. We now have a distillation of research and theoretical constructions which can be used to evaluate the outcome of the empirical work of this research study.

It is clear that the extensive analysis of secondary data in chapters 2 and 4 has lead to a synthesis which is closely related to the outcome of the analysis of the primary data which has produced table 15. However there two important differences.

The first of these is that the features in Table 15 do not emphasise that knowledge must be *applied* and that there may be a *skill* associated with this application. The reason for this is likely to be that interviewees probably took it for granted that any knowledge-base they needed was only useful if it was applied in some way in their work. The problems of exploring aspects of work which scientists "take for granted" and fail to articulate has been discussed in chapter 5, p75. The application of knowledge as a *skill* is potentially a very important aspect of this study since there are different views as to the primary function of

science education in schools. One perspective is that students need to learn the basic ideas for application later (broadly an academic perspective), another view is that students need to learn how to apply what they know to improve this capability (broadly a general vocational perspective). This issue is discussed further in the next chapter.

The second area of difference between the primary data and the secondary data is that the primary data reveals a much broader focus on the context of scientific work. The feature F in Table 15 includes a social and economic dimension whereas the conclusion from secondary data analysis about the *knowledge of how scientific work progresses* seems to be a more academic or theoretical appreciation of the nature of science. The issue of the importance of context for scientific work is also taken up in the next chapter.

In summary, the model of scientific capability developed through analysis of primary data has strong support from other theoretical and empirical perspectives. The important feature of the new model is that it has been designed for use in evaluating science education and training programmes.

Drawing all of the arguments above together, and using primary and secondary data, it is now possible to attempt a description of scientific capability.

A person who is scientifically capable can use scientific knowledge and skills to do such things as synthesise knowledge, develop procedures, analyse and make materials and artifacts, provide services, maintain facilities and monitor effects of human activity

Typically such capability is demonstrated through use of scientific ideas, general skills, practical skills, problem solving by experimentation, decision making by analysing evidence. The person will appreciate how scientific work progresses and contributes to society, business and changing the environment.

People can be scientifically capable at a range of levels. As a person becomes more scientifically capable they are likely to be working with more conceptually demanding ideas in more complex situations. They will often use a broader repertoire of skills including those of strategic thinking and management skills such as those used in supervising and guiding the scientific work of others.

## Chapter 8: Education and training for science

### What are the ways in which science education and training could respond to the description of the work of scientists?

This question is discussed in this chapter against the evidence gathered for this thesis. However this can only be the beginning of a discussion and, for the moment, it must remain at a broad level of discussion. For example it is not possible at this stage to distinguish sharply between the different phases of science education or different qualifications. A detailed analysis of this type could only follow a consideration of the features of science education and of how much impact the practice of science in work should have on each phase of education. The discussion which follows touches on some problematic areas of science education such as the role of practical work and the relationship of science to technology. These problematic areas must also await detailed discussion in follow-up work to this research, when reliable information about practice in education has been analysed.

### Science education from an employment perspective

There are many reasons for reviewing the way science is taught and learned with a employment perspective. A review of the purposes and features of science education which is conducted from outside the system is likely to examine parts of science education which can be assumed to be fixed and are often exempted from evaluative studies; see Eraut (1998) for a discussion of this notion as it applies to curriculum frameworks in 16 - 19 education.

School science education can appear a closed system. It seems to recycle a long established view of science which is centred on theoretical knowledge rather than the routes to such knowledge. Practical knowledge (applied knowledge) is undervalued relative to theoretical knowledge across the education system (Eraut 1998). This may be because curriculum planners may not be sufficiently knowledgeable about how science is used. Planners may know of *applications* of ideas, for example, the energy transfers in cooling towers in power plants, but do they know how people who work with science use it? People use it in different ways - nurses use science differently to research chemists. Generally science courses do not lay emphasis on issues related to people, the environment and the economy<sup>25</sup>; although there are notable exceptions (e.g. Salters' schemes) and some new schemes are focusing strongly on these issues (e.g. Science for Public Understanding - a new AS qualification). Science curricula are not sufficiently refreshed by interaction with society; the employment perspective, gained through interaction with businesses and services, may provide part of that refreshment.

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<sup>25</sup> I have recently reviewed physics attainment at 16+ in England and Wales as part of a European Union/Socrates research project. The lack of emphasis on social, economic and environmental implications of physics is clear and is also the case in some other EU countries.

Knowledge of the traditional facts and concepts of science is relatively easy to use in planning, teaching and assessment and can dominate curricula. This may be to the detriment of the development of broader capabilities such as gaining access to information resources and using them effectively. General skills such as communication are also often neglected. Practical scientific capability is also adversely affected by the dominance of a knowledge of facts. It is only recently we have faced up to the challenge of teaching and assessing investigational science in schools. Increasing the status of practical abilities and general skills and would add weight to arguments for more liberal assessment regime (such as a wider range of methods, or different weightings for methods used).

Another reason for looking at science curricula from a work perspective is because there is now more central control over curricula than previously (e.g. National Curriculum, core content for GCE A levels and GNVQs). This has led to a curriculum which is designed to meet a very broad range of needs. However there are stark differences in the needs of different students and many variations in preferred learning styles. For these reasons one general science curriculum is unlikely to meet the needs of many students. Science curriculum development has also weakened: LEA advisers and Advisory Teachers who have traditionally had a significant influence on the developing curriculum and on the co-ordination of in-service training for teachers have been directed to other professional activities such as inspecting schools (House of Commons, 1995). To recharge the system there needs to be a reappraisal of what is valued. Consultation with employers and the consideration of a vocational perspective can be a key part of this process.

It is almost self evident that school science needs to articulate with the science practised in industry, services and research. Many students will work in technical jobs. The way that businesses operate has been changing rapidly in recent years. Young people need to be aware of how businesses organise their work if they are to make good career choices and be well prepared for entry into work. Care is needed here since many people would say that it is a disposition to provide for those who will pursue science courses in higher education which has led to the current narrow curriculum in the UK. A balanced approach is needed if differentiation between students (those that wish to continue and those that do not) at 14 is to be avoided.

There are also problems with low levels of recruitment of young people into careers in science and technology. Increased motivation to study science and technology may arise from a better appreciation of the type of work scientists do. This might then lead to increased recruitment. If school science were informed by the way science is practised in businesses and services, young people would then be able to sample the activities which

working scientists use. They should be able to make career decisions based on firm, first-hand experience.

These reasons for evaluating science education against what scientists do in work make it clear that there is potential for science curricula to become broader, more varied, more relevant and allow students to become more aware of the practice of science and, if it is their intention, more employable in scientific work.

There is no sense in which the work reported here is driven by a functionalist approach, aiming simply to deliver to employers applicants with the “right” characteristics. Most people do not work in a science-based job and may not require the type of education which is geared to capability in such jobs. General science education, which is appropriate for all students may need to be protected from too great an influence from those with the interests of the few (future scientists) in mind. Nevertheless I believe the views of the many employers who have contributed to this research study should not necessarily be taken to be at odds with the goals of good, general science education.

Chapter 6 (section B p90) included a review of the opinion of scientists about their scientific education and training. Those interviewed were also asked about the education and training received by recent recruits to their organisation which often included sandwich course students. These two sets of primary data are now coupled with commentaries on the education system from authoritative sources in the UK and Europe. The headings of the sections that follow therefore include the main findings described in chapter 7 but are necessarily broader to take into account evidence from authoritative sources such as those which informed the discussion in chapters 2, 3 and 4. Each section concludes with some questions which might form an agenda for further inquiry.

### **The scientific knowledge-base**

The central position of explanatory concepts (scientific facts, principles, laws and theories) was clear from all the research evidence considered in this thesis. Almost all interviewees identified their knowledge-base as an important aspect of their capability. There is some evidence that, for jobs at higher levels, working scientists see some specialisation in the knowledge-base as a useful feature in the later stages of education. Some interviewees talked of having knowledge of more than one field and for certain occupations this was an explicit requirement. The problem with developing this knowledge-base in education is determining what counts as useful knowledge. The methodology employed in the Coles and Matthews (1996) *Fitness for Purpose* study was an attempt to narrow down the field of knowledge seen as important; this is summarised in Annex I. It can also help define the demand or level at which the ideas should be taught and learned. The *Fitness for Purpose* methodology is particularly effective in identifying “action” knowledge (knowledge used frequently in a job).



It could assist in weeding out of existing programmes of knowledge which has become redundant through progress in the field. One problem with the process of defining the knowledge-base in this way is that people in work have personalised<sup>26</sup> the knowledge-base as described earlier (see p75). Nevertheless the idea of getting professional scientists to explain their way of understanding should be pursued since it is an effective way of training new professional scientists (Argyris and Schon, 1974) and encouraging more analytical thinking amongst practising scientists.

One of the problems of modernising the knowledge-base is that science educators see a core of ideas as central to most scientific activity, for example the concepts of the conservation of energy, and the notion of a dynamic equilibrium or homeostasis. These are important parts of science courses. The problem is that there are many of them and they quickly fill the space available in the core. Furthermore they are basic ideas and are usually well established. This can lead to a feeling that the core is dated. During the definition of a core for A level physics syllabuses in 1992, a commentator speaking for the Institute of Physics felt moved to remark that *it was a pity a core for advanced physics education in the late twentieth century contained no twentieth century physics*. When a core is large, the non-core material to be included has to be limited. This additional material is usually drawn from a bank of explanatory concepts which are traditionally part of a particular area of science. The introduction of new areas of science knowledge becomes very difficult. If syllabuses are not modernised teachers can become over familiar with content and this may lead to dull, routinised teaching. These problems may be eased by using a knowledge-base determined through the analysis of action knowledge. There is also the possibility that educationalists can be persuaded that a knowledge-base derived from science practice is at least valid in the sense it will prepare students better for scientific work. This may be more convincing than arguments which may appear to teachers to be about what content seems most fashionable at a particular time.

Another issue which arises as a result of having a large core of knowledge is that the assessment of knowledge can dominate the overall assessment regime in a given qualification. Knowledge can be assessed by straightforward methods of written answers to questions. The assessment method can require recall of facts, application of ideas and analysis of data. The examinations can be shown to be fair and yield reliable data. However, fairness and reliability may be more difficult to establish in the examination of the scientific skills associated with experimentation. The same will apply to the examination of general skills - for example those associated with managing a project. The examination of aspects of scientific capability (and general skills) which complement knowledge of explanatory

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<sup>26</sup> Public knowledge which gets incorporated into action knowledge undergoes a process of personalisation in which some interpretations and uses become prominent while others get neglected. Hence its personal significance and meaning will show some variation between one professional and another.

concepts, can become complex and expensive to operate. Outcomes of these relatively complex procedures often command less public confidence than those derived from written examinations. This is not the place to discuss the advantages and disadvantages of various assessment instruments but the issue is important because there will be pressure to give more weight to written papers focused on explanatory knowledge. This will lead to less time and effort being applied to the examination of other aspects of scientific capability. The size of the core of explanatory concepts which are included in a qualification, and the weight given to them in examination, needs to be held in check so that the important skills of science, which are not generally assessed through examination, are not undervalued.

The interviews which form part of this study placed emphasis on the skills associated with scientific work, such as experimentation and analysis. These skills do not function in isolation from the knowledge-base. In scientific activities there is extensive interplay between knowledge associated with explanatory concepts, the knowledge associated with experimentation and data, and a range of manipulative skills.

The development of a knowledge-base is already a common feature of general science education. However the following questions need to be addressed.

- What are the central underpinning ideas?
- How much time should be devoted to learning of explanatory concepts?
- What depth of knowledge is required?

### **The development of practical skills**

A second area of science education which can be reviewed using the evidence gathered in this study is the development of practical skills. The scientists interviewed in this research study identified some weakness in the training of students in practical skills and in their awareness of the ways laboratories function. This weakness was identified across the spectrum of levels and types of work. School, college and university courses were criticised for the low levels of relevant practical experience they provide. The scientists wanted more attention to be focused on the ability to manipulate equipment and materials and the ability to measure and create observations, including the need for accuracy and consistency. It is not possible to isolate practical skills from any other form of learning such as the analytical skills of experimentation and evaluating data which have been discussed earlier. There are people working in the laboratories visited as part of this research study who, at first sight, could fulfill their role by following instructions (for example preparing culture medium and disposing of used cultures). It would appear that they use no knowledge-base. However on questioning they explained the value of having some idea of the background to the observations or measurements they were making and the way the equipment functioned. Sparkes (1994) definition of a skill as *a complex sequence of actions which have become so routine through practice and experience that it is performed almost automatically* seems to

describe the situation accurately. The actions are *almost* carried out automatically. This is taken to mean there is some cognition needed to accompany the following of instructions.

Education at all levels provides opportunities for the practice of practical procedures. There is a debate in science education about the purpose of practical work in science education (Osborne, 1996; Stonehouse, 1998). That debate is mainly concerned with the ways practical work can aid learning of explanatory concepts. There may be questions to be asked about the value of practical work in its own right. The evidence in this research study suggests students need to be able to:

- practice and improve skills;
- explain the background to the measurements and observations and also to the levels of instrument error and human error;
- appreciate the importance of this type of skill in laboratory work.

In fact this range of practical activities is similar to a list produced by Kerr (1963):

*...teachers thought the most important reasons for doing practical work were: to encourage accurate observation, to produce scientific ways of thinking and to provide an opportunity to find out facts and principles by investigation.*

Kerr J. F.,1963, p95

It might be argued that practical skills are best learned on-the-job. When a person joins a science-based team they will be inducted into the specialist procedures the laboratory uses. Often they will shadow an experienced worker until they become proficient in these skills. There is no substitute for this on-the-job training but it may be to the advantage of students considering scientific work if they had had experience of aiming for consistency and optimising accuracy in school or college practical work. They can then recognise the demands likely to be made of them in work. The beginning of their working career is likely to be predominantly practical in nature. This might add further weight to an increased focus on practical work in the later stages of full-time education.

Practical skills can have relatively little effect on the reported outcome of achievement in qualifications (other than any effect on the learning of explanatory concepts). There are possibly two main reasons for this. Firstly the attainment in practical skills is sometimes has a low weighting relative to other attainment. In GCE A levels for example the weighting given to practical skills<sup>27</sup> is about 8% of the marks available. A second reason why qualification outcome does not reflect good practical skill attainment is because there is little differentiation between capable students in these skills and those who are less capable.

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<sup>27</sup> This does not include marks for planning and evaluating.

Assessment instruments for practical skills are often not designed well enough to allow differentiation to occur (see chapter note A). Whether this reflects their importance relative to other aspects of science capability needs to be reviewed.

Practical work is part of some science education provision. However the following questions arise.

- What are the key aspects of practical skills that need to be developed?
- How much time should be devoted to practical work?
- Should the topic of experimental design be reserved for the most able students?
- How should progress in learning these practical skills be assessed and reported?

### **Educating analytical thinkers**

Most, if not all, science syllabuses aim to develop analytical thinking (for example, Department for Education and Science/Welsh Office, 1995; School Curriculum and Assessment Authority, 1996). Analytical thinking is important because it is a key aspect of problem solving and many scientists are employed as problem solvers. The evidence in chapter 4 and chapter 6 (section G) shows this to be a very important aspect of scientific capability. What is special about the way analytical thinking is developed in the context of science and how is it best developed through the education and training system?

There are possibly three dimensions of scientific subject matter which make analysis particularly challenging. The first dimension is that the subject matter could be practical or physical in nature. This introduces the need for decisions about such things as manipulation, sequences of actions, spatial orientation and costs. This may be the only concrete aspect of the analysis. The second dimension is that mathematical thinking may be required. The third dimension is that the explanatory concepts (facts, principles and theories) involved may be demanding in themselves. They can be largely abstract in nature. Some of these explanatory concepts are susceptible to change when applied in certain conditions. Analysis in scientific contexts can involve all three dimensions and can be very demanding.

The fact that people with scientific training are sought after for non-science jobs has been referred to earlier. A significant economic analyst has written about the nature of work in the 21st century and suggested that scientific workers may become more highly valued. Robert Reich (1996), a one-time Secretary of State for labour and an economic adviser to the President of the USA, has described in his book *The Work of Nations: a blueprint for the future*, the likely effects of current economic trends, in particular globalisation, on the work people will do. He identifies a person capable of good analytical thought as a *symbolic analyst* (see p27) and goes on to suggest how such a worker might be educated. He proposes they need to acquire four kinds of *basic* skills.

1. Abstraction: the capacity to discover patterns and meanings;
2. System thinking: seeing reality as a system of causes and consequences;
3. Experimentation: to speed up the process of learning through experience;
4. The capacity to collaborate: analysts will often work in teams.

Reich's analysis has massive implications for the planning, management and content of educational programmes. It is not appropriate to discuss them all here. In terms of science education the first three points are usually embodied in the aims and practice of science education. Reich's last point - *the capacity to collaborate* - is often not an explicit part of science education courses. There is no place in Reich's *basic skills* for the body of scientific knowledge but presumably this provides one of the contexts *symbolic analysts* will use.

*Abstraction* is usually at the centre of higher level science practice. In science education its significance is not consistently clear. Some approaches have stressed the ability to see trends and patterns (for example, Nuffield Foundation, 1970; DfEE/WO, 1995), and one could argue that much of chemistry education is about detecting patterns in data (e.g. reactivity series, periodicity). However, there is a question about who seeks out the pattern - the teacher, the text book author or the student? Which is more efficient - to tell the student of a pattern or to encourage them to discover it for themselves? This represents an analogue of the larger problem in science education "which is more important, the efficient transmission of the knowledge-base or the opportunity for students to practice certain valued skills and develop a knowledge-base for themselves?"<sup>28</sup> A recent study commissioned by the Royal Society of Chemistry into changes in chemistry GCSEs (Coles and Flemming, 1997), found that during the period 1988 to 1995 there was a move away from asking questions of students about trends and patterns in chemical behaviour of substances, in favour of requiring them to recall specific aspects of chemistry knowledge (facts). This points towards lower expectations of students in terms of analysis and abstraction. Research into how much pattern seeking and abstraction is carried out by students, as opposed to students being informed of patterns and trends which have been identified by others, would be useful.

There is some evidence in higher education of increased use of discourse and problem based approaches which might encourage analytical thinking.

*There's been a move away from the very didactic teaching to discourse and debate. At first students feel very uncomfortable, they are used to sitting down and taking reams of note. They feel as though they've not been taught if they walk out without a pad of information. Part of the training is about developing an attitude of mind, they're not*

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<sup>28</sup> This problem has been to the fore in discussions of the strengths and weaknesses of GCE A levels and Advanced Science GNVQ. The former focuses on developing (systematically) a body of knowledge in a discipline, the latter focuses on problems solving across a range of disciplines.

*robots, they're expected to think as well. They have to go out and research something and get away from the view that the only place they can get information is in that one hour session with the teacher. We get them to accept a different way of learning we provide lots of interaction, lots of discussion, lots of deep learning.*

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One reason for using discourse as a learning method is to replicate (as far as is possible) the work situation in which the students will operate at the end of their study. In this method of teaching/learning students are introduced to a problem and then begin a process of research which provides them with background knowledge and the seeds of a solution to the problem. The students then engage in discourse with one another, often in groups, and share knowledge, perspectives and ideas on possible solutions. Certainly this approach compels the students to be analytical in that they abstract information and seek evidence to support a theory they have developed. The extent to which these skills are assessed and reported in the course outcome is not known. The approach leads to an 'action' knowledge-base which can be assessed as an end in itself.

A growing body of evidence from various research traditions points to a problem with the nature and role of evidence in science education in the UK. Whilst many students are able to carry out scientific experiments and investigations, their evaluation and use of the resulting data is weak (Gott and Duggan, 1996). If students do not appreciate the significance and the limitations of data, they may not be able to relate science to everyday problems since they may view data-sets as facts rather than as human constructions which always need to be examined for inconsistencies.

*System thinking*, Reich's second *basic* skill, requires that events are not seen in isolation but that they have arisen because of some action, and further action could change them again. This may be a high level skill, best learned at the highest levels of education. It might also be a skill which is properly developed in the work place. But the basis for the skill, the notion of 'cause and effect', is embedded in general science education through experimental work. Many of the scientists interviewed in this research study practice *system thinking*. The strongest manifestation of this ability was in senior managers who were attempting to optimise a research system by strengthening support for some lines of inquiry whilst attenuating others. Scientists on the bench were *system thinking* too. The cause and effect notion is integral to experiments of the type, "what happens to this factor if I vary this factor whilst holding these other factors constant". If Reich's analysis is supported by policy makers this aspect of education will require further development.

The skill of *experimenting* to optimum effect is identified in the research reported in this thesis to be a key part of scientific work. It is interesting to see that this characteristic of

Reich's *symbolic analysts* is so prominent. He sees the experimenting process as one which allows workers to learn quickly from the evidence of some action. The need for bright, adaptable and powerful analysts in business is clear. That these qualities may depend on their ability to learn for themselves through experiment goes some way to explaining why science graduates are valued outside the science domain and perhaps why so many go on to be managers early in their careers.

Experimenting has always had a place in science education but closer analysis of the experiments students perform may reveal that many experiments are in fact practice in following instructions, rather than considering the experimental options and making decisions about independent variables, dependent variables and controlled variables (Meester 1994; Gott 1994). The introduction of the National Curriculum in England, Wales and Northern Ireland in 1989 required students to begin to think about experiments in this way. See Annex H for an extract of the requirements. As discussed in the preface, the negative reaction to this requirement provided the initial motive for this research.

The financial pressures currently operating in schools, colleges and universities may reduce the level of practical work which is carried out by students. Providing laboratories, specialist equipment, meeting safety requirements and employing technicians makes practical work a relatively expensive provision. This will have a knock-on effect on the level of experimentation and further reduce opportunities for students to develop this critically important skill.

Reich's fourth *basic skill* is the *capacity to collaborate*. It is clear from all the evidence considered in this thesis that practising scientists consider this to be a crucial quality in people. The development of this skill is not generally an explicit part of science qualifications, possibly because UK assessment practises are usually strongly focused on the individual student rather than the student operating within a group. Students do in fact work with others but this may be more to do with limited resources and having to share, rather than aiming to improve the skills of collaboration. More needs to be done to require students to think about making the way people work with others more effective. The key skill of *Working with others* (see below p146) is a step towards achieving this.

In her study of practising engineers Rowell et. al. (1997) realised that what we call problem solving in education often differs in a critical way from the sort of problem solving that takes place in work. This critical difference hinges on collaboration. Rowell makes the point that when a team of people get together to solve an engineering problem, they bring to the collaboration very different sets of skills and experience. However, when this process is simulated in education we put students with broadly similar skills and experience together. The dynamic which ensues in the student group is likely to be very different to the

engineers' experience. If we are to simulate, in an educational setting, how people work together it will be necessary to prepare students for distinctly different roles in a collaborative group. Problems will need to be set up which require inputs from all the students. This points to the need for an analysis of how collaborative group work is planned in educational settings.

If general education is to address the development of analytical skills more directly, the following questions arise.

- What is the nature of these 'analytical' skills?
- To what extent are these abilities scientific?
- How can courses be developed to encourage development in these abilities?
- How should progress in the development of these abilities be assessed and reported?

### **The development of general skills**

It is difficult to overestimate the importance attached to general skills by employers (see for example CBI 1989 and 1993; Engineering Employers' Federation, 1994) and those interviewed as part of this research (see p111). In the UK there has been a strong and consistent pressure from business organisations for a better foundation in general skills to be established in schools and colleges. A pivotal moment in the effort to create a better base of general skills came in 1989 when the Secretary of State for Education (Kenneth Baker) gave a speech to the Association for Colleges of Further and Higher Education (DES, 1989). He called for "core" skills to be identified and incorporated into post-16 curricula and qualifications. Baker believed these skills to be of value to all and transferable across different activities. The National Curriculum Council (NCC) was charged with the responsibility for consulting and identifying core skills. The skills which the NCC identified were:

- communication;
- problem solving;
- personal skills;
- numeracy;
- information Technology skills, and
- modern foreign language competence.

The NCC report raised the profile of core skills in education and led to consideration of how these skills could be embedded in curricula and academic qualifications. They already had emphasis in some vocational qualifications. Progress was at first slow, concerns about the dilution effect these skills would have on the teaching and learning of the subject matter in qualifications thwarted the incorporation of the skills into GCE A levels. However there was a wholly more positive approach to these skills from the National Council for Vocational Qualifications (NCVQ) where new General Vocational Qualifications (GNVQs) were in the early days of development. Gilbert Jessup - the director of the GNVQ development, and



Tim Oates - an expert in the field of general skills - knew the employer perspective well and, recognising the importance of these skills in work, made them an integral and critical part of the new qualifications. Jessup and Oates developed the list of core skills by dropping the modern language competence as a set of skills that everyone should develop and splitting personal skills into two clearly defined aspects: *Working with others*, and *Managing own learning*<sup>29</sup>.

*Communication, Numeracy and IT skills* were included in all GNVQs and *Working with others*, and *Managing own learning* made optional. Jessup and Oates believed *Problem Solving* should be contextualised in every GNVQ subject area and assessed and reported within the subject, rather than as a separate core skill. More recently attention has once again been given to the generic nature of problem solving. Greater detail of the development of core skills can be traced through NCC, Core skills 16 -19, 1990; Jessup, Common Learning Outcomes: core skills in A and AS levels and NVQs, 1990; and Oates, The development and implementation of key skills in England, 1996).

The GNVQs (GSVQs in Scotland) have the advantage of combining development in subject expertise with the development of core skills (these are now referred to as key skills). There is evidence that employers view qualifications which do not incorporate key skills less positively. For example, consider the CIA, ABPI and Ford lists in chapter 4, pp31/32 and Spurling (1993). Zahra & Eberer (1992), Mallia (1994) and others reported that employers were interested in academic qualifications but were seeking evidence of such qualities as motivation, adaptability, willingness to learn, self-discipline, perseverance, positive attitude to work, good listening, oral and writing skills, capability to assume personal responsibility, ability to play effective team role, ability to think critically, having positive attitudes to task completion, and business awareness.

Commentary on the need for recruits with good key skills is usually made in general terms, applying to all occupations. It is likely that some occupational areas have higher requirements in general key skills development than others. For example the manager of a hypermarket will need excellent personal skills, communication skills, number skills and use information technology effectively. It is difficult to place scientific workers in terms of how much they need to be trained in key skills before they take up employment. People in training to be scientists need to develop an extensive knowledge-base and this may be a more important consideration for scientists in training. On the other hand many key skills are part of personal and social development and are needed in learning itself.

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<sup>29</sup> Detailed descriptions of the nature of these key skills were developed by the National Council for Vocational Qualifications and are also published by the main providers of school and college general qualifications in the UK.

The priority given to the practice and refinement of these skills in scientific work raises more questions for general science education where they are often, at best, implicit.

- What are the main general skills which are needed in scientific work?
- Should the explicit development of general skills be an aim of science courses?
- How should progress in learning these skills be assessed and reported?

### **The distinction between science and technology**

School science needs to be reviewed from a technological viewpoint since the evidence considered in this thesis suggests a strong differentiation between the two does not exist in work practice. It seems in life and in work, science and technology interact strongly; to be effective in work, people need to have scientific skills and be able to use them to solve problems, improve products and optimise processes. They need to have a firm grasp of explanatory concepts and of concepts of evidence and be able to apply them both. The literature on technical work rarely distinguishes between science and technology (IRDAC, 1990; CSTI, 1993; OST, 1995b; Chancellor of the Duchy of Lancaster, 1993). The scientists interviewed in this study preferred to use the terms such as 'technology' and 'technical skills' as they described their work. Many were involved in the technical enterprise of production and improving processes. Ziman (1984) attempted to distinguish between the work of scientists and technologists.

*The research scientist is concerned with knowledge as such; the technologist is concerned with knowledge only as a basis for action. He or she must not tarry too long in the ivory towers of academia. A sound grasp of scientific principles, some acquaintance with the body of knowledge, and a brief introduction to recent advanced theories are all that he or she can afford to pick up on the way through to the real work.*

Ziman, 1984, p 10

The way practice was described by interviewees in this study indicates that there is a spectrum of activity which spans Ziman's distinction.

If people work by integrating science and technology activities - even research scientists carry out technological functions - why are the distinctions so persistent in training? Is a science education the best way to train someone who will eventually work as a technologist? These questions are not new, yet we still have a strong commitment to maintain a distinction between the two fields. In education today from the primary phase through to support for higher degrees, science and technology are largely planned and taught separately. They seem to be based on the philosophy 'first you study science and then you can learn some ways of using the science'.

There have been calls for the broadening of science education to make it more technological. The UK Government Advisory Council on Science and Technology (ACOST) have sought a stronger link between science and technology in schools and in university courses. The Council have commented on the unattractive nature of A level science courses:

*... they are thought [by students] to lack direct relevance to day to day issues such as employment industry and the environment.*

ACOST, 1991, p9

The Council for Industry and Higher Education (CIHE) have underlined the importance of *applied learning* in their publication A Learning Nation, (1996), which summarises arguments for a more relevant and (economically) responsive higher education system.

The Scottish Consultative Council on the Curriculum (SCCC) in its publication Science Education in Scottish Schools, states

*... the schools curriculum should encourage imaginative and enterprising use of scientific ideas and processes for practical purposes, providing opportunities for pupils to integrate and apply knowledge and skills from scientific and other aspects of learning. In this way learning in science can contribute, along with learning in other areas of the curriculum, to development of the perspective, confidence, sensitivity and creativity which are key aspects of technological capability.*

SCCC, 1996, p14

Researchers into employer and higher education tutor requirements (Coles and Matthews, 1996) have also noted the call for more application of ideas and greater business awareness in the training of scientists. In Canada, Hepburn (1997) has set up pilot education schemes to bring together academic study and the skills of applying knowledge and skills. This scheme has met with strong support from industry and business. In the UK two of the most popular science schemes for secondary students, Science at Work<sup>30</sup> and Suffolk Coordinated Science<sup>31</sup> were essentially technological in style. These schemes emphasised the learning of scientific principles through applications and gave emphasis to general skills. Both schemes have been subjected to major changes of content, assessment objectives and assessment procedures as a result of Government policy for science as expressed in the National Curriculum. The schemes are now much less “technological” than they one were. The drive to separate science and technology seems as strong as ever.

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<sup>30</sup> The scheme originated in Manchester Local Education Authority and is now the basis of several GCSE syllabuses.

<sup>31</sup> A GCSE scheme administered by the Cambridge and Oxford Schools Examination Council and now administered in much changed form by the Midland Examination Group.

One of the problems with developing a view of science which concentrates on its use is that it tends to look more like technology and engineering - a meeting of need rather than an exploration of new and reliable knowledge. Teachers in schools work within one framework for science and another for technology. Developing a technological approach to science causes overlap between the two frameworks which can result in confusion and create problems for the assessment of the separate disciplines. This is a strong disincentive to such approaches.

The evidence from this research work is that the divisions between science and technology are maintained by education whilst work practice calls for a more integrated view of science, technology and engineering in school education. Questions about further investigation of this field include:

- how can educationalists in science education and technology education work with a common vision and within a common single coordinated framework?
- what are the obstacles to greater coordination of teaching and learning in science and technology education?

### **The importance of context**

The scientists interviewed in this study were keen to explain how important they considered it to feel involved in their work. They wanted to know of the purpose of their work and its consequences. In many of the working situations people worked in teams; in effective teams the purpose of the team was appreciated by all members and each member had a personal responsibility which was known to colleagues. In some teams these responsibilities were rotated around members so that individuals could learn the range of requirements of the team as a whole.

In recent years there has been increasing research interest in the transferability of knowledge and skills from one domain to another. Research evidence suggests that, at best, a student will learn to apply a skill more quickly in a new context if he or she has practised the skill previously elsewhere. Evidence of complete transfer is weak. The area of school mathematics has been the focus of much research into transfer. Teachers have found that the process of learning an idea or technique in a mathematics lesson and, at some later time, applying the learning to a problem in a lesson in another subject is more problematic than it might seem. The same problem is likely to beset transfer of scientific skills to, say, technology settings. Science education needs to be reviewed from the perspective of how well teaching approaches encourage knowledge and skill transfer between contexts.

The abstraction of mathematics from settings has been suggested as a reason for the general dissatisfaction of employers and tutors in higher education with students' maths

achievement (London Mathematical Society/Institute of Mathematics and its Applications, 1996). Tutors in a major medical school are alarmed because students cannot do decimal percentage calculations. Clearly the students have been taught (and have learned) percentage calculations. The dissociation of school and work could be the key to poor transfer.

One of the interviewees in the research exercise asked for caution in the teaching of experimental skills, he felt that the best approach was teaching and learning by *doing* experimental work for real. This person, a research chemist, would find support for his belief from research. Firstly there is a school of thought that has highlighted the centrality the process of doing things in order to learn (sometimes referred to as experiential learning). Aristotle coined the term practical knowledge and this idea has been further refined by Ryle (1949) and Oakeshott (1962). Dewey (1917) viewed learning as the process of reflecting on and organising one's experiences. Schon, in The Reflective Practitioner (1974) has shed light on how the process of reflecting on experience can lead to effective learning. A second school of thought arises in the field of *situated cognition*. Newman, Griffin and Cole (1989) found that the ability to solve problems depends to a large extent on the context of the problem. This outcome draws substantially on Jean Lave's work (1991). In one study she found that although grocery shoppers could successfully solve ratio problems using paper and pencil, they rarely used that approach when confronted with real life ratio situations such as price comparisons. Shoppers took note of contextual clues to solve problems. For example they would choose the larger size because that was *usually* a better price. Or if the ratio was too difficult to work out in context they would change the goal and choose their favourite brand name.

The proponents of the theory of situated cognition would explain poor transfer by proposing that knowledge (explanatory concepts, concepts of evidence and general skills) is linked to the situations in which it is learned **and** to the situations where it is applied. When students learn facts, principles and skills in situations which are distant from those situations where they will be applied, they have difficulty in transferring their abilities. Scientific work settings are not accessible to most students and it might therefore be expected that whilst some students will have learned useful science in school and college, they will have a problem applying it in practice. There are many examples of school and college science programmes where the situational base is extended to enhance transfer (e.g. in vocational science courses<sup>32</sup>, teacher placements in industry<sup>33</sup>). The need for real contextual experience does put some doubt on the long term value in teaching scientific investigation in schools as a academic construction rather than as a problem solving activity. Another way of developing contexts

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<sup>32</sup> GNVQ science courses require links with science based business. Some of the contexts for study are derived from real business problems, scientists from businesses are invited into schools and colleges. BTEC science courses have work experience built in to the scheme.

<sup>33</sup> For example Corrigan (1997) in Australia and School and Industry, IRDAC (1992)

with a greater chance of allowing transfer to work situations is to use discourse or problem based methods as discussed earlier (p142). The method has advantages in that it has a closer fit to the way people may learn in work and this may increase potential for transfer from one situation to another.

**Problem solving**

Many of the scientists contributing to this research study claimed they were essentially problem solvers (see p109). Problem solving is also a key feature in the literature describing employers’ needs (see p35). Contexts for problem solving are therefore important and science education needs to be reviewed from this perspective. Problem solving in education can be very different to that practised in business. Table 17 shows two very different contexts for problem solving. The school situation is more likely to draw on the left hand model of problem solving, science workers are more likely to be associated with the right hand column.

**Table 18: Contexts for problem solving**

Limited context	Extended context
short time scale	long time scale
time limited	unlimited time
limited resources	unlimited resources
specified resources	resources unspecified
work done by individual	work done by team
group work done by peers	group made up of different experts
collaboration not allowed	collaboration encouraged
little technical support	technical support unlimited
no expert advice	expert advice ready at hand
outline of procedure given	new territory
result known to manager	result unknown
assessed for process and outcome	assessed by outcome

Problem solving in schools and colleges suffers many constraints and it would be unrealistic to believe the process of problem solving in business could be faithfully replicated in schools and colleges. Nevertheless there are business practices which could be adapted to educational settings and this might enhance transfer.

Another implication of Lave’s work on situated cognition for education is that if chances of transfer from school to work are to be optimised, it may be effective to explore a range of learning approaches which have different objectives, for example including group activities where each member has a personal agenda and a shared one. In a deep social study of an

international scientific research institute, Max Charlesworth (1989) came to appreciate something of the ways people become effective scientists.

*Becoming a scientist - unlike studying science - requires a great amount of practical experience, not just acquiring a knowledge system. Scientific knowledge and the many recipes and techniques - even if not exactly secret (and sometimes perhaps increasingly, they are secret) - cannot be learned by simply reading the technical literature.*

Charlesworth, 1989, p121

Work experience is a useful way of introducing a different context and is a feature of most curricula, at all levels of education. Perhaps a greater focus on the usefulness of placements with a scientific focus would benefit potential science workers. Recent deregulation of the National Curriculum in England and Wales<sup>34</sup> allow for 14 - 16 year olds to follow a more work oriented study programme; this allows for some students to follow courses other than the (almost) universal GCSE sciences provision.

For general science education the need to focus on the context of science studies raises the following questions.

- Can education to give a real-world perspective to students or is this something that is best learned on-the-job?
- What methods are best for teaching this real world perspective?

### **The currency of science qualifications**

Having considered some of the main ways in which the teaching and learning of science should be reviewed it is useful to consider the way scientific abilities are recognised in qualifications.

It is extremely difficult to generalise about the value of qualifications in preparing people for scientific work - even when the field is limited to science qualifications. Nevertheless it is important to attempt to do so. Evidence in favour of one particular qualification may suggest that an aspect of content, learning style or the assessment regime may have particular value and relevance to employers in science-based organisations. For example, a science qualification which gives a strong emphasis to “hands-on” practical work may appeal to a person recruiting a technician.

Evidence from this analysis suggests ways in which science qualifications could achieve higher value for employers in science-based organisations. However this is not the only perspective from which to assess the value of science qualifications. General science

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<sup>34</sup> Wider use of work-related learning in Key Stage 4, DfEE, 1998

qualifications, and certainly those for students under 16, need to create a broad awareness of science ideas and processes since, for most students, career choices will not have been made. Even those students studying for advanced science qualifications may not have a science-based career in mind since organisations not based on science increasingly seek out science graduates (THES, August 22, 1997, p5). However it is possible that what is valued by employers in science-based organisations and what is of value more generally is not very different. This is an area that requires further research.

It is also clear that qualifications are only part of the information which determines whether a person is successful in getting a job. There is evidence that the match between qualification and job is dependent on market forces, and in times of job shortages, the qualification levels of successful applicants are higher (Sultana, 1997; Mallia, 1994). There is also evidence from the same research teams that certain general skills are highly valued (confirmed in this study) and that evidence of these skills can outweigh evidence of higher abilities suggested by examination success. These factors need to be borne in mind when attaching weight to the value of a given qualification as a preparation for work in a science-based organisation.

The possession of a specific grade in a qualification may simply signal the minimum threshold used to differentiate between applicants. Within science there is some evidence, albeit generally weak and poorly documented, that qualifications have characteristics which do have identifiable value, for example the relatively deep knowledge-base in A levels and the business awareness that is developed in Science GNVQs (Coles and Matthews, 1996).

What are the factors that are, in the eyes of employers, likely to add value or subtract value from an advanced science qualification? The primary and secondary data (see Chapter note B) considered in this research suggest the following (Table 19).



**Table 19: Valuing the features of qualifications**

<b>Feature of qualification</b>	<b>Adds value</b>	<b>Subtracts value</b>
Content: explanatory concepts (facts, laws, principles, theories)	<p>Breadth of coverage of basic principles and underpinning ideas with some specialisation.</p> <p>The need to know how the science has developed and been applied in public service and commerce.</p>	A general coverage of applications without underpinning theory.
Content: concepts of evidence	<p>Experience of designing experiments and seeking and analysing data.</p> <p>Understanding of sources of error and their effect.</p>	No understanding of this type required.
Content: practical experience	Hands on practical work such as observation, preparation, analysis, measurement, derivation, calibration	weak emphasis on practice of techniques.
Content: general skills	Explicit development	Implicit coverage only
Content: problem solving	<p>Includes project work with opportunities for making decisions about ways of tackling problems.</p> <p>Encourages development of depth of knowledge.</p>	Problem solving restricted to written answers to questions.

**Table 19: continued**

<b>Feature of qualification</b>	<b>Adds value</b>	<b>Subtracts value</b>
Content: work experience	Required	Not required
Assessment methods	A balance of written, oral and practical methods with some synoptic terminal assessment.	Any approach which undervalues terminal assessment or places insufficient emphasis on the assessment of general and practical skills.
Differentiation	The “all-round” student obtains the highest grades	Higher grades go to students who nevertheless have weaknesses in one aspect of the qualification.
Outcome	Reflection of current performance and potential for further advancement of skills and knowledge.	Insufficiently indicative of current standard (too skewed a profile of achievement) or too limited/closed to allow potential to show through.

Further research into employers perceptions of what an applicant’s examination outcome means to them would be useful. Why do recruiters and potential working scientists place great value on formal academic qualifications, which often take little account of the skills and attributes needed in professional practice? Why are the “red brick” universities in the UK so successful in attracting the better qualified, and probably more able, students than the “new” universities? It is the latter which are more likely to offer applied courses with periods of work experience which count towards professional membership and consequently a student’s “licence to operate”. Another example of the added value associated with academic qualifications (and the development of a strong knowledge-base) is the relatively low take-up of advanced science vocational qualifications relative to the pure A level sciences. The design of GNVQs (and GSVQs) is based on employer needs, yet the students, or their teachers/parents, see the academic route as potentially more valuable (see Chapter note C). There are some contradictions to this pattern in other countries, notably Germany where the dual system is not so strongly differentiated in terms of abilities. German students seem to see the value in vocational orientation through working and studying with a company (see Chapter note D). This probably shows a deep cultural difference between UK and German society which could be linked to the strength of the German guild system and the value it

placed on time-serving professional practice. The guild system in Germany was able to stand up to the challenge of the universities and their offering of high quality knowledge-based general subject education. The university system, which emphasises the front loading of knowledge in the preparation of a professional scientist has become dominant in the UK.

Any review of science education and training should include evaluation of provision against evidence of what is regarded as important in science qualifications. Without such a perspective the qualifications and the systems which support them may remain unchanged whilst a curriculum change is planned. The questions which need to be addressed in a review of qualifications are:

- What are the main progression routes of students aiming for the qualification?
- What knowledge, skills and attributes are sought in students who move on to these destinations?
- How can the qualification recognise, assess and report attainment in knowledge, skills and in the development of desirable attributes?

In this chapter we have considered a range of features of science education and training which could usefully be reviewed on the basis of the evidence of scientific practice described in this thesis. In the next chapter we go on to consider the ways science education needs to change to address scientific practice more directly.

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## Chapter notes

**A** In GCSE Science for example the bulk of candidates score more highly on the coursework component than on the written papers they complete. This has the effect of generally raising attainment as reflected in the written papers. However the overall outcome does not reflect more highly developed practical skills because there is weak differentiation in this component. The tendency is for GCSE to reflect a general basic ability in practical skills without indicating that a particular student has strengths in this area.

**B** A significant contribution to Table 18 draws on the author's involvement with employers and higher education tutors who select recruits for science jobs or science courses. The development of a new advanced vocational qualification which is deemed to be equivalent in standard to a well established advanced academic qualification meant that the different characteristics of qualifications were thrown into sharp relief. Another source of evidence was the *Fitness for Purpose* study (Coles and Matthews, 1996).

**C** In the UK, the take-up of the advanced academic qualification in the sciences compared to the vocational equivalent qualification is in a ratio of at least 50 - 1. There is

substantial statistical evidence produced by studies at the Universities of Newcastle (Meager, 1997) and Durham (Fitzgibbon et al, 1997) that students following vocational courses are weaker students. The measure used for student 'ability' is the average GCSE score for the student (grade A=7, grade B=6, etc.)

**D** In Germany a dual system of education and training has developed where vocational training has high status. At age 14 students can move into an academic study (gymnasium), which will usually take them through to higher education, or they can elect to move into a vocational programme which will usually lead them into a full-time job. The academic route is full-time schooling which is paid for through local and national taxes. The vocational route can take the form of two days per week basic schooling (in a school and paid for through taxes), two days a week industrial training (in a business, paid for by the company) and one day a week working for the company. Until recently it was generally the case that vocational students were offered jobs if they satisfied course requirements.

## Chapter 9: Changing science education and training

There are some general messages for developing science education which can be constructed on the basis of the evidence analysed in this research. These areas of development are discussed in this chapter. However it will be necessary to have a reliable description of current practice in science education before the results of this research study are used as a template against which to evaluate aspects of science education. This description might be constructed on the basis of, for example, inspection reports on institutions, National Curriculum requirements, examination syllabuses, examination papers, examination performance of students, course documents, schemes of work, and data on take-up of different types of qualification.

### Areas of development

Having considered all of the primary and secondary data and the analyses in the previous two chapters, some areas are now defined where science education could develop so that it better matches the ways scientists work in public and private organisations. Eight areas are suggested; they are listed in Table 20. These areas are not independent of one another; however each of them can be considered separately and could become the focus of independent curriculum development.

**Table 20: Areas of development for science education and training**

	Area of development
1	Focus on the purposes of scientists' work
2	Use contexts for study which are work-related and based on problems encountered in science-based organisations.
3	Provide opportunities for practical activities
4	Provide opportunities for students to analyse situations and data
5	Use active learning methods
6	Make assessment of students' progress continuous and course-work based.
7	Make processes and purposes of work explicit
8	Provide scope for the student to impose a structure on the work.

Current provision of science education and training is likely to address some or all of these areas. The aims of specific courses will mean that one or more of the areas identified here will receive emphasis at the expense of others. This is inevitable with such diverse provision. The potential value of the listing in table 20 is that it serves as a checklist for evaluating provision which aims to prepare students for scientific work. The list will be of less value for evaluating general science education courses where most students are unlikely to join a specialist science course or work in a science based job.

Each of the eight areas for development in Table 19 are now discussed. At the end of each discussion the link to the nature of scientific work is outlined.

### **The eight areas**

#### **1. Focus on the purposes of scientists' work**

This involves developing themes in courses which make explicit the main purposes of the work of scientists as opposed to the more common themes based on the structure of scientific knowledge. The thrust for change here is that the purposes of the work of scientists rises to a more prominent position in courses. This change need not, by itself, lead to a change in what is taught. The knowledge-base currently used in science courses could be mapped on to the types of work that scientists do. This is normal practice in vocational and applied science courses. Another method of bringing the purposes of scientific work to the fore is to set up re-enactments of the development of a substance, a process or a device. Case studies of scientists' work (as individuals and in teams) might highlight some of the approximations scientists make whilst working on a subject which is, for theoretical purposes, clear, unambiguous, accurate and pure. This focus on purposes also serves as a reminder that many scientists work across the fields of science and technology.

The sampling of scientists' work in this research study includes the following purposes of work:

- researching the nature and properties of matter, devices and processes;
- analysis of materials;
- preparing materials for particular applications;
- developing physical devices;
- providing health services;
- maintaining a laboratory;
- maintaining physical devices;
- monitoring the environment;
- optimising agricultural production;
- preparation of chemical materials;
- providing education and training;
- recruitment of scientific personnel;
- management of scientific functions.

Some of these purposes will only be appropriate for courses with a strong vocational emphasis, for example the *maintaining a laboratory* function. Other purposes can provide a

focus for purer courses which are designed to have little vocational emphasis, for example *analysis of materials*.

Using purposes of this type in preparing general science courses could enhance relevance and increase motivation for learning. Some of the satisfaction which many scientists gain from their work might surface in discussions.

It is possible to make more radical changes using the analysis of the work of scientists. The verbs used in the listing above can be used as a guide to 'what scientists do'. Courses (mainly vocational courses) which focus on the work of scientists can be constructed around units of study which use these verbs. The Science GNVQs (NCVQ, 1996) are examples of this more radical use of the purposes of scientists' work<sup>35</sup>.

The features included in Table 15 which can be enhanced significantly by focusing on these broad purposes of scientists work are:

- *ability to manipulate skillfully equipment and materials* because the purposes often have a practical emphasis; and
- *appreciating the nature and structure of science work* because the use of a real purpose may lead to a better appreciation of what it is that scientists are employed to do.

## **2. Use contexts for study which are work-related and based on problems encountered in science-based organisations.**

Using real contexts can help students appreciate the varied nature of scientific work and the ways people collaborate with others to solve problems. Scientists in this study said they need to know about the setting for their work (the background leading to their current activity and the potential of the outcome of the activity). Students need to have opportunities to practice science in a range of settings if they are to be better prepared for thinking and working in scientific organisations. In the field of medical education there has been some significant research into the use of teaching methods based on real-life problems for example: Ramsden et al., (1989), and, for a review of the effectiveness of such approaches, Norman and Schmidt, (1992).

The use of real contexts for study is also likely to lead to an appreciation that the boundaries between science and technology are not clear and fixed in the work of scientists.

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<sup>35</sup> The designers of the Science GNVQs (see Coles, 1995) used the notion that the new qualification should be based on "what scientists do". The qualification was constructed using verbs such as make, analyse, investigate, monitor and control.

Again the feature of Table 15 which is likely to gain extra emphasis is:

- *appreciating the nature and structure of science work.*

### **3. Provide opportunities for practical activities**

This includes opportunities to solve problems through experiment (including design of experiments) and practice techniques. Students need to consider the nature of problems, resources (available and required), and experimental set-up (independent, dependent and control variables); and to practice ways of improving the accuracy of their measurements and observations.

Practical work is important for new recruits to scientific work because almost all will begin their career with a work load which includes a significant practical element.

Most provision for science education and training contains an element of practical work. The rationale for including practical work is often not clear. When a rationale is evident, it often includes objectives other than the straightforward development of techniques. For example it is used to interest and motivate students or to enhance the learning of explanatory concepts. This study emphasises the need for students to develop and refine experimental and practical skills as a clear objective, uncluttered by other purposes. This feature often has a stronger focus in courses with a technology bias.

In recent years there has been a strong emphasis on teaching students about ways of investigating through science ( for example through the National Curriculum in England and Wales and (consequently) GCSE Science requirements). This aspect of science practice has been shown through this study to be more prominent in the work of senior scientists and for people in research rather than production. It could be argued that this feature should be more comprehensively addressed in the education and training of more able students or possibly left for on-the-job training. This would leave more time for other students to develop features of scientific capability which could be of more immediate value in work.

Added emphasis on practical work associated with improvement of skills and problem solving would be likely to enhance the match of a learning programme with the:

- *ability to manipulate skillfully equipment and materials; and*
- *understanding how to experiment.*

It is also likely to enhance *the ability to analyse data*. This is addressed in the next section.

### **4. Provide opportunities for students to analyse situations and data**

The data may be in oral, in visual form, numbers, words or symbols. These data can be used to describe trends, patterns and conclusions. This is a feature of the work of people



employed as scientists - analytical thinking was critically important for many of the scientists interviewed.

Many science courses aim to develop analytical skills. Major examinations give significant rewards to candidates who are able to analyse information with speed and accuracy. Course providers could present situations and data in a variety of forms so that students can begin to appreciate the abilities which are required to show good analysis. The data currently presented to students are often organised and edited for the purposes of teaching. For example they are tabulated or presented with anomalous data removed. Experiments are set up so that the data emerges in a form which is ready for processing. Students are not required to look for weaknesses in method or determine accuracy and confidence limits. At some stage, perhaps when students have gained some experience of using data, raw data can be collected or provided which do not lead to obvious conclusions but require careful analysis of the level of confidence which can be attached to any of the conclusions drawn.

Analytical thinking could take a more explicit form in some courses. The value placed on analytical thinking could be made explicit in assignments. Outcomes could contain reference to the *process* of arriving at a (correct) solution.

Scientists are required to appraise the work of other scientists. Students should have opportunities to be critical of the analyses of others and eventually to be able to propose tests for the validity of conclusions drawn by others.

The features of Table 15 which would be enhanced by a rigorous approach to learning how to analyse are:

- *being able to use a science knowledge-base*, because the data are rarely independent of scientific facts and explanatory ideas;
- *generic (non scientific) skills* because data-sets which are complex can lead to a range of conclusions which are often best evaluated through group discussion (proposal and defence) and the seeking of information from experts;
- *understanding how to experiment* because the reliability of data depends on an appreciation of valid scientific approaches; and
- *the ability to analyse data*;
- and, at least to some extent, *appreciating the nature and structure of science work* because decisions based on weighing evidence require a knowledge of the basis for the original inquiry and an idea of the likely consequences.

##### **5. Use active learning methods**

Active learning methods involve making the student responsible for making decisions during an assignment, seeking relevant information, deciding how best to organise group working,

obtaining interim feedback on work produced and deciding the optimum way of presenting work to a specified audience. The contrasting more passive approach requires the student to respond to a teacher-structured assignment using information provided and defined routes to an outcome.

Active learning methods are important because they allow the students opportunity to develop general skills such as planning, information seeking and team-work which have been identified as important features of the work of scientists. Other methods are less effective because the student needs room for manoeuvre; they have to be able to make their own decisions about such things as approaches to assignments, sources of information and how to contribute best in a group exercise. These more general skills are difficult to teach and learn in any formalised didactic presentation.

Scientists at work learn on-the-job. They can, like students, seek help from more senior scientists or use reference texts or papers. However the steer to solving their problem often comes from themselves and draws on discussion with others. The worker is mostly an active learner, they are much less often in the position of being the passive recipient of information and solutions to problems.

Active learning methods will help to address the following features of Table 15.

- *generic (non scientific) skills;*
- *the ability to analyse data* because students will be free to seek out patterns and trends; they will also be encouraged to discuss data with others.
- *appreciating the nature and structure of science work.*

#### **6. Make assessment of students' progress continuous and course-work based**

Scientists in work generally receive feedback on their progress regularly. Those working on more basic tasks will probably have their results checked every day and their procedures reviewed every month or so. More senior scientists will probably be subject to team (peer) review every week or every month or so. The most senior managers will be checking on the progress of their teams regularly and they will be providing periodic reports to their seniors. Continuous assessment and review is part of the life of scientists in work. It is also the case in some parts of the education system. However in others great emphasis is put on terminal assessment. A science-based organisation could find itself in serious difficulties if such emphasis was placed on assessing progress at the end of a process.

The diverse nature of scientific work means that any system of assessment for one part of work could be inappropriate for assessing other parts. Different procedures are likely to be needed, each of which is fit for the purpose in which it is used. Continuous assessment methods tend to be more flexible than terminal methods. They are also effective for

monitoring the development of general skills such as planning, information seeking and working with others. Project work is better assessed periodically rather than simply on the outcome.

Many of the features of Table 15 are likely to receive extra emphasis from using continuous assessment methods. This largely results from the opportunity for students to apply their newly learned knowledge and skills and to receive immediate feedback on their strengths and weaknesses. The following features listed in Table 15 may benefit most directly from the use of continuous assessment of progress.

- *being able to use a science knowledge-base;*
- *generic (non scientific) skills;*
- *the ability to analyse data;*
- *appreciating the nature and structure of science work.*

#### **7. Make processes and purposes of work explicit**

In scientific employment the anticipated outcome of the work being carried out is usually clear. So too are the processes by which the outcome will be achieved. A person involved with quality control during the production of a device will know the materials they need, the process they will use to test sampled devices, and the tolerances which are acceptable in specific uses of the device. In education the desired outcomes of learning are also clear. The process used to reach these outcomes depends on the learner, the tutor, the course, and the context of the learning. The processes can be implicit in courses, assignments and learning activities. There is possibly much to gain by making these processes explicit. This can be done by explaining why a particular method is appropriate; why a certain measuring device is used; why it is important to know where to look for data in a research paper; why a line graph is appropriate for continuous data, and why interacting positively with other students is a good skill to develop. Yet many of these explanations can remain implicit in current courses.

Research by Millar et al (1995), showed that making students aware of the goals of an investigation increased performance. Work in hand by Ryder and Leach at Leeds University (unpublished), aimed at improving the effectiveness of undergraduate science teaching, indicates that making explicit what is often implicit to practicing scientists would improve student understanding. The research project involved student interviews spanning a range of science departments including biochemistry and Earth sciences. The research lends strong support to several of the conclusions reached in chapter 7. For example students completing their final year research project seemed to benefit greatly from interacting with the culture of a research team. Their perspectives on research methods were broadened and deepened by the experience. Another example was that talking about the science involved in their work improved their confidence and understanding.

Making the processes and purposes of work explicit will enhance the following aspects of Table 15:

- *the ability to manipulate skillfully equipment and materials;*
- *understanding how to experiment;*
- *the ability to analyse data;*
- *appreciating the nature and structure of science work.*

Each of these features can be part of scientific investigation. Experienced science educators recognise that they are implicit requirements in investigations. However students may not be clear about the form of each of these features, they need to be drawn out and made an explicit requirement of investigations.

#### **8. Provide scope for the student to impose a structure on the work**

This area of potential development has been partly covered by some of the discussion above, particularly though the use of active learning methods. However it stands out as an area on its own because scientists invariably work on projects. At all levels, but particularly at the higher levels, the scientific worker will be required to determine their work pattern. They will need to meet deadlines and produce products and data of a specified standard.

If the student is to be prepared for scientific work they should have some opportunity to develop project management skills. Students need be required to demonstrate that they appreciate the meaning and importance of criteria for success. Many parts of the education and training provision provide such opportunities through coursework but they are more common in courses with a strong technology bias.

The main features of Table 15 which will be addressed by allowing some structure to be imposed by students are:

- *generic (non scientific) skills;*
- *appreciating the nature and structure of science work.*

#### **Alternative analyses**

There are probably other ways of using the data from this research study to provide a guide to how science courses could be better matched to the work of scientists. For example if each sector of science course provision (general education, vocational education, occupational training, higher education) was analysed in turn, a different set of areas for development might emerge and these might be more readily matched to the constraints of that sector. This approach requires a solid, research-based view of the sector which is not available at present.

Another way of using the research data to provide pointers for areas of development would be to review the *aims* of different kinds of provision (e.g. general education, vocational education, occupational training, higher education). This might aid both policy makers in modernising provision and staff who guide students towards appropriate courses. However such a study needs to span subject areas beyond the scientific and it is well beyond the scope of this study.

In this chapter the primary and secondary data have been used to provide some pointers to areas of science education and training which could be usefully adapted to provide a better match with science as practised in work. In the next chapter the outcomes of the research project as a whole are reviewed and some areas for further research are identified.

## Chapter 10: Science education and science in work

In this concluding chapter I wish to reflect on some key points raised in this thesis. I begin by considering the need for studies such as this and the degree to which we should be encouraged or discouraged to continue to develop increased relevance in science studies by this means. Building on this, I then review the main findings in the thesis and their implications for further research and science education and training. As with many research studies, this project raises questions which could form the basis of further research. Some of these questions are posed and each is accompanied by a brief outline of what the research might involve.

As a science educator I have had many opportunities to reflect on what I have heard, seen, read and written as the research work has progressed. In the penultimate section of this chapter I outline some of the changes in my thinking in relation to some key areas of science education. I conclude the study with a short summary decisions about the content, teaching and learning of science education which could be informed by this study.

### The study

Research about scientific work is important: about one in ten people in the UK use science, technology or mathematics as part of their work. This high ratio confirms the importance of technically trained people in the economy. There are indications that some of the qualities of scientifically trained people will become more highly valued in future and this could lead to improvements in working conditions and the general quality of entrants to the profession.

With scientific work being so important it is surprising that this thesis covers ground which is poorly researched. Whilst authoritative studies of professional work exist for teaching, for nursing and many other professions, the work of scientists is so broad, and the academic perspective on scientific work so dominant, that study of scientific work practices for the purposes of improving education and training has, to date, mostly remained peripheral to these other studies.

The use of scientific knowledge and skills can be analysed in many ways and the identification of the knowledge and skills that scientists use has proven to be problematic. The work of scientists also includes technical skills, some of which may be non-scientific and a range of general skills. The field of science is vast, as is the range of educational provision. This study is an attempt to indicate the sort of insights that a larger study could bring. However, in addition to being a pilot of a methodology, this study has produced valuable information about the work of scientists. The fieldwork part of the research study has created an evidence base which includes data from interview, work observation and documents. Eighty six scientists from 28 organisations contributed information and opinion, and between them they covered the main domains of science. Organisations included public

and private organisations; these ranged from small departments to research units in multi-national companies.

It is argued in the thesis that the knowledge-base which underpins scientific work has two dimensions, the knowledge of explanatory concepts (facts, laws, principles and theories) and the knowledge of concepts of evidence (designing experiments and analysing data-sets). In addition to these two dimensions practical skills and some general skills are required to make people effective in scientific work.

### **The features of scientific work**

More specifically, analysis of the evidence base has identified the following features of scientific work:

- ability to use a science knowledge-base;
- generic (non scientific) skills;
- ability to manipulate skillfully equipment and materials;
- understanding how to experiment;
- the ability to analyse data;
- appreciating the nature and structure of science work.

Whilst all of these features can be found in science education and training courses there may be ways in which the courses could become more relevant and more efficient by reviewing the prominence of these features in courses. In addition there may be teaching strategies for increasing emphasis on some courses where particular features are less pronounced. For example by:

- focusing on the broad purposes of scientists' work;
- using contexts for study which are work-related and based on problems encountered in businesses and public services;
- providing opportunities for practical activities;
- providing opportunities for students to analyse situations and data;
- using active learning methods;
- making the assessment of students' progress continuous and coursework based;
- make processes and purposes of work explicit;
- providing scope for the student to impose a structure on the work.

Many of the features of the work of scientists (and ways of developing them in science courses) are already part of technology education. The research signals that the separate development of science and technology is to a large extent, not appropriate, particularly when viewed from a work perspective.

Thus the research shows how the analysis of practice has potential for modernising educational provision. This could be achieved without major upheaval of current courses.

### **The direction of further research**

The relationship between education and training and the work of scientists is an interesting field for research. During the course of this project several particularly interesting and potentially useful questions have arisen each of which could form the basis of further enquiry. These questions are now discussed briefly.

*What are the key perspectives on science education which, together with the work perspective, could provide a sound, modern philosophical underpinning for science education?*

This question has already been addressed indirectly by science education specialists. A good example is the schemes developed by Nuffield Foundation which aimed to produce a thoroughly consistent general education courses with scientific thinking at their core. More recently educationalists such as Millar (Millar, 1997) have called for greater emphasis on scientific literacy. The latter perspective involves science for public understanding, a course which includes a knowledge and skills component, an awareness component and practice in discussion of public issues related to scientific advancement.

Striking a balance between all of these perspectives to provide a good general education in science is extremely difficult and are often confounded further by attempts to differentiate general science education according to a student's age, ability or career intention.

A research study on these different perspectives could be useful. It could lead to development work on how they could be combined, deciding for which students they are most appropriate, how courses could be effectively differentiated and when such differentiation could begin.

*How does current science education and training match the requirements of scientists in work?*

This question follows directly on the research questions addressed in this study. It forms a natural second step. Central to the follow-up study is the collection and review of information about content and common practice in each of the main components of science education and training. Making decisions about common practice will prove a difficult task which will require careful weighing of evidence that may sometimes be conflicting. The research will need to include a review of the aims of each part of the science education and training provision and possibly an evaluation of how well each part is measuring up to its aims. This review of aims is necessary in order to gain a perspective on the degree to which particular courses are reflecting the way science is used in work settings.



Employers often use qualifications as a method of selecting staff. The extent to which qualifications meet the information needs of employers is poorly documented although several studies have provided an indication of what employers value. A study of science education and training practices could include an analysis of syllabuses, question papers and student performance. This could be matched against employer needs.

*What science is best learned in schools and colleges and what is best learned in work?*

This question arose many times during this study; it has two aspects. Firstly it is important that the education and training system is efficient and responds to the needs of students and employers. Secondly, the work of the *situated cognition* school suggests that the socio-cultural dimension in which learning takes place has a significant effect on the learning itself. There are also interesting international comparisons to be made here. For example the German dual system has a clear dividing line between the science which is learned in different settings; whereas in many countries including India and the USA, some education and training provision is tightly matched to the needs of local business. A *compact* is established with teaching, tutoring and mentoring shared between the partners.

This type of study could also include a closer look at the importance of context on science learning. In particular a study could usefully research:

- the practice of science in work settings (i.e. take a broader view of learning).
- ways of developing general skills in people to reflect those needed in work settings.
- develop learning / teaching situations where the feel of a work setting is simulated (bringing industrialists into schools, visiting businesses, carrying out work in teams etc.).

*How do people in scientific work personalise scientific principles and theories?*

This question arose from the literature study, particularly reviewing the work of Argyris and Schon (1974). It became more prominent in the fieldwork phase when there was sometimes a sense that the scientists in interview were trying to find the standard (theoretical and educational) language to describe their understanding of the work. Such a study would be an important contribution to theorising about the nature of people's understanding of concepts and would complement the work on constructivism which has been helpful in education practice.

*What purposes are served by scientific practical work in schools and colleges?*

This question has already been the subject of research projects. A typology of practical tasks would be helpful in the evaluation of the extent to which the types important in work are addressed in education and training. A study of this kind could also test the three-part theoretical model developed in the thesis (see p45).

*Is it possible to develop a combined science and technology course which meets the needs of the various users of science and technology qualifications?*

Science and technology are often combined in work. Research could be conducted into potentially popular curriculum models for courses leading to combined general qualifications.

### **Some personal insights**

Whilst carrying out this research I have experienced some insights into the way science works. These insights have naturally caused me to reflect on the aspects of science education that I know best - general and vocational science education up to advanced level. I now have a new position on, for example, the centrality of scientific knowledge and on the roles of different types of practical work. I now take the development of general skills through science education much more seriously than I did previously and see much more clearly the need for setting scientific learning in contexts which mean something to the learner.

### **The performance of science educators**

One of the strongest messages which emerged from interviewing scientists was that most felt that the science education students received was good. Many had criticisms to air, such as the narrowness of A levels, or the second-rate nature of vocational qualifications, but generally speaking they felt students arriving for interview were reasonably well-prepared. Many cited both the resource and the social problems faced in schools and believed that teachers were doing a good job in the face of these difficulties. It needs to be borne in mind that the students coming up for recruitment were distinctive in that they were likely to be scientifically able and interested in a branch of science.

### **An interesting job**

A second striking feature of the interviews and reading of the transcripts was that the people interviewed seemed to enjoy their work. Few gave any indication that they were unhappy or bored. The majority seemed absorbed with the problem they were tackling and spoke about the pleasure of making progress and the commitment to overcoming set-backs. Some of the work was health related, and people in these jobs clearly gained fulfillment from helping others.

This enjoyment of scientific work does not generally come across to students in schools. There are clearly opportunities to communicate the satisfaction many scientists get from their work to students. This could help overcome some of the poor images young people have of science and scientists.

### **The place of knowledge of facts, principles, laws and theories**

It is difficult to argue that general education in science should not have the acquisition of science knowledge at its core. Nevertheless I believe it has become too dominant in defining the curriculum. In many courses it has squeezed out from the curriculum some important components of a broad science education. Students of science should be encouraged to appreciate the features of scientific approaches, ways of analysing data, and the social

dimension of science, and they should be able to carry out a scientific project of their own. These features can be found in the broad aims of current science courses but through pressures brought about by limited assessment procedures and teaching related to assessment, they become implicit and weakened whereas facts and principles tend to receive added emphasis.

This research study has underlined the importance a good knowledge-base as a preparation for scientific work or further study. It has also highlighted some other areas which are important and which curriculum and syllabus developers must take seriously. I now see the need for the curriculum to change in the following ways.

- The core of scientific knowledge needs to be limited so that a maximum of 70% of teaching time is concerned with facts and principles. Likewise the weighting of recall, understanding and application of knowledge in examinations should be limited to a maximum of 70% of the marks available.
- A proportion, say 5 - 10% of the core knowledge should be “modern”. The definition of any core will lead to a list of basic scientific principles. Many of these have not changed for years and the can lead to a dated and uninspiring feel to the curriculum. A small section covering a new, leading edge, aspects of science may be more interesting both for teachers and students. It is also likely to lead to engagement with public understanding of scientific ideas.
- The remaining part of curriculum time should be reserved for making explicit scientific approaches, analytical techniques and the social aspects of science. It should also include opportunities for the refinement of practical techniques. Assessment schemes should reward good skills in these areas.

### **The importance of practical work**

There have been major shifts in recent years in the focus of practical work in schools. I believe there is now a confusion of goals for practical work in schools and colleges. The process of listening to scientists and watching them work has clarified for me the reasons for carrying out practical work. Many teachers would say that practical work motivates students and brings the subject to life for them. They would also say that it illustrates certain key ideas and eases or consolidates the learning of these ideas. These features of practical work have not been challenged by the experience of this research but they have been extended. The key shift in perception in understanding the role of practical work is that students need to:

- be able to work on a technique repeatedly so that by learning to monitor their own performance, they can experience finding ways to improve accuracy;
- evaluate data (primary and secondary) and do this on their own and in groups;
- design their own experiments to solve problems.

All three aspects need an explicit focus in teaching. For many teachers this explicit work will be challenging and classroom support materials will be necessary to effect change.

### **General skills**

Working on vocational qualifications which incorporate the development of skills such as communication, the use of information technology and number skills, had given me an awareness of the importance employers attach to these. My visits to places of scientific work have heightened this awareness and enhanced the range of skills which I now see as important. It is now my belief that, in most work environments, a lack of general skills can be the limiting factor in their overall effectiveness. A work team can compensate for the lack of a certain technical skill or weak background knowledge in one area of science, but it will experience chronic problems with a team member who cannot function properly in the team because she cannot work with others or because he has poor personal organisation.

In schools and colleges the development of these skills may be an institution-wide goal but it is important that during scientific work students are introduced to the importance of refining these skills. This means finding ways of making these skills explicit.

### **Science and technology**

Before work on this project I saw the separation of science and technology as a convenient way of teaching these areas where specialist staff could work to develop their subject to the full. The fact that the subjects complement one another strongly and in some ways overlap was, in my opinion, a matter for inter-departmental liaison rather than a fault in curriculum design. After the research work I think differently. From a work perspective it makes little sense to structure the teaching of science and technology entirely separately. Combining them in education provision may better meet the needs of students and employers. When I consider some of the most popular science GCSE courses of the last 15 years (NEAB science, Suffolk coordinated Science, Edexcel "Science at Work" GCSE) I note a strong technical flavour to the science with real life problems being addressed scientifically. Of course both science and technology have features which are not shared with the other and these are important (the knowledge-base in science, the design and aesthetics feature in technology). However we need to do more to show students the ways in which these subjects relate and the benefits of doing so.

### **Perspective and context**

Setting scientific learning in context is a common feature of many courses. It probably raises interest in some students. The school/college context for learning science can never replicate the working laboratory to the extent that the transfer of skills from the educational context to the work context is straightforward. Questions remain in my mind about the value of trying to imitate the work environment in schools and colleges. It probably makes more sense for

the education system to do what it does best and to leave the development of some skills for on-the-job training.

Three steps which will help students appreciate the work context are:

- the setting up of a school-business link and using it in the classroom;
- visits to businesses where the work relates to the syllabus;
- the use of a collaborative group project during a course, where each student has a certain defined and explicit contribution to make to team success.

These steps are probably at the limit of how far schools and colleges should go to develop a work-like context for science learning.

### **Using the research findings**

In the preface to this thesis I explained how it became clear to me that research of this type was needed. Essentially, more information was needed about scientific practice so that school and college science curricula could become more relevant. Such information from research could also fuel discussion about the most appropriate content and form of the curriculum. I sensed that decisions about the curriculum were often made on the basis of previous practice and did not include any in-built mechanism for development.

Studies such as this one, if conducted regularly, have great potential for modernising the curriculum. However, the potential will not be realised unless action is taken by teachers, the government, government agencies and employers.

A teacher's overriding aim is to do well by their students. Indicators of success will be through student interest in the subject and examination success. A broader indicator of success is how well the student progresses after they have left school or college. Teachers need to consider how far teaching which leads to success in examinations reflects the way science is practised in work settings. They also need to consider how to aid the acquisition of skills which are of use to people in types of jobs or courses which extend beyond the scientific. Such is the level control of the curriculum imposed by tests, examinations and prescribed curricula that teachers will have to work within tight constraints if they are to develop science courses which better reflect practice.

The Government and its agencies face a difficult task of regulating a system to improve the poorest practice whilst not constraining teachers and schools who, by their own efforts, are able to excel by extending core provision. These bodies also have a responsibility to maintain public confidence in national qualifications; high levels of confidence are in everyone's interest. To maintain and develop confidence in the education system the Government and its agencies need evidence of the need for developments which might go beyond current policy. The Government and its agencies also need to test periodically the effectiveness of

science and technology education in delivering the requirements of people who value a scientific training. These users include students, employers and tutors in higher education. The science education system should resist the internal forces for little change and invest in a modernisation programme that will lead to a more responsive national education and training provision. The objectives outlined in the Labour party document 'Aiming Higher' (Labour Party, 1997) have the potential to begin this task. For example by broadening of students' study programmes to include a wider range of studies, Key Skills and work experience.

Employers are not a homogeneous group and views expressed by representatives from different companies and from organisations representing different sectors of the economy can lead to confused messages. Effective modernisation of the curriculum will depend on employers collaborating with educational institutions, assisting with research enquiries and providing information to employer agencies. These agencies can then support a coordinated policy on the main areas for curriculum (including assessment) development.

The data and analyses generated as part of this study has the potential to modernise science education in schools and colleges. I hope that I have presented the data and analyses sufficiently clearly for researchers, teachers, curriculum developers, assessment agencies and policy makers to see their value and be able to use them to enhance science education.

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## Glossary

Action knowledge	A synthesis of forms of knowledge (e.g. public knowledge and personal knowledge) which develops through use. A working knowledge of a situation or problem
Advanced qualification	Normally aimed at able 16 - 19 year olds, often a pre university qualification. See level 3 criteria in the NVQ system (annex N). In the UK GCE A levels, Scottish Highers and advanced GNVQs
Concept	A generalised idea or model which (in scientific activities) aids thinking about phenomena or materials
Concepts of evidence	The concepts associated with obtaining data through experiment and the analysing the data. They include the concept of the fair test, validity and reliability
Empirical	About observation and experiment
Experiment	A means of securing an answer to a specific question. An experiment often has a practical aspect
Explanatory concepts	The facts, principles, laws, theories of science e.g. the reactions of sodium with oxygen, the structure of DNA, the conductivity of metals, gravity, photosynthesis. Also known as declarative concepts
General skills	The non scientific skills needed by working scientists. For example the skills associated with collaboration with others
Hypothesis	A suggested explanation for a group of facts or a relationship, or an event. It could change when it is subjected to experimentation
Investigation	A specific type of problem-solving. Phenomena, artefacts, ideas, predictions or hypotheses are tested through observation, measurement and experiment
Know-how	A problem solving capability based on experience (a combination of knowledge, skills and intuition)
Knowledge	The internalisation of explanatory concepts leading to subsequent recall and application
Model	A construction which aids understanding by showing relations between the parts of a system
Primary data	Information gathered first-hand. In this study the interview data is referred to as primary data
Problem-solving	Applying understanding and skills to situation to seek new information
Procedural	Knowing how to do science. Using of concepts of evidence. Procedural understanding is complementary to conceptual

## **The nature of scientific work - annexes**

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understanding	understanding
Processes	Scientific methods, routines and practices
Propositional knowledge	Knowledge of explanatory concepts
Secondary data	Data which has been collected and organised by another person or group. In this study the literature on science and work is referred to as secondary data
Skills	A sequence of actions or thoughts which has become routinised through practice and experience. For example where a protocol is followed, where measurements and observations are made. It will also include the application of explanatory concepts to practical situations or synthesis brought about by linking one explanatory concept with another
Synthesis	Bringing together knowledge and skills into a connected whole so that a new structure emerges
Understanding	The ability to explain and interpret information within a given context

## Abbreviations

ABPI	Association of the British pharmaceutical Industry
B.Sc.	Bachelor of Science
CIA	The chemical Industries Association
CBI	Confederation of British Industry
CIHE	Council for Industry and Higher Education
CSTI	The Council for Science and Technology Institutes
GCE A level	General Certificate in Education at Advanced level
GCSE	General Certificate of Secondary Education
GNVQ and	General National Vocational Qualification
GSVQ	General Scottish Vocational Qualification
HNC	Higher National Certificate (Edexcel (BTEC)), a part-time advanced course
HND	Higher National Diploma (Edexcel (BTEC)), a full-time advanced course
HMSO	Her Majesties Stationery Office
HPLC	High performance liquid chromatography
ICI	Imperial Chemical Industries
IMS	Institute of Manpower Studies
IRDAC	Industrial Research and Development Advisory Committee
LAATSI	Laboratory and Associated technical Standards Initiative
M.Sci	Master of Science
NCC	The National Curriculum Council
NCVQ	The National Council for Vocational Qualifications
NVQ	National Vocational Qualification (SVQ in Scotland)
NEAB	Northern Examinations and Assessment Board
NUD*IST	Non Numerical Unstructured Data * Indexing, Searching and Theorising
OECD	Organisation for Economic Cooperation and Development
OPSS	Office of Population Survey Statistics
Ph.D.	Doctor of Philosophy
SCAA	Schools Curriculum and Assessment Authority
SOP	Standard operating procedure
ST&M	Science, Technology and Mathematics
R&D	Research and Development
Sc1	National Curriculum Science Attainment Target 1
THES	The Times Higher Education Supplement
UCAS	University Council Admissions Service



## **Annexes**

- A** List of participating organisations
- B** A sample of the specification of NVQ standards
- C** Interview schedule
- D** data nodes used for analysis
- E** Areas of scientific work
- F** Levels of work - the NVQ system
- G** Work observation schedule
- H** CSTI components of scientific work and the match with the features in Table 15
- I** Investigational work - National Curriculum in England, Wales and Northern Ireland in 1989
- J** Summary of methodology - Fitness for purpose project

## Annex A

### List of participating organisations

**Key:**

! = on site visit

\* = knowledge-base definition off site (Fitness for Purpose)

+ = on site interview with n scientists

Aerial Group Ltd\*

Agriculture and Food Research Council\*

Agriculture Training Board\*

Allied Colloids Group plc\*

Anglesey Aluminium +(1)

Babergh District Council (Environmental Health) +(2)

Bass Brewers Ltd\*

Bloxwich Engineering Ltd\*

BP Chemicals (Research) Ltd\*+(5)

British Aerospace plc\*

British Biotech plc\* +(6)

Brunel University, Department of Materials Technology\*

Brunner Mond!

Cambridge University+(2)

Campden and Chorleywood Food Research Association+(6)

Chemical Industries Association\*

Cranfield University/Royal Military School of Science +(1)

Doncaster College, Department of Minerals Engineering\*

English China Clay International (Europe)\*

Forensic Science Service\*

Glaxo Wellcome Research & Development\*

H.M. Customs and Excise\*

Hampshire County Council Planning Department (Environmental Records)\*

Hoechst + (7)

ICI Chemicals & Polymers\* +(3)

Imperial College of Science, Technology and Medicine: Departments of Physics and Chemistry\* (+1)

Institute of Wastes Management\*

King's College London, Department of Nutrition & Dietetics\*

Laboratory of the Government Chemist\*!  
Lambeth College, Dental Technology\*  
Lea Ronal plc\*  
Leeds College of Health, Biomedical Sciences\*  
Leeds Metropolitan University, Faculty of Health & Social Care\* +(3)  
Liverpool City Council Public Analyst's Laboratory+(4)  
Loughborough University of Technology, Department of Chemical Engineering\*  
Ministry of Agriculture Fisheries and Food\*  
Ministry of Defence\*  
Moy Foods + (4)  
National Farmers Union\*  
National Institute for Medical Research \* + (5)  
National Power + (1)  
NESCOT, Faculty of Science & Technology\*  
Nestle UK\*  
Pfizer UK+ (5)  
Public Analysts Laboratory \* +(3)  
Queen Mary & Westfield College, Department of Chemistry\*  
REME Training & Development Team\*  
RHM Grocery\*  
Rhone Poulenc Chemicals Ltd\*  
Royal Agricultural College\*  
School of Electrical and Mechanical Engineering, REME + (5)  
School of Electronics and Aeronautical Engineering, REME + (4)  
SCM Chemicals\*  
Smiths Industries Aerospace\*  
South Bank University, Division of Imaging and Radiography\*  
South West Water plc\*  
Southmead Hospital Blood Services Unit +(2)  
St Regis Paper Company Ltd\*  
Technical and Training Enterprises +(1)  
Thames Region NRA\*  
The Association of the British Pharmaceutical Industry\*  
UMIST, Department of Paper Science\*  
Unilever: Central Research Laboratory\* +(3)  
University College London, Department of Civil Engineering\*  
University College London, Dept. of Adv. Chem and Biotech Engineering + (4)  
University of Bristol, Department of Geology\*  
University of Hertfordshire: Radiography, Manufacturing Systems Engineering\*  
University of Kent, Chemistry Dept., +(1)

University of Leeds, School of Chemistry\*  
University of Liverpool, Department of Environmental Biology\*  
University of Manchester, School of Biological Sciences\*  
University of Nottingham: Medical School, School of Physiotherapy\* +(2)  
University of Plymouth, Department of Electronic Engineering\* +(5)  
University of Reading, Food Technology\*  
University of Southampton, Centre for Environmental Sciences\*  
Warwick University: Departments of Chemistry and Engineering\*  
West End Nursery, Van Heyningen Bros. Ltd\*  
West Sussex County Council Surveyor's Department\*  
Worcester Grammar School +(1)  
Writtle College\*  
York University Chemistry Dept.+(2)

## **Annex B**

### **A sample of the specification of NVQ Standards**

#### **Unit 19 Calibrate equipment**

##### **Element 19.1 Perform calibration**

###### **Performance Criteria**

- a) Calibration is carried out at specific intervals according to standard operating procedures
- b) Integrity of calibration equipment and materials is maintained
- c) Relevant personnel are informed if calibration reveals results that are not within specified operational limits
- d) Action is taken in the event of an abnormal occurrence or malfunction to minimise hazards, loss of materials or data and to report the occurrence
- e) Environmental and health and safety requirements are complied with

###### **Range Statement**

Integrity of equipment and materials: referenced against methods and internal and external standards, traceability; verification; valid certification;

###### **Knowledge Specification:**

Principles of calibration

Importance of calibration

Calibration requirements

Appropriate calibration procedures and routines

Environmental and health and safety requirements when calibrating

Appropriate calibration equipment

Units of measurements

Appropriate marking requirements for calibration equipment and materials

Potential impact of non-conformance

Key features of traceability

Methods of recording calibration status

Ways of ensuring controlled conditions for calibration

Ways of ensuring the integrity of standards being used in calibration

Acceptable tolerances

Recording and reporting procedures

Actions available in the event of abnormal occurrences

**Evidence Requirements**

Observation of normal working activity, with the production of evidence over a sustained period of time sufficient to demonstrate all the performance criteria in the context of the specified knowledge. Simulation will be allowed as an alternative to direct observation in appropriate situations when real task performance in real working environments is not possible. This observation will be supported by documentary evidence of having met all components of the range.

This may be supplemented by assessor questioning of the candidate regarding the dealing with contingencies and own responsibilities together with specific “What if?” questioning on any aspect of the knowledge specification not demonstrated by performance.

**Assessment Guidance**

Observation of performing 3 routine calibrations supported by calibration record Assessor “what if ?” questioning on the event of results not being within specified operational limits.

## Annex C

### Interview Schedule

#### Preliminaries

*The research is about the ways people use science in their work.*

Confidentiality

Permission will be sought if any attribution is made

The time it will take

Will recording the interview pose particular problems

The Interview will have two parts

- i) general enquiries, your background etc.
- ii) matters to do with your job and scientific knowledge and skills

#### Prompts/questions

##### Area A Professional Standing

- a. Experience (*where have you worked before this?*)
- b. Qualifications (*school, college, professional, current study*)
- c. Current work (*job title, scientific basis*)
- d. Membership of professional groups (*organisation, local, national, international*)

##### Area B Training

- a. Describe key aspects of your training leading to competence in your current job (*refer to formal education, on the job training*)
- b. Evaluate it (*how was it? inspirational /sound/weak parts? functional parts/missed opportunities? how would you change it?*)

- c. How much of the training was actually needed to do your job? (*focus on basic necessity*)
- d. How do you rate
- school qualifications
  - vocational qualifications
  - higher education qualifications
- in preparing young people for work as a XXX here? A single sentence answer is needed to get at your perceptions - (*what would you change if you could better prepare recruits for work with you?*)

**Area C - Work**

- a. Have you a job description? (*can I have a copy?*)
- b. Describe work setting
- function
  - resources
  - colleagues
  - responsibilities
  - imminent changes
- c. Describe a typical day (*level of routine? things you do every day, most days, some days, typical problems that disrupt your day*)

**Area D - Scientific Knowledge**

- a. What are the key topics, concepts which underpin or are at the heart of your work? (*looking for 5 -10 areas*)
- b. New recruits to different levels of work - how do they fare in terms of underpinning knowledge? (*get an idea of requirements at levels below that at which the interviewee is working*)

**Area E - Scientific Skills**

- a. describe the skills that you use often to do your work? (*Give an example of the level of detail required - e.g. practical skills, thinking skills, analysis skills, problem solving skills*)



- b. New recruits to different levels of work - how do they fare in terms of scientific skills? *(get an idea of requirements at levels below that at which the interviewee is working)*

**Area F - Generic knowledge and skills**

- a. describe the skills that you use often to do your work? *(Give an example of the level of detail required - e.g. key skills capabilities, communication, numeracy, IT capability, self reliance, resourcefulness, personal effectiveness, interpersonal relationships, initiative)*
- b. New recruits to different levels of work - how do they fare in terms of general skills? *(get an idea of requirements at levels below that at which the interviewee is working)*

**Area G - Development**

What could be done to enhance the quality of your work? *(emerging skills requirements, problems based on the interviewee rather than people working in that area/level in general)*

In what ways do you think your work has changed over the last five years?  
What changes do you anticipate in the next five years?  
*(Company and structural changes as well as personal work changes)*

**Area H - Feedback**

Anything overlooked? Anything you want to add?

Observations and suggestions? Willing to participate further?

## Annex D

### Data Nodes used in the analysis

Q.S.R. NUD.IST Power version, revision 3.0.5.  
Licensee: Mike Coles.

PROJECT: Ph.D. Nudist, User Mike Coles, 12:59 pm, 18 Aug, 1997.

- (1) /Capability
  - (1 1) /Capability/Science
  - (1 2) /Capability/Biology
  - (1 3) /Capability/Chemistry
  - (1 4) /Capability/Physics
  - (1 5) /Capability/skills
  - (1 6) /Capability/procedural understanding
  - (1 7) /Capability/techniques
- (2) /Employment
  - (2 1) /Employment/Industrial
    - (2 1 1) /Employment/Industrial/Chemistry
    - (2 1 2) /Employment/Industrial/Physics
    - (2 1 3) /Employment/Industrial/Biology
    - (2 1 4) /Employment/Industrial/Engineering
    - (2 1 5) /Employment/Industrial/Technology
    - (2 1 6) /Employment/Industrial/recruitment
    - (2 1 7) /Employment/Industrial/skills
  - (2 2) /Employment/Public service
- (3) /Univ. R&D
- (4) /Education
  - (4 1) /Education/Curriculum
    - (4 1 1) /Education/Curriculum/National
    - (4 1 2) /Education/Curriculum/Assessment
    - (4 1 3) /Education/Curriculum/Degree courses
  - (4 3) /Education/Qualifications
    - (4 3 1) /Education/Qualifications/GCSE
    - (4 3 2) /Education/Qualifications/Assessment
    - (4 3 3) /Education/Qualifications/A Levels
    - (4 3 4) /Education/Qualifications/GNVQs
    - (4 3 5) /Education/Qualifications/Degrees

- (4 3 6) /Education/Qualifications/Others
- (5) /Training
- (5 1) /Training/Schools
- (5 2) /Training/FE
- (5 3) /Training/Universities
- (6) /Literacy
- (7) /Compacts
- (8) /Gov. Policy
- (8 1) /Gov. Policy/OST
- (8 2) /Gov. Policy/SCAA
- (8 2 1) /Gov. Policy/SCAA/Gov. policy - SCAA
- (8 2 2) /Gov. Policy/SCAA/Government - NCVQ
- (9) /general skills
- (9 1) /general skills/communication
- (9 2) /general skills/maths
- (9 2 1) /general skills/maths/number
- (9 3) /general skills/personal effectiveness
- (9 4) /general skills/decision making
- (9 5) /general skills/problem solving
- (9 6) /general skills/team working
- (9 7) /general skills/motivation
- (9 8) /general skills/IT
- (9 9) /general skills/planning
- (9 10) /general skills/leadership
- (9 11) /general skills/foreign language
- (9 12) /general skills/cultural awareness
- (9 13) /general skills/initiative
- (9 13 1) /general skills/initiative/and creativity
- (9 14) /general skills/creativity
- (9 15) /general skills/research
- (9 16) /general skills/adaptability
- (9 17) /general skills/business awareness
- (9 18) /general skills/legal awareness
- (9 19) /general skills/management
- (9 20) /general skills/Time management
- (10) /competitive position of UK
- (11) /scientific
- (11 1) /scientific/facts, principles, ideas
- (11 2) /scientific/logical thought
- (11 3) /scientific/practical

(11 4) /scientific/skill and technique

(11 5) /scientific/analytical thinking

(21) /chemistry

(22) /physics

(23) /biology

(24) /engineering

(25) /technology

(26) /industry

(27) /University-HE

(28) /R&D

(29) /Quality of entrants

## Annex E

### Areas of scientific work

#### An economic focus

##### *(i) Using occupational indices*

Occupational figures - this is a composite list created through examination of employment statistics and rationalisation of overlapping areas (CSTI 1993). Top ratings are:

- Biologists (including biological scientists and biochemists)
- Chemists
- Education professionals
- Engineers (including mechanical, electronic, chemical, design, process)
- Health related - medicine and occupations supportive to medicine (including dentists, doctors, opticians, nurses, radiographers, veterinarians, midwives, psychologists)
- Physicists/geologists/meteorologists
- Technicians (including laboratory, medical, dental, electrical/electronic, engineering)

##### *(ii) Using economic data*

Economic areas - informed by Research and Development (R&D) spend per sector (Central Statistical Office, 1993) and general employment data on companies and sectors (CSTI, 1993), resulting data has been rationalised. Top rated are:

- Aerospace
- Agriculture
- Automotive
- Chemicals
- Construction
- Electricals
- Food
- Fuel
- General manufacturing
- Healthcare
- Materials extraction and processing
- Pharmaceuticals
- Telecommunications

#### An education and training focus.

##### *(iii) Using traditional sub-disciplines of science*

Traditional academic discipline boundaries are as follows.

- Biology
- Chemistry
- Physics
- Earth science

- Astronomy
- Behavioural sciences

*(iv) Using student populations in higher education courses*

Higher education course provision based on the range of courses offered by most UK universities (UCAS, 1995). The list has been rationalised to show the main scientific areas. The numbers of courses on offer in UK Universities in 1996 are shown in brackets.

- Agricultural Science (20)
- Anatomical Sciences (14)
- Applied Biochemistry (3)
- Applied Biology (27)
- Applied Chemistry (11)
- Applied Geology (3)
- Applied Physics (2)
- Applied Physiology (2)
- Applied Plant Biology
- Applied Psychology
- Biochemistry (35)
- Biological Science (25)
- Biology (31)
- Biomedical Science (14)
- Biotechnology
- Botany
- Chemistry (55)
- Computer Science (48)
- Dentistry (15)
- Engineering
  - Civil (45)
  - Electrical and Electronic (43)
  - Mechanical (32)
  - Aeronautical (25)
  - Chemical (16)
  - Manufacturing (2)
  - Automobile
- Environmental Health (2)
- Environmental Science (18)
- Food Science (6)
- Genetics
- Geology (16)
- Health Science (3)
- Horticulture (7)
- Human Biology (6)
- Marine Science (3)
- Materials Science (8)
- Medicine (39)
- Microbiology (3)
- Molecular Biology (2)
- Nursing (14)
- Occupational Therapy (5)
- Optometry (5)
- Pharmacy/pharmacology (14)
- Physics (34)

- Physiotherapy (3)
- Podiatry
- Psychology (18)
- Radiography (3)
- Sport and Exercise Sciences
- Veterinary Medicine (8)
- Zoology (4)

*(v) based on vocational qualifications*

The following are areas where work based vocational qualifications (NCVQ, 1996) exist in the UK and where the practice of science and use of scientific information might make a significant contribution to the work.

- agriculture
- horticulture
- animal care
- environmental conservation
- laboratory operations
- mining
- processing plant operations
- public utilities/services
- building
- electrical engineering
- mechanical engineering
- aeronautical engineering
- process engineering
- transport engineering
- automotive engineering
- technical services (health, beauty, catering, cleansing, sport, fire, waste management, information systems, media)

**A research and development (R&D) focus**

*(vi) Using EU Venture Economics Industry codes*

This listing is derived from the current European Union Research, Technology and Development data. The categories are broader than the finest definition available in the original data. A research focus has already been included in list (ii). This list provides a European perspective.

- Communications
- Facsimile transmission
- Computer related
- Other electronics related
- Genetic engineering/molecular biology
- Medical/health related
- Energy
- Consumer related
- Industrial products
- Other - such as transportation, manufacturing, construction

*(vii) COST (the European Co-operation in the field of Scientific and Technical Research)*

This is another framework established in 1971 by Ministerial Conference to coordinate national research at European level. It has the following domains

- Food technology
- Agriculture and biotechnology
- Meteorology
- Materials
- Oceanography
- Transport
- Telecommunications
- Informatics
- Fluid dynamics
- Forestry
- Chemistry
- Civil engineering
- Medical research
- Social sciences

*(viii) Using Technology Foresight*

The Office for Science and Technology identified the main areas for focusing technological research and development in the next century. This listing is the basis of the Technology Foresight programme (Technology Foresight, 1995).

- Chemicals
- Construction
- Financial services
- Health and life sciences
- Transport
- Communications
- Food and drink
- IT and electronics
- Manufacturing, production and business processes
- Materials
- Agriculture, natural resources and environment
- Defence and aerospace
- Energy
- Leisure and learning
- Retail and distribution



## **Annex F**

### **Levels of work - The NVQ system**

- Level 1:** Competence in the performance of a range of varied work activities, most of which may be routine and predictable.
- Level 2:** Competence in a significant range of varied work activities. Some of the activities are complex and non-routine, and there is some individual responsibility or autonomy. Collaboration with others, perhaps through membership of a work group or team, may often be a requirement.
- Level 3:** Competence in a broad range of varied work activities performed in a wide variety of contexts and most of which are complex and non-routine. There is considerable responsibility and autonomy and control and guidance of others is often required.
- Level 4:** Competence in a broad range of complex, technical or professional work activities performed in a wide variety of contexts and with a substantial degree of personal responsibility and autonomy. Responsibility for the work of others and the allocation of resources is often present.
- Level 5:** Competence which involves the application of a significant range of fundamental principles and complex techniques across a wide and often unpredictable variety of contexts. Very substantial personal autonomy and often significant responsibility for the work of others and the allocation of substantial resources feature strongly, as do personal accountabilities for analysis and diagnosis, design, planning, execution and evaluation.

## **Annex G**

### **Work Observation schedule**

#### **Applying scientific abilities**

- generate own ideas, hypotheses & theoretical models and/or utilise those postulated by others
- design investigations, experiments, trials, tests, simulations and operations
- conduct investigations, experiments, trials, tests and operations
- evaluate data and results from the processes and outcomes of investigations, experiments, trials, tests and operations

#### **Communication**

- determine current and projected requirement from within and outside the organisation, for science mathematical and technological skills/services
- research all potential sources of information to establish current knowledge, understanding, practices and procedures
- communicate the results and outcomes of present and previous scientific, technological and mathematical investigations and/or activities
- teach, train and assess students/clients/trainees in the knowledge, understanding and practices(both new and established) of science, technology and mathematics

#### **Managerial**

- develop policies and strategies which will lead to the achievement of objectives (set by self and others) and the efficient, effective and safe execution of the operation/organisation
- determine appropriate policy/practices for the safe and effective utilisation of resources
- administer policy/strategies to ensure achievement of objectives

- **monitor and evaluate the efficient and effective running of an investigation, programme, initiative, section, department, branch or organisation**

## Annex H

### CSTI components of scientific work and the match with the features in Table 15

Component of scientific work	Ref. to Table 15
Advertise/market the Scientific, Technological & Mathematical skills/services within & outside the parent organisation	B and F
Negotiate/liaise with employers & clients	B
Access all potential sources of information	B
Retrieve & evaluate information required	B and E
Collate & store relevant information	B and E
Design the most appropriate communication method/media/timing for employers & target audience	B and F
Disseminate new & established Scientific, Technological & Mathematical knowledge, understanding and practices	B and F
Evaluate new & established teaching/training methods & media	A and D
Develop appropriate teaching/training methods & media	A, B, C
Teach, train & assess students/clients/trainees	B
Supervise & administer courses/training	B
Advise, counsel & guide students and others	B
Respond to opportunities/needs generated by self, other individuals, the organisation &/or society	F
Formulate ideas/hypotheses and theoretical models which can be tested	D
Define the scope & nature of the investigation etc.	D
Devise an appropriate Action Plan	B and D
Validate the design	D and F
Set up investigations, experiments, trials, tests and operations	C
Monitor & control the procedures, practices & equipment	C and D
Record results/outcomes to ensure integrity of observation	B and D
Process & review data and results	E
Analyse data using appropriate and accepted methods/techniques	E

**CSTI components match with the features in Table 15 continued**

<b>Component of scientific work</b>	<b>Ref. to Table 15</b>
Interpret data to determine significance, validity & implications of the results in relation to the original objectives	E
Evaluate the benefits & implications of the results for future work/activities	E and F
Evaluate the information to facilitate the development of policies, strategies & objectives	B and F
Develop aims, objectives, strategies & policies	B and F
Prepare Corporate Plan & revise annually	B and F
Evaluate the type & nature of resources required for the operation	B and F
Develop an Action Plan for researching & procurement activities	B and F
Organise labour and deploy human resources	B and F
Control, co-ordinate strategies & policies to ensure that they are being effectively, efficiently & safely implemented	B and F
Establish efficient & effective feedback procedures	B and F
Review the processes & practices used in light of the outcomes	B and F

## **Annex I**

### **Investigational work - National Curriculum in England, Wales and Northern Ireland in 1989**

#### **The programme of study requirements for Exploration of science**

Pupils should be encouraged to develop their investigative skills and understanding of science in activities which:

- are set in the everyday experience of pupils and in novel contexts, involving increasingly abstract concepts and the application of knowledge, understanding and skills, where pupils need to make decisions about the degree of precision and safe working required.
- promote invention and creativity.
- encourage detailed planning of the activity and its subsequent evaluation in the light of findings.
- encourage the use of secondary sources in investigative work.
- are increasingly complex because there are derived and/or interacting variables.
- require key variables to be controlled and pupils to recognise that need.
- require pupils to generate theoretical models and to test them by investigation may take place over an extended period and may call for the use of sampling techniques.
- require accurate measurement, with quantification of, and accounting for, experimental error and anomalous results.
- encourage the systematic recording and presentation of data using, as appropriate, a full range of forms, including graphs, and mathematical relationships.
- encourage pattern searching in complex data and predictions requiring abstract reasoning.
- involve the critical evaluation of data.
- promote the production of written critical accounts.

## Annex J

### Summary of methodology - Fitness for purpose project

The project employed a qualitative methodology, drawing on evidence gathered in meetings of small expert groups. The stages of the project were as follows:

1. **Development of framework** for describing the knowledge, skills and understanding required.
2. **Definition and mapping domains:** identification of employer and higher education (HE) representatives.
3. **Piloting/validation** of framework and method.
4. **Development of qualitative coding frame:** used through each stage of the project.
5. **User meetings** of employer and HE representatives to identify the range of knowledge and skills and understanding required in a qualification at advanced level.
6. **Claiming round:** postal validation/prioritisation of components of knowledge, skills and understanding identified in user meetings. Claimers included original user group and additional representatives. Claimers were invited to identify additional components if required.
7. **Selection of qualifications for analysis:** meetings with all awarding bodies for each qualification type (GCE and GNVQ Advanced). Selection of representative syllabus/specification, discussion of methodology for qualification scrutiny.
8. **Scrutiny of selected qualifications:** review of the components of the qualifications concerned (including those which do not appear to be subject-specific). Carried out by subject experts including chief examiners and external verifiers of qualifications. These experts made judgements about the range and level of knowledge, skills and understanding demanded by the qualifications.
9. **Development of common statement:** collation and coding of all the components identified in user/claimer and scrutiny phases.
10. **Interrogation of data:** analysis of components to answer research questions.

