A Review of the Research on Practical Work in School Science

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Foreword

It is often argued that practical work is central to teaching and learning in science and that good quality practical work helps develop pupils' understanding of scientific processes and concepts. The UK has a long tradition of practical work in school science and of valuing fieldwork, particularly in biology. It is a reasonable assumption, based on what evidence is available, that students in UK schools undertake more practical work in science that do students in most other countries in the world.

However, there are, and have been for some time, concerns about practical work in school science. For example, Ofsted (HMI/Ofsted, 2004a/b) are of the opinion that scientific enquiry in primary schools is both variable and vulnerable and that, at secondary level, the range of investigations is narrow and is dominated by the perceived demands of assessed coursework beyond Year 8. These concerns have been echoed by sections of the science community, industry and business, and teachers themselves, who have argued that schools in general are not doing enough practical work, both in and out of the classroom, and that its quality is uneven.

SCORE (*S*cience *Co*mmunity *R*epresenting *E*ducation) is a partnership between the Association for Science Education, the Biosciences Federation, the Institute of Biology, the Institute of Physics, the Royal Society, the Royal Society of Chemistry and the Science Council. The Government's STEM High Level Strategy Group has asked SCORE to lead on developing a focussed strategy to promote high quality practical work in school science. This strategy would build on what is already in train and involve the charitable and private sectors working alongside the Department for Children, Schools and Families and SCORE.

On behalf of SCORE, in partnership with the ASE, and as part of a package of work including a teacher survey and consultation with stakeholders, the Royal Society commissioned this focused review of research regarding the state of practical work in school science. This review encompasses both quantitative and qualitative evidence. The overarching emphasis throughout is on research regarding effective practical work.

Executive summary

Definitions and purposes

1. There is confusion in the broader science education community about the definition of ‘practical work’. This confusion makes discussions about the value of ‘practical work’ difficult. A variety of terms exist to describe practical work, many of which are frequently used with little clarification. For example, *Science in the National Curriculum* uses several terms with little attempt to explain their meaning: *‘Practical and enquiry skills’*, *‘practical and investigative activities’*, *‘independent enquiry’* and *‘experimental work’* (QCA 2007a/b).

2. The most recent published review of the literature on learning and teaching in the school science laboratory gives what it calls a classical definition: *‘learning experiences in which students interact with materials or with secondary sources of data to observe and understand the natural world (for example: aerial photographs to examine lunar and earth geographic features; spectra to examine the nature of stars and atmospheres; sonar images to examine living systems)’* (Lunetta *et al.*, 2007). This inclusive definition might act as a starting point for clarifying terms in the UK science education community.

3. There are many espoused purposes for doing practical work in school science. Some of the most frequently stated by teachers are: to encourage accurate observation and description; to make phenomena more real; to arouse and maintain interest; to promote a logical and reasoning method of thought.

4. Since the introduction of the National Curriculum in England and Wales, four other aims have become more commonly stated by teachers: to practice seeing problems and seeking ways to solve them; to develop a critical attitude; to develop an ability to cooperate; for finding facts and arriving at new principles. There is no clear consensus that the broader science education community agrees on the aims and purposes of practical work in science. A discussion about the value, aims and purposes of practical work among stakeholders might be a useful first step in addressing some of the criticisms made by various concerned bodies.

What we know about the impact of practical work

5. In general, teachers and students are positive about 'practical work'. For example, in a recent NESTA survey (n=510), 99% of the sample of UK science teachers believed that enquiry learning had a positive impact (83% - *'very'*; 16% - *'a little'*) on student performance and attainment (NESTA, 2005, p. 5).

6. The quality of practical work varies considerably but there is strong evidence, from this country and elsewhere, that: *'When well planned and effectively implemented, science education laboratory and simulation experiences situate students' learning in varying levels of inquiry requiring students to be both mentally and physically engaged in ways that are not possible in other science education experiences'* (Lunetta *et al*., 2007, p. 405).

7. Evidence of effective practice in the use of practical work comes from a range of studies. For example, White and Gunstone's (1992) study indicates that *'students must manipulate ideas as well as materials in the school laboratory'* (Lunetta *et al*., 2007). There is a growing body of research that shows the effectiveness of 'hands-on' and 'brains-on' activities in school science inside and outside the laboratory.

8. There is evidence that practical work can increase students' sense of ownership of their learning and can increase their motivation.

9. There is evidence that the teacher's role in helping students to compare their findings with those of their peers and with the wider science community is critical.

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10. Abrahams and Millar (2008, forthcoming) argue that *'teachers need to devote a greater proportion of the lesson time to helping students use ideas associated with the phenomena they have produced, rather than seeing the successful production of the phenomenon as an end in itself.'* This finding has implications for pre-service and in-service teacher training.

11. Students (and their teachers) need to understand something about the nature of science if they are to appreciate the limits and value of practical activities. The evidence suggests that teachers appear to adapt their practices slowly when faced with new curricula such as *Twenty First Century Science*. This findings also have implications for pre-service and in-service teacher training.

Practical work in UK schools

12. International comparisons (such as TIMSS) indicate that students in the UK spend more time on practical activities than do students in most other countries. The evidence seems to suggest that the amount of practical work in schools in the UK has not varied substantially in recent years. For example, in NESTA's survey of 510 UK science teachers, while 42% thought that the amount of practical work had increased over the preceding ten years, 32% thought the opposite (NESTA, 2005, p. 7)

13. There is some evidence that a significant number of students see science experiments as being enjoyable. For example, an online survey of students (n=1,450) reported that in terms of enjoyability of school science activities, the top three were *'going on a science trip or excursion'* (85%), *'looking at videos'* (75%) and *'doing a science experiment in class'* (71%) (Cerini *et al.*, 2003, p. 10).

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14. When asked to choose the three methods that were most useful and effective in helping them to understand school science, 32% of respondents to an online survey chose *'doing a science investigation'* and 38% chose *'doing a science experiment in class'*. The two approaches that were regarded as being most useful and effective were *'having a discussion/debate in class'* (48%) and *'taking notes from the teacher'* (45%) (Cerini *et al.*, 2003, p. 10).

15. There is strong evidence that the current assessment regime in England and Wales has had a major impact on the amount and variety of practical work that many teachers carry out. There are growing concerns that the amount and quality of practical work carried out in schools have both suffered as a result of the impact of the national tests in science. This is the key finding in this review.

16. There is a *'chasm'* between what teachers identify as their outcomes before lessons and the outcomes that their students perceive.

17. Students fail to perceive the conceptual and procedural understandings that were the teachers' intended goals for the laboratory activities.

18. Students spend too much time following *'recipes'* and, consequently, practising lower level skills.

Implications

19. Advocates of more practical work in school science need to be clear about why they take this position and what types of activity they want to see happening. Woolnough and Allsop (1985) suggested three categories which might aid discussion about practical work: exercises, experiences and investigations.

20. Training in using practical activities might include developing teachers' understanding of theories of learning (such as the role of cognitive conflict), the use of argumentation in science and assessment for learning.

21. Training might usefully focus on the need to develop an awareness of the ranges and types of

practical work, of the need to be clear about the purpose of activities carried out in school science education, and of how to assess learning outcomes.

22. Training, both pre-service and in-service needs to be refocused and supported by more effective resources than are currently available.

23. More does not necessarily mean better.

1. Introduction

1.1 Background

> The worst science teachers make no attempt at all to embellish the curriculum by taking their students out of the classroom […] and they make minimum effort to run practical classes. Indeed, their sole aim appears to be to cover the curriculum so that their students will achieve the highest grades possible in examinations, even by abandoning many of the practical classes if that should prove necessary.
> *Dr Brian Iddon MP, January 16, 2008*

In opening the Parliamentary debate on ‘Science Teaching’ earlier this year, Dr Brian Iddon MP, noted that *‘recent surveys by the Science museum in Kensington and the awarding bodies have shown that hands-on practicals in laboratories and visits and excursions outside school are the most enjoyable aspects of studying the sciences’* and he continued, *‘I have been following closely the introduction of the new ways of teaching science in the classroom, and particularly the 21st century science syllabuses, of which there are a number.’* While being impressed with the *‘enthusiasm of the two young teachers and the students I observed’*, he noted, however, that *‘when I spoke to pupils after the classes in the two schools that I visited […] one thing came over loud and clear: “Please can we do more practical work?”’*

SCORE, the Science Community Partnership Supporting Education, responding to a recommendation in the House of Lords Science and Technology Committee report into Science Teaching in Schools, noted that:

> The importance of practical work in school science is widely accepted but it is important we ensure that such practical work genuinely supports learning and teaching, and that flexibility is given to the teacher to do this in relation to their pupils’ needs and the courses they are studying. In particular, SCORE feels that the introduction of ‘How Science Works’ to A levels in the sciences needs to be closely monitored by QCA for impact on practical work, as anecdotal reports suggest inconsistencies of interpretation between Awarding Bodies. (SCORE, 2007, p. 8)

SCORE drew attention to what they identified as most science teachers' main need which was to *'be able to try out practicals and develop their own confidence and skills, together with technician support'* (ibid.). Similarly, in their *Tenth Report*, the House of Lords Science and Technology Committee called on the Government:

> to review the place of practical science within the national tests as a matter of urgency so as to secure the future of genuinely open-ended, investigative science both inside and outside the classroom. Similarly, the new A-levels should place greater emphasis on practical work, including that outside the classroom or laboratory. (House of Lords, 2006, p. 33)

The Government's response confirmed *'the importance the Committee has placed on practical science.'* Noting that the *'changes proposed by the Committee in relationship to the national tests were instituted in 2003'*, the Government pointed out that the *'Qualifications and Curriculum Authority's monitoring subsequently showed some increase in teaching scientific enquiry skills'* (HM Government, 2007) adding:

> From 2008, most A levels will have only four assessment units. However, A levels in the sciences will continue to have six units specifically to allow the requirement to assess practical skills. The subject criteria for A levels in the sciences have been revised to emphasise the importance of practical work and out-of-classroom/out-of-laboratory work, and to include 'How science works', ensuring progression from the new GCSEs. (HM Government, 2007)

In a section of their report entitled *'The role of the practical'*, the Science and Technology Committee pulled together testimony from witnesses called to provide evidence to aid its deliberations:

> Practical work—both in the classroom and outdoors—is an absolutely essential component of effective science teaching. As the Consortium of Local Education Authorities for the Provision of Science Services (CLEAPSS) noted, *"appropriate practical work enhances pupils' experience, understanding, skills and enjoyment of science"*

(p 109). Moreover, NESTA commented that practical work *“allows science education to become something that learners participate in, rather than something they are subject to”* (p 165) and, in the words of the QCA, supports *“aspirations towards further study and science-related work.”* (House of Lords, 2006, p. 195)

However, there is a danger that the rhetoric surrounding ‘practical work’ neglects important findings from research and ignores the complexity of several key issues relating to the teaching of science in schools. This review takes a critical look at the research evidence relating to the teaching of practical work in schools. The review looks at eight issues:

- definitions of ‘practical work’, specifically if there is a current consensus about what is meant by this term, and what alternatives are in use which are more meaningful to encompass unique activities associated with scientific enquiry and experimentation;
- the impact of practical work for those learning science, particularly how benefits can be maximised, and how far they extend across all types of learner;
- the place of practical work: within the curriculum; as part of ‘enrichment and enhancement’ activities; and outside the classroom; and how this is changing over time;
- the quantity and quality of practical work being undertaken in schools and colleges in the UK, and any patterns of activity;
- the role that information technology can and might play in supporting teaching and learning in practical work;
- research, comparative or otherwise, exploring practical work in science in other countries;
- the relative strength of factors cited as barriers to practical work in the UK, such as the assessment system, teacher confidence, technical support, finances, and health and safety concerns;
- research and researchers at the cutting-edge – who is framing today’s debate on practical work and what are they saying.

1.2 Methodology and methods

Given the restricted time available to carry out the review, this report highlights the critical issues in the debate rather than provides a comprehensive compendium of the literature.

The approach taken to reviewing the literature involved several parallel steps:

1. Searching the major electronic bibliographic database (*Google Scholar*) for references to: ‘practical work in science’; ‘science inquiry’; ‘science enquiry’; ‘investigative work in school science’, etc. This search resulted in a primary database of books, papers, etc. As a way to ensure that all relevant material was identified, *Google Scholar* was searched for references to research that had cited the primary database.

2. The most recent review (Lunetta *et al.*, 2007) of the literature on practical work in school science was identified and read. An electronic copy of the review was obtained from the lead author and this was used to search for new references not revealed by the original search.

3. Searches were made of relevant websites (Ofsted, Royal Society, etc.) for documents, press releases, etc.

4. Recent and relevant books on practical work were identified and skimmed (for example, Abrams *et al.* (2008)).

Material was selected that appeared in international peer reviewed journals (for example, *Science Education*, *Journal of Research in Science Teaching* and the *International Journal of Science Education*) and professional journals such as *School Science Review*. Although account was taken of the number of participants, studies in peer-reviewed journals were not excluded or included simply as a result of the ‘sample’ size. In the case of surveys carried out on behalf of organisations which support science education, due care was taken in interpreting their findings.

An issue to be considered in reading the report is the extent to which teachers’ and students’ voices are heard. In the case of the teachers, there are several examples of surveys involving large numbers of respondents (for example, NESTA, 2005a) and others involving interviews with smaller numbers of individual teachers (for example, Ratcliffe *et al.*, 2007). One issue here is how representative is the research of the teaching community. Few studies are designed to be fully representative, however, there is little reason to doubt that the overall findings of many of the studies give a reasonably accurate picture of the overall situation.

In terms of the student voice, there is less certainty that their views are fully captured by the surveys reported in this review. Few large-scale studies have been carried out in recent years and those that have seem to have skewed samples. The larger international surveys (TIMSS and PISA) provide data from more representative samples of students.

Turning now to consider the degree to which successful innovations from one context can be applied to anther school, region or country, a considerable degree of caution has to be exerted. The assessment regime in England and Wales is quite different from that in many parts of the world and exhortations to implement 'solutions' from abroad need to be treated with caution.

Another issue here is that the UK has a relatively long history of practical work and has been through several of the stages that other countries are now undergoing. Adopting initiatives from other countries might actually be a retrograde step for the UK (see Section 7).

2. Definitions of practical work

Wellington (1988) notes that there are *'at least six types of activity'* that take place in school science *'that we would probably all class as practical work'* (p. 12):

> teacher demonstrations; class practicals, with all learners on similar tasks, working in small groups; a circus of *'experiments'* with small groups engaged in different activities, rotating in a carousel; investigations, organized in one of the above two ways; and problem-solving activities. (p. 12)

The different types of activity have different purposes (Gott and Duggan, 1995) but, as Wellington also points out, many *'experiments'* are nothing of the sort (see, also Gough, 1998), not least because no new knowledge is being made. Woolnough and Allsop (1985) have suggested three categories which might aid discussion about practical work: exercises, experiences and investigations:

> Schoolteachers themselves get very keen on new approaches – which in itself is half the battle won – but their enthusiasm is not untinged with scepticism about the value of pupils finding out for themselves in the laboratory ... Demands on time mean fewer facts – that is, a lower syllabus content; and that is a price which, in present circumstances, we can afford to go on paying for some time yet as long as we get the right kind of return in the form of minds which are lively and inquiring and not going under in a morass of information. (Jevons, 1969, p. 147)

The authors of the most up-to-date review of the relevant literature in the recently published *Handbook on Research on Science Education* (Abell and Lederman, 2007) provide what they call a classical definition of *'school science laboratory activities'* (which it notes are called '*practical activities* in British Commonwealth parlance'). Such activities are:

> learning experiences in which students interact with materials or with secondary sources of data to observe and understand the natural world (for example: aerial photographs to examine lunar and earth geographic features; spectra to examine the

> nature of stars and atmospheres; sonar images to examine living systems). (Lunetta *et al.*, 2007, p. 394)

The Royal Society's stated position on terminology is that *'"practical science" is used as shorthand for the full programme of experimental and investigative activities (including fieldwork) conducted as part of science education in schools and colleges'* (House of Lords, 2006, p. 63). However, various terms are in common use in science education to describe different sub-categories of practical work. For example, the *Student Review of the Science Curriculum* (Cerini *et al.*, 2003) reported findings of an online questionnaire survey which asked students aged 16-19 what they thought about different methods of teaching and learning in school science. It was noted above that Dr Iddon MP referred to one of the survey's findings – respondents reported the three activities judged as the most 'enjoyable' were: *'going on a science trip or excursion'* (85%), *'looking at videos'* (75%) and *'doing a science experiment in class'* (71%) (p. 10).

However, when asked to choose the three methods that were most useful and effective in helping them to understand school science, 32% of respondents chose *'doing a science investigation'* and 38% chose *'doing a science experiment in class'* (*ibid*.). Does separating experiments and investigations clarify or confuse? The report begs the question, how many of the respondents chose both *'doing a science investigation'* and *'doing a science experiment in class'* and how many of them thought they meant the same thing.

More importantly, for those advocating practical work, the two approaches that were regarded as being most useful and effective were *'having a discussion/debate in class'* (48%) and *'taking notes from the teacher'* (45%) (*ibid*.). The question arises as to why students aged 16-19 ask for *'more practical work'*? The answer might be because they want more fun rather than because they don't think that they're learning effectively. However, an element of caution needs to be maintained when considering the results of the survey. As the authors point out: *'The students who completed the survey did not constitute a truly representative sample'* (Murray *et al.*, 2003, p. 29).

The identification of *'science experiments'* and *'science investigations'* points to the frequency with which both terms appear in the discourse of science teaching. Other terms are in common use. Commenting on a survey of 510 UK science teachers, NESTA, the National Endowment for Science, Technology and the Arts noted that *‘science teachers are resolutely committed to the principle of practical and experiment-based science enquiry learning’* (NESTA, 2005, p. 4). It is unlikely that the term *‘practical and experiment-based science enquiry learning’* will replace *‘practical work’* in UK science teachers’ vocabulary however, it does illustrate the need for a degree of clarity when discussing the types of activities that teachers carry out.

In a report written for the US National Academy of Sciences, Robin Millar pointed out that when using the term *‘practical work’* he referred to *‘any teaching and learning activity which at some point involves the students in observing or manipulating the objects and materials they are studying’* (Millar, 2004, p. 2). By way of explanation, Millar added:

> I use the term *‘practical work’* in preference to *‘laboratory work’* because location is not a critical feature in characterising this kind of activity. The observation or manipulation of objects might take place in a school laboratory, but could also occur in an out-of-school setting, such as the student’s home or in the field (e.g. when studying aspects of biology or Earth science). I also prefer not to use the term *‘experiment’* (or *‘experimental work’*) as a general label, as this is often used to mean the testing of a prior hypothesis. Whilst some practical work is of this form, other examples are not. (Millar, 2004, p. 2)

If the defining feature of school science is ‘the practical’, its characteristics have changed substantially during the lifetimes of many science teachers. Writing in the late 1950s, Kerr stated that there was ‘some evidence that teachers of science, particularly in grammar schools, still consider the chief value of their work is associated with the claims made for the study of science as a mental discipline’ (1958-59, p. 156). Even as late as the 1960s and 1970s, experimental work served primarily to demonstrate techniques and to verify theory. Writing a few years later, Kerr, reviewing practical activity in school science, commented that:

> There was a lack of consistency between some kinds of experiments which teachers said they did and the stated value of such experiments. Verification experiments were frequently used but teachers thought their educational value was limited. Tradition and convenience perpetuated outmoded methods. On the other hand, finding out or 'getting-to-know-by-investigation' experiments were infrequently used, especially by the chemists and physicists, although the teachers ranked their educational value high. (Kerr, 1963, p. 54)

It may well be the case that tradition and convenience perpetuate outmoded methods. Dissatisfaction with the large number of science facts (the 'content') in the curriculum and the emphasis on rote learning have driven debates about science education for many years and prompted new approaches to science education in the mid-to-late 1980s (Hodson, 1990; Donnelly and Jenkins, 2001). This shift occurred partly as a result of an increased focus on the processes of science and how they could be taught and assessed. The movement was recognised and accelerated by the publication of *Science 5-16: a Statement of Policy* (DES, 1985).

Osborne (1993), amongst others, argued for more thought and discussion in school science and less rote-practical work (see also Gunstone (1991) and Solomon (1991)). Hodson (1990; 1992) criticised poorly planned practical work, describing its use as being *'ill-conceived, muddled and lacking in educational value'* (1992, p. 65). The process/content debate was not about practical work, *per se*, rather it was more about the relative efficacy of different ways of teaching science (see, for example, Wellington, 1981). Those promoting a process-led approach to science education argued that if pupils were to learn about how science works, then they needed to develop an understanding of the processes of science [that is, the skills used in doing experiments]. As Jevons (1969) put it:

> The case for investigational work in the laboratory rests partly on its supposed resemblance to the 'real thing', creativity in research, and the hope that in consequence it will stimulate and foster the right kind of abilities and ways of thought. (p. 147)

Millar (2004) provides an explanation as to why the notion of 'pupil as scientist' is attractive to science educators:

> Encouraging students to pursue their own enquiries taps into their natural curiosity. Finding things out for yourself, through your own efforts, seems natural and developmental, rather than coercive, and may also help you to remember them better. It seems to offer a way of holding up evidence, rather than authority, as the grounds for accepting knowledge. It is enabling, rather than dismissive, of the individual's ability, and right, to pursue knowledge and understanding for her/himself. Indeed one of the great cultural claims of science is its potential as a liberating force – that the individual can and may, though his or her own interaction with the natural world, challenge established tradition or prejudice, by confronting it with evidence. An enquiry-based approach may also encourage students to be more independent and self-reliant. In this way it supports general educational goals such as the development of individuals' capacity for purposeful, autonomous action in the world. (p. 3)

Early attempts to focus on the processes of science tended to take an atomistic view of what science involved. For example, the science education research team of the Assessment of Performance Unit, which commenced its work in 1979, devised a set of categories of skills (see, for example, Gott and Murphy, 1987). This atomistic, skills-based approach had an impact on science teaching and on its assessment during the 1980s and 1990s.

The advent of the National Curriculum in England and Wales led to a focus on 'investigations' in school science and several curriculum development projects were supported by government agencies and by charitable trusts. The OPENS project (Jones *et al.*, 1992) and the AKSIS project (Watson *et al.*, 2001; Wood-Robinson *et al.*, 1999) were research-based curriculum development projects that produced innovative materials for science teachers. After ten years of working with the National Curriculum, Watson and Wood-Robinson (1998) found that teachers had identified the following two characteristics of investigations.

- In investigative work pupils have to make their own decisions either individually or in groups: they are given some autonomy in how the investigation is carried out.
- An investigation must involve pupils in using procedures such planning, measuring, observing, analysing data and evaluating methods. Not all investigations will allow pupils to use every kind of investigational procedure, and investigations may vary in the amount of autonomy given to pupils at different stages of the investigative process
(p. 84)

Critics of the impact of the National Curriculum in Science pointed out that teachers were adopting a narrow range of teaching strategies when it came to doing investigations (Donnelly *et al.,* 1996). Recent revisions to the National Curriculum have sought to broaden the range of scientific investigations carried out in science lessons.

Currently, the National Curriculum at key stages 3 and 4 uses the term *'Practical and enquiry skills'*. At key stage 3, although the heading *'Practical and enquiry skills'* is the same, the phrase *'plan and carry out practical and investigative activities'* is used (QCA, 2007a, p. 209). QCA states that pupils should be offered opportunities to *'pursue an independent enquiry into an aspect of science of personal interest'*. In an explanatory note, QCA notes that *'Independent enquiry … could include using primary sources from experimental work or using secondary sources from desk-based research'* (2007a, p. 212). So teachers are faced with several different expressions: *'Practical and enquiry skills'*, *'practical and investigative activities'*, *'independent enquiry'* and *'experimental work'*.

The key stage 3 attainment targets contain more examples of activities that pupils should undertake. So, for example, at Level 6 of Attainment target 1 (*How Science Works*):

> Pupils identify an appropriate approach in investigatory work, selecting and using sources of information, scientific knowledge and understanding. They select and use methods to collect adequate data for the task, measuring with precision, using instruments with fine-scale divisions, and identify the need to repeat

> measurements and observations. They recognise a range of familiar risks and take action to control them. They record data and features effectively, choosing scales for graphs and diagrams. They analyse findings to draw conclusions that are consistent with the evidence and use scientific knowledge and understanding to explain them and account for any inconsistencies in the evidence. They manipulate numerical data to make valid comparisons and draw valid conclusions. They communicate qualitative and quantitative data effectively, using scientific conventions and terminology. They evaluate evidence, making reasoned suggestions about how their working methods could be improved. (QCA, 2007a, p. 215)

Other countries have adopted different terminologies. In the United States, as Keys notes, *'the current wave of science education reform literature emphasises learning science as inquiry'* (1998, p. 301) (see, for example, Hofstein *et al.*, 2004, 2005). The US *National Science Education Standards*, which form the basis of most states' science curriculum, is unequivocal: *'Inquiry into authentic questions generated from student experience is the central strategy for teaching science'* (National Research Council (NRC), 1996, p. 31). Roth and Roychoudhury (1993) report positive impacts on learning when an 'authentic' science inquiry was carried out by students in grades 8, 11 and 12 (ages 13-14, 16-17 & 17-18), arguing that *'integrated process skills develop gradually and reach a high level of sophistication when experiments are performed in meaningful context'* (p. 127). Keys (1998) notes that despite the rhetoric *'there is relatively little classroom research on how young students respond when they are asked to pose their own questions and design investigations to answer those questions'* (p. 301).

In the introduction to a recent book, published in the USA, Abrams *et al.* (2008), while noting that 'inquiry' plays a prominent role in discussions about science education reform, suggest that it would be a mistake to assume that the *'science education and research and teaching communities wholeheartedly embrace it'* (p. xi). They go on to point out that Settlage (2003) has argued that *'inquiry'* has been *'one of the most confounding terms within science education'* (p. 34) (and see also, Anderson, 2007; Barrow, 2006; Camins, 2001; DeBoer, 1991; Martin-Hauser, 2002; Minstrell, 2000; Minstrell and van Zee, 2000; Wellington, 1998). The recently published *'Rocard Report'* (Rocard *et al.*, 2007) uses the term inquiry-based science education (IBSE) (see Section 7).

In a statement that could equally easily be made by UK science educators, Abrams *et al.* (2008) write:

> Surprisingly, the lack of a clear and commonly held definition of inquiry in the classroom, the ambiguity in terms of the kind of knowledge it is to engender, and even nagging questions regarding its effectiveness as a pedagogic tool have not stopped the push by those involved in science education reform to integrate inquiry into K-12 classrooms. This widespread acceptance by the research and teacher education community in the face of such uncertainty leaves classroom teachers the burden of crafting their own definitions of inquiry in the classroom, selecting their own approach to this method and determining its strengths and weaknesses for their particular students, context and content. Placing such a nebulous construct at the center of science education reform effort with such scant support for teacher thinking about these constructs calls into question the eventual success of these reforms. (p. xii)

Lunetta *et al.* (2007) point to an ambiguity in the use of the term *'inquiry'*:

> Further complicating research into school laboratory practices have been ambiguous use of terms such as *"inquiry science teaching"* which may refer to teaching science *as* inquiry (helping students understand how scientific knowledge is developed) or teaching science *through* inquiry (having students take part in inquiry investigations to help them acquire more meaningful conceptual science knowledge.) (p. 396)

In attempting to clarify the complex nature of inquiry, Abrams *et al.* (2008) examine two US policy documents. The first, *Project 2061: Science for All Americans* (AAAS, 1989), states its position on inquiry thus:

> Over the course of human history, people have developed many interconnected and validated ideas

> about the physical, biological, psychological, and social worlds. Those ideas have enabled successive generations to achieve an increasingly comprehensive and reliable understanding of the human species and its environment. The means used to develop these ideas are particular ways of observing, thinking, experimenting, and validating. These ways represent a fundamental aspect of the nature of science and reflects how science tends to differ from other models of knowing. (p. 1)

In 1996, the US National Research Council's (1996) *National Science Education Standards*, stated that:

> Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of how scientists study the natural world. (p. 23)

Specifically, the NRC note that inquiry is *'multifaceted'* and involves:

> making observations; posing questions; examining books and other sources of information to se what is known; planning investigations; reviewing what is already known in the light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations. (p. 23)

Abrams *et al.* (2008) identify three goals for inquiry implicit in the two standards documents: understanding how scientific inquiry proceeds, being able to perform some semblance of scientific inquiry, and, understanding how inquiry results in scientific knowledge (NRC, 2000). *'Learning about inquiry'* involves students understanding *'how scientists go about constructing explanations of natural phenomena and come to recognise these methods are appropriate for questions posed in their own lives'* (Abrams *et al.*, 2008, p. xvi) (see also, Flick, 2003). *'Learning to inquire'* involves students becoming *'capable of participating in inquiry that bares some semblance to* *the activities that are going on in science'* (p. xvii). *'Inquiry and constructing learner's scientific knowledge'* which is distinct from the other two processes, is based on the premise that active engagement in doing science can lead to increased understanding of scientific concepts. The evidence for this assertion is examined in a later section.

One of the key arguments for the inquiry/enquiry-based approach is that it provides an authentic experience of doing science. Lunetta *et al.* (2007) point out that a critical difference exists between inquiry carried out by pupils and *'authentic'* science as done by scientists:

> Inquiry investigations conducted by novices in school science laboratories differ in important ways from authentic scientific investigations conducted by expert scientists, and to enable development of the science education field, it is important for teachers and researchers in science education to define and use central technical terms precisely and consistently. (p. 396)

In a paper written for the US National Academy of Sciences in 2004, Robin Millar wrote:

> Unlike scientific knowledge, where there is consensus about core knowledge claims, there is rather less agreement about the characteristic features of scientific enquiry and scientific reasoning. In one sense, professional scientists clearly know more 'about science' than any other group, but their knowledge is often largely tacit – 'knowledge in action' rather than declarative, propositional knowledge. The eminent philosopher of science, Imre Lakatos, once memorably commented of scientists' explicit knowledge of their practices that 'most scientists tend to understand little more *about* science than fish about hydrodynamics' (Lakatos, 1970, p.148). (p. 2)

In conclusion, the term practical science, though widely used, is unhelpful and imprecise. *'More practical work'* is a slogan without agreed meaning. It would help science teachers and those who work with them if there could be better agreement on what kind of science activities are effective. A more sophisticated vocabulary of science teaching might help science teachers and focus the efforts of those who promote the cause of science education. However, the term practical is so embedded into the discourse of science education that promoting its demise might be a forlorn endeavour. Greater use of the term *‘practical and enquiry skills’*, as found in the National Curriculum, might be a step in the right direction.

3. The purpose of practical work in science and its place within the curriculum

3.1 The purpose of practical work

> It is my belief that unpicking the Gordian knot that ties science education to its practical base requires, first and foremost, a reconceptualisation of the aims and purpose of science education. (Osborne, 1998, p. 164)

Wellington (1998) comments that *'teachers are always surprised, even shocked, when asked to consider what practical work in science is for'* (p. 6; see also Donnelly, 1995). This phenomenon might simply reflect the almost sacrosanct position of 'the practical' in school science (Delamont *et al.*, 1988). Less anecdotal evidence of teachers' attitudes towards practical work comes from sources such as the ICM survey carried out on behalf of NESTA (the National Endowment for Science, Technology and the Arts) (n=510). ICM reported that 84% of the participants considered practical work to be 'very' important with 14% considering it 'quite' important (p. 5). The high level of importance attached to practical work begs the question, why is practical work so important? The answer to that question emerges from an examination of the research into teachers' views of the aims of practical work.

Over the years, there have been several studies that have reported teachers' views of the aims of practical work. Kerr (1964) identified 10 aims reported by teachers and a further 10 more were reported by Beatty and Woolnough (1982). Swain, Monk and Johnson (1998) in an unpublished study found another 10 aims. However, the four most popular aims in all three studies were:

- to encourage accurate observation and description;
- to make phenomena more real;
- to arouse and maintain interest;
- to promote a logical and reasoning method of thought.

By comparing the three studies, some trends appear, which might be explained by the influence of the

National Curriculum. Four aims were rated more highly in the 1998 Swain *et al.* study than they were in the Beatty and Woolnough study carried out in the late 1970s:

> • to practise seeing problems and seeking ways to solve them;
> • to develop a critical attitude;
> • to develop an ability to cooperate;
> • for finding facts and arriving at new principles.

Millar (2004) argues that:

> It is also important to distinguish, and keep in mind, that the school science curriculum in most countries has two distinct purposes. First, it aims to provide every young person with sufficient understanding of science to participate confidently and effectively in the modern world – a 'scientific literacy' aim. Second, advanced societies require a steady supply of new recruits to jobs requiring more detailed scientific knowledge and expertise; school science provides the foundations for more advanced study leading to such jobs. These two purposes may lead to different criteria for selection of curriculum content, to different emphases, and (in the particular context of this paper) to different rationales for the use of practical work. (p. 2) (see, also, Abrahams and Millar, 2008, forthcoming)

In an attempt to make sense of the various aims, Wellington (1998, p. 6) offers a *'crude summary of arguments'* for the use of practical work (p. 6):

> *Cognitive arguments*: It is argued that practical work can improve pupils' understanding of science and promote their conceptual development by allowing them to 'visualise' the laws and theories of science. It can illustrate, verify or affirm 'theory work'.
>
> *Affective arguments*: Practical work, it has been argued, is motivating and exciting – it generates interest and enthusiasm. It helps learners to remember things; it helps to 'make it stick'.
>
> *Skills arguments*: It is argued that practical work develops not only manipulative or manual

> dexterity skills, but also promotes higher-level, transferable skills such as observation, measurement, prediction and inference. These transferable skills are said not only to be valuable to future scientists but also to possess general utility and vocational value
> (p. 7)

However, Wellington notes several counter arguments to all these claims for practical work. Firstly, doing science and understanding science theories are different (Theobald, 1968; Leach and Scott, 1995). Secondly, there is evidence that many pupils, particularly girls, are not very positive about doing experiments (Murphy, Qualter *et al.*, 1990). Thirdly, evidence for the transferability of skills is limited (Ausubel, 1964; Chapman, 1993; Lave, 1998). Wellington also notes that the arguments for the value of practical work in promoting group work have also been criticised (see, Wellington, 1994, ch. 8).

It would appear that the might be some scope for the science education community to engage in consideration of the purpose of science education and, in particular, the aims and purpose of ‘practical work’. As Bennett and Kennedy (2001) point out, the plurality of espoused aims for practical work in science make the task of assessment very difficult.

3.2 The place of practical work within the science curriculum

> We use practical work in science classes when students are unlikely to have observed the phenomenon we are interested in, or to have observed it in sufficient detail, in their everyday lives. In such situations, it is essential and irreplaceable. (Millar, 2004, p. 9)

> … the centrality of the laboratory to the teaching of science has become like the addicts' relationship to their drug – an unquestioned dependency which needs to be re-examined and weakened if not broken altogether. (Osborne, 1998, p. 156)

It has been noted already that practical work has become a central plank - a defining feature of school science. In this section, the place of practical work in the science curriculum is examined.

It was noted above that current National Curriculum documentation at key stages 3 and 4 uses the term *'Practical and enquiry skills'*. At KS4, teachers are told that:

> Pupils should be taught to:
> a) plan to test a scientific idea, answer a scientific question, or solve a scientific problem
> b) collect data from primary or secondary sources, including using ICT sources and tools
> c) work accurately and safely, individually and with others, when collecting first-hand data
> d) evaluate methods of collection of data and consider their validity and reliability as evidence.
> (QCAa, 2007, p. 222)

At key stage 3, pupils should *'plan and carry out practical and investigative activities'* (QCA, 2007a, p. 209). Pupils should be offered opportunities to 'pursue an independent enquiry into an aspect of science of personal interest'.

Although the curriculum specifies that practical and investigative activities must be carried out by pupils, and research indicates that teachers strongly advocate the use of practicals, it has to be noted that there is, as in many places in school education, a gap between policy and practice, between what is written in curriculum documents, what teachers say they do, and what pupils actually experience. For example, Lunetta *et al.* (2007) note that despite a recent shift of emphasis towards learning outcomes, the evidence suggests that there is a *‘chasm’* between what teachers identify as their outcomes before lessons and the outcomes that their students perceive (Hodson, 1993, 2001; Wilkenson and Ward, 1997). Hodson (2001) found that teachers’ stated lesson aims frequently failed to be addressed during actual lessons.

Tamir and Lunetta (1981) found that despite curriculum reform aimed at improving the quality of practical work, students spent too much time following *‘recipes’* and, consequently, practising lower level skills. As a result, students *‘failed to perceive the conceptual and procedural understandings that were the teachers’ intended goals for the laboratory activities’* (Lunetta *et al*., 2007, p. 403). This pattern of underutilisation of the opportunities provided by practical activities has been reported by several researchers (Tasker, 1981; Hofstein and Lunetta, 1982; Champagne *et al.*, 1985; Domin, 1988; Eylon and Linn, 1988).

International comparisons (such as TIMSS) indicate that students in the UK spend more time on practical activities than do students in most other countries (TIMSS, 1997). However, there is some disagreement among science teachers as to whether the amount of science enquiry has changed in recent years: NESTA’s (2005a) survey of 510 UK science teachers found that 42% thought that the amount had increased over the preceding ten years while 32% thought the opposite (p. 7). The NESTA study begs the question as to whether the teachers responding to their questionnaire shared the same meaning for the term ‘enquiry’.

Changes to the science curriculum in England at key stages 3 and 4 may result in changed pedagogy. However the changes are relatively new and, in some cases, still to be implemented. An evaluation of the Twenty First Century Pilot scheme by Ratcliffe, Hanley and Osborne (2007) involved a questionnaire survey of 121 teachers (from 84% of the pilot schools), 28 lesson observations in 9 schools, 22 teacher interviews and 8 pupil focus groups in 6 schools. The authors concluded that:

> The evidence collected suggests that teachers are developing and extending their range of pedagogic strategies through the experience of teaching *Twenty First Century Science*. Many reported more use being made of activities that rely on student contributions, e.g. voicing and sharing ideas through discussion. The use of more interactive teaching methods was, however, still low compared with the ‘knowledge transmission’ approach that characterises much science teaching – and may be lower than is necessary for the aims of the course to be realised. (p. 14)

Adding that, *‘Teachers sympathetic to the aims of the Core Science course often perceived a need to adapt their practice, but do not find it easy or quick to do so’* (*ibid*.)

QCA, in their evaluation of the pilot commented on the absence of practical work in the Core, a point picked up by Donnelly, in his role as evaluation co-ordinator:

> it is clear that significant numbers of teachers and students took the view that the Core contains less practical work than existing courses, and were critical of this. (I ought to note here that this view is not necessarily shared by members of the development team.) At any rate it is probably fair to say that the place of practical work within the aims and preferred methods of the Core is less central than has been common in the established wisdom of science teaching. (Burden *et al.*, 2007, p. 32)

The situation in other parts of the world is less positive, particularly in terms of primary education. For example, recent evidence from the USA indicates that, following the introduction of the *No Child Left Behind* initiative, the amount of time devoted to science has decreased (CEP, 2008).

4. The impact of practical work on students

> Many scientists and science educators are convinced that practical work *must* play an important role in learning science, but the reasons for its prominence are less clear. This lack of clarity lies in the vagueness of the questions asked about the role of practical work. Asking about the effectiveness of practical work for learning is like asking whether children learn by reading. The answer lies in the nature and contents of the activities and the aims which they are trying to achieve.
> (Watson, 2000, p. 57)

In a recent NESTA survey, 99% of the sample of science teachers believed that enquiry learning had an (83% - *'very'*; 16% - *'a little'*) impact on student performance and attainment (2005, p. 5). However, views about the role of processes in science education have been contested: some science educators have argued that practical work might help students to understand how scientists work, while others (see above) have argued that a process-based approach (that is, an approach that focused on experimental skills) was likely to lead to better understanding of science concepts (Donnelly *et al.*, 1996). A wave of predominantly key stage 3 curriculum development, led by *Warwick Process Science* (Screen, 1988), *Science in Process* (Wray, 1987) and *Active Science* (Price *et al.*, 1992), reflected a concern for more active process-based science as opposed to courses that contained a comprehensive range of subject matter.

Kind (1999) carried out an analysis of the TIMSS data by comparing the scores of 13-year-old students from England, Norway and Portugal. The three countries have different traditions of investigative work and Kind argues that although students in English schools did better at practical tasks than did the children from Portuguese schools that the results *'may be related as much to the type of practical work as to the quality'* (1999, p. 91).

Evidence of effective practice in the use of practical work comes from White and Gunstone's (1992) study which indicates that *'students must manipulate ideas as well as materials in the school laboratory'* (Lunetta *et al*., 2007, p. 405). Students need to understand something about the nature of science if they are to appreciate the limits and value of practical activities (Wolpert, 1992; Matthews, 1994; Lunetta, 1998; Abd-El-Khalick and Lederman, 2000; Duschl, 2000). The teachers’ role in helping students to compare their findings with those of their peers and with the wider science community is critical (Driver, 1995).

Freedman (1997), investigating the impact of a hands-on science programme on attainment and attitudes reported that:

> students [aged 14-15] who had regular laboratory instruction (a) scored significantly higher ($p < .01$) on the objective examination of achievement in science knowledge than those who had no laboratory experiences; (b) exhibited a moderate, positive correlation ($r = .406$) between their attitude toward science and their achievement; and (c) scored significantly higher ($p < .01$) on achievement in science knowledge after these scores were adjusted on the attitude toward science covariable. (p. 343)

Some researchers have reported that practical work can increase students’ sense of ownership of their learning and can increase their motivation (Johnstone and Al-Shuaili, 2001). Thompson and Soyibo (2001), in a comparison study, reported positive impacts of a combination of lectures, teacher demonstrations, discussion and practical work on Jamaican 10th grade [age 15-16] students’ attitudes to chemistry and understanding of electrolysis.

Other research (Brown *et al.*, 1989; Roth, 1995; Williams and Hmelo, 1998; Wenger, 1998; Polman, 1999) indicates that learning needs to be contextualised to be effective. As Lunetta *et al.* put it, *‘learners construct knowledge by solving genuine, meaningful problems’* (2007, p. 405). These findings suggest that practical activities which have no context and are simply set up to practise skills or for assessment purposes, may generate lower quality performance than tasks which appear to students to have a purpose connected to their daily lives.

Barron *et al.* (1998), working with 5th grade (UK Year 6) students in the US describe a process of designing, implementing, and evaluating problem- and project-based curricula. They describe four design principles that lead to positive effects on student learning: (a) defining learning-appropriate goals that lead to deep understanding; (b) providing scaffolds such as *'embedded teaching'*, *'teaching tools'*, sets of *'contrasting cases'*, and beginning with problem-based learning activities before initiating projects; (c) ensuring multiple opportunities for formative self-assessment and revision; and (d) developing social structures that promote participation and a sense of agency. Barron *et al.* (1998) point out that:

> A major hurdle in implementing project-based curricula is that they require simultaneous changes in curriculum, instruction, and assessment practices – changes that are often foreign to the students as well as the teachers. (p. 271)

Adey *et al.* (2004) also promote the value of cognitive conflict, meta-cognition and bridging from concepts to new situations and provide substantial evidence of the impact of cognitive acceleration through science education on science attainment. The success of the CASE and CAME programmes (aimed at pupils aged 11-13) point to the need for any innovation to be supported by classroom-focused coaching and modelling which involves at least 20-30 hours of professional development. Such approaches provide teachers with opportunities to engage students in activities which are *'minds on as well as hands-on'* (Gunstone, 1991, p. 159). The role of teachers in scaffolding learning – that is, *'sequencing complex ideas and experiences'* (Lunetta *et al.*, 2007, p. 406) – is critical (Davis and Linn, 2000). These conclusions echo Robin Millar's (2004) summary in a recent report for the US National Academy of Sciences:

> There is some evidence that experience of carrying out extended practical projects can provide students with insights into scientific practice and can increase interest in science and motivation to continue its study (Jakeways, 1986; Woolnough, 1994). Examples of the successful use of extended projects are, however, mainly at upper secondary school level or above, where students are to some extent self-selected, teachers have (in general) better subject knowledge, and group sizes are smaller. (p. 16)

Other evidence of the long-term effects of practical activities comes from a study by Gibson and Chase

(2002) who studied the impact of a Summer Science Exploration Program (SSEP), a 2-week inquiry-based science camp in the US. The camp was designed to stimulate interest in science and scientific careers among middle-school students. The Science Opinion Survey and the Career Decision-Making Revised Surveys were taken by 79 SSEP students and 35 students who applied but were not accepted. The authors report that *‘the interviews and surveys suggested that SSEP students maintained a more positive attitude towards science and a higher interest in science careers than students who applied to the program but were not selected’* (p. 693).

Millar (2004) identifies the value of practical activities in school science:

> More specifically, practical work is essential for giving students a ‘feel’ for the problematics of measurement, and an appreciation of the ever-presence of uncertainty (or measurement error). It is also an important tool for teaching about experimental design. Indeed research suggests that students design better investigations when they actually carry them out than when only asked to write a plan; feedback from experience improves design (APU, 1988: 100). (pp. 18-19) (see, also, Kannari and Millar, 2004)

However, he adds a note of caution when he comments on the success of scaling up innovations across an education system:

> There are few examples of the successful implementation of extended practical projects or investigations as part of the science curriculum in the context of ‘mass education’, where large numbers of teachers and students are involved. Teachers find it difficult to devise or to help students to generate enough project ideas, year on year. It is easy for the activity to become routinised, and become something very different from what was originally envisaged when it was included in the curriculum. (p. 16)

Summing up the findings of their recent review of research into laboratory work, Lunetta *et al.* (2007) conclude:

> When well planned and effectively implemented, science education laboratory and simulation

> experiences situate students' learning in varying levels of inquiry requiring students to be both mentally and physically engaged in ways that are not possible in other science education experiences. (p. 405)

They go onto explain that he laboratory can be *'an environment particularly well suited for providing a meaningful context for learning, determining and challenging students' deeply held ideas about natural phenomena, and constructing and reconstructing their ideas'* (Lunetta *et al*., 2007, p. 406). In terms of a pedagogical approach, they contend that: *'Social learning theory makes clear the importance of promoting group work in the laboratory so that meaningful conceptually focused dialogue takes place between students as well as between the teacher and students'* (p. 406).

An increased focus on the use of informal contexts for science education is evident in the UK. A review of the literature on outdoor education by Rickinson *et al.* (2004) concluded that:

- Substantial evidence exists to indicate that fieldwork, properly conceived, adequately planned, well taught and effectively followed up, offers learners opportunities to develop their knowledge and skills in ways that add value to their everyday experiences in the classroom.
- Specifically, fieldwork can have a positive impact on long-term memory due to the memorable nature of the fieldwork setting. Effective fieldwork, and residential experience in particular, can lead to individual growth and improvements in social skills. More importantly, there can be reinforcement between the affective and the cognitive, with each influencing the other and providing a bridge to higher order learning.
- Despite the substantial evidence of the potential of fieldwork to raise standards of attainment and improve attitudes towards the environment there is evidence that the amount of fieldwork that takes place in the UK and in some other parts of the world is severely restricted, particularly in science.
- The number of studies that address the experience of particular groups (e.g. girls) or students with specific needs is negligible, although those

that have been done draw conclusions that are important in terms of both policy and practice. Some children are more likely to take part in fieldwork than others for a range of reasons, many of which could and should be addressed.

- A minority of studies provide a health warning to proponents of outdoor education. Poor fieldwork is likely to lead to poor learning. Students quickly forget irrelevant information that has been inadequately presented.

(p. 4)

The specific impact of practical work during fieldtrips has received little study and much of the literature reports on attitudinal impacts rather than on conceptual development. There are some exceptions, though, for example, in a recent study, Prokov *et al.* (2007) found that a one-day field-trip resulted not only in *‘significant and positive’* increases in 11-12-year-old Slovak students’ (p. 247) attitudes toward biology, the natural environment outside and future careers in biology but that students displayed *‘a better understanding of ecology concepts like ecosystems and food webs’* (*ibid*.).

5. The frequency and quality of practical work in school science and factors affecting teaching and learning

This section examines what is known about the amount and quality of practical work carried out in school science. It also looks at some of the factors affecting teaching and learning as they impact on practical work.

5.1 The frequency and quality of practical work

It is generally the case that it is teachers that control the frequency and, to some extent, the quality of practical work in schools and colleges. In the *Annual Report of Her Majesty's Chief Inspector 2004/05*, Ofsted (2005a) reported that:

> If teachers do not select appropriate work this results in pupils being taught the same content, often in the same way as they learned in the previous key stage. (unnumbered)

Ofsted pointed out the result of such an approach was *'demotivating for pupils and is a poor use of teaching resources'* which could lead to *'disengagement and to a depressing of standards'* (*ibid*.). Ofsted identified reasons that teachers had given for this state of affairs:

> Too often teachers have felt they have to teach didactically to get through the content of programmes of study or awarding body specifications. In the worst cases this is so that they can say they have taught it, regardless of whether pupils have understood or learned effectively. Similarly, where pupils only carry out instructions from worksheets to complete a practical activity, they are limited in the ways they can contribute. Some approaches to the GCSE also have a narrowing effect: the assessment of scientific enquiry through GCSE coursework using only a handful of experiments enables pupils to score highly but without deep scientific engagement. (*ibid*.)

The Wellcome Trust (2006) report, *Life Study: Biology A-level in the 21st Century* reporting on views and attitudes towards GCE biology A-Level in schools in England found that there was *'considerable variation* *in the amount of practical work undertaken by A-level students but, overall, students were doing less practical work now than in the past and often had weaker practical skills at university level'* (p. 222).

In reporting on science and mathematics in sixth-form and further education colleges, the *Annual Report of Her Majesty's Chief Inspector of Schools 2004/05* (Ofsted 2005b, unnumbered) noted that *'the pursuit of scientific enquiry can make a significant contribution to the excitement of science'* (unnumbered) and that *'pupils need to participate in all aspects of the investigation, forming hypotheses, planning, carrying out and evaluating.'* However, Ofsted noted that *'the assessment of scientific enquiry through GCSE coursework has led to a narrowing of pupils' experience of enquiry contexts and skills.'* (*ibid*.).

In terms of the relative weighting of different factors affecting teachers' use of practical work the major factor seems to be time. NESTA's (2005) survey of science teachers (n=510) found that 64% lacked time for experiments (this figure rises to 68% among female science teachers; 71% among those aged 55+; and, 92% among those teaching in Northern Ireland (ibid.)) while many teachers said that safety rules had put them off. 87% of respondents said learning which allowed more experiments and scientific enquiry would have a significant impact on performance (p. 6).

A small-scale survey by the Save British Science survey (n=67 heads of science) stated that around half the respondents reported being unable to carry out practical activities because of behavioural problems, lack of equipment or class size. According to SBS *'When pupils were likely to be behaving badly, the use of gas burners and acids was not an option …'* (BBC, 2007). The issue of safety in school science is discussed in a study by CLEAPSS commissioned by the Royal Society of Chemistry. CLEAPSS and its 'sister' body in Scotland, sent questionnaires to almost 1,700 secondary schools of all types, across the UK. 24% of schools responded to the survey. Questionnaires were also sent to 634 education officers across the UK (excluding Scotland) yielding a 10% response rate. The RSC concluded that:

- there are a number of myths and misunderstandings about presumed bans on particular chemicals, activities or procedures in school science; and

- much effective teaching of practical science is being inhibited on spurious grounds of health and safety.

(p. i)

The report commented that:

> Almost 61% of education authorities replying (all from England and Wales) indicated that they did not ban any chemicals or activities, many amplifying this by saying that they strictly followed CLEAPSS guidance. There was a small number of returns which showed an inaccurate understanding about perceived national bans on a range of activities such as dissection, reduction of lead oxide and use of air rifles. However, almost all of the 40 items in the list [of materials which might be used by schools or practical activities they might undertake], and indeed a few others not listed, were banned locally by at least one of those authorities who had such prohibitions in place. Officers from the same authority were not always in complete agreement about local policy and practice. (p. i)

UK science teachers are not alone in reporting lack of time as a barrier to doing more practical work. For example, a recent small-scale study in Hong Kong, found that *'science teachers generally find inquiry-based laboratory work very difficult to manage'* (Cheung, 2008, p. 107). Cheung went on to explain that the seven teachers in his study 'were most concerned about the lack of class time, shortage of effective instructional materials, and the need to teach large classes' (*ibid*.).

In a survey commissioned by the Institute of Biology (2007) and completed by 186 science teachers, 85% of respondents reported believing that less dissection work was being carried out than was the case before the introduction of the National Curriculum. It should be noted that 74% of the respondents were specialist teachers of biology. The study found that *'three in five participants believed that more dissection work should be done in school biology'* than was then the case. The respondents identified the factors that explained why they did not do more as being time, funding. *'what activities are permissible, acquisition of materials and the need for a resource handbook'.*

In terms of the focus and the quality of practical work, several authors note a lack of a focus on teaching about the nature of science. For example, Lunetta *et al.* (2007) note that despite a succession of reforms to the science curriculum focusing on the promoting the history of science *'the predominant pattern of science teaching visible in schools through the turn of the twenty-first century has omitted the story of science'* (p. 396). On the contrary, they note that *'the science visible in schools has focused on "covering" knowledge of science topics and limited problem-solving skills.'* Worse still, *'laboratory activities have engaged students principally in following ritualistic procedures to verify conclusions previously presented by textbooks and teachers.'* This point is echoed in the UK context by Donnelly *et al.* who claimed that teachers tended to develop a narrow canon of experiments that allowed their students to gain higher marks than might more experimental, creative inquiries (Donnelly *et al.* 1996).

The importance of the relationship between developing skills and developing scientific concepts has attracted several authors' attention. Lunetta *et al.* note that:

> Objectives articulated for teaching and for student behaviors have often focused on specific tasks to be accomplished such as *"doing the density lab"* rather than on the student learning that is to be accomplished such as *"learning about the relationships between mass and volume for different materials".* (Lunetta *et al.*, 2007, p. 396)

By way of explanation for this phenomenon, Duschl and Gitomer (1997, p. 65) found that teachers in their study tended to see teaching as *'dominated by tasks and activities rather than conceptual structures and scientific reasoning.'* Another US study, carried out in middle-schools by Kesidou and Rossman (2002), looked at nine widely-used teaching programmes. The authors reported that:

> whereas key ideas were generally present in the programs, they were typically buried between detailed or even unrelated ideas. Programs only rarely provided students with a sense of purpose for the units of study, took account of student beliefs that interfere with learning, engaged students with relevant phenomena to make abstract scientific ideas plausible, modeled the use of scientific knowledge so that students could apply what they learned in everyday situations, or

> scaffolded student efforts to make meaning of key phenomena and ideas presented in the programs. (p. 522)

Schmidt *et al.* (1999), in analysing the Third International Mathematics and Science Study (TIMSS) described US science teachers as being obsessed with seemingly unrelated tasks and activities and summed up the curriculum as being *'a mile wide and an inch deep'*. In another major study of science education in the US, Weiss *et al.* (2003, p. 1) described 59% of the science and mathematics lessons they observed as being low in quality. The authors found too much *'passive learning'* and *'activity for activity's sake'* (ibid.).

One of the challenges that teachers and researchers face is the difficulty in assessing the impact of practical work on students. For example, Millar (2004) points out the difficulties in evaluating the effectiveness of enquiry-based approaches in terms of conceptual development:

> As regards knowledge *about* science, the enquiry-based approach often aims for a largely tacit understanding. As a result, it is difficult to assess how successful it is, as the outcomes are rather imprecise and difficult to measure. Are students becoming better enquirers or not? And how do we claim to know? (p. 3)

Some of the problems that children face when carrying out investigations have been pointed out by Keys (1998):

> … children have difficulty making sense of the goals, purposes and motivation of investigations, while research emanating from the perspective of students' authentic questions has shown that children lack the processing strategies to conduct meaningful investigations. (p. 303)

Keys adds that *'it is not clear whether children of upper elementary age are interested in or spontaneously conceive of experimental designs with controlled and manipulated variables'* (1998, p. 303). The scale of the problem confronting science teachers is clear from Keys' summary of relevant research:

> Some recent classroom studies of experimental design in children aged 11-13 years (Duggan, Johnson, & Gott, 1996; Germann, Aram, & Burke,

> 1996; Gott & Duggan, 1995) indicated that most 11 year olds were able to design clear experiments when given only one independent and one dependent variable, but had difficulty with cognitive tasks such as manipulating two independent variables, conceptualising data as continuous, quantifying data, graphing, and evaluating the validity of data. DeTure, Fraser, Giddings and Doran (1995) found that Year 5 students were fairly proficient at observing, describing, and measuring, but their processes of hypothesising, concluding, and explaining were generally weak. Duggan *et al.* (1996, p. 472) suggest that children's failure to "keep the whole task in *mind,"* including their lack of understanding about the purpose and ultimate goal of data collection may be a barrier to rigorous experimental design and analysis. Thus, there is substantial evidence that children do have difficulty mentally processing the investigation problems put to them by adults, even when they appear to be actively engaged in these investigations. Rath and Brown (1995) report that children approach inquiry from motivational frames that differ significantly from the intentions of adults, including performance, fantasy, pet care, exploration and engineering. (Keys, 1998, p. 303)

Dissatisfaction with school science education was evident in the USA and in the UK before the launch of the Sputnik satellite in 1957 (Klainin, 1988). International comparisons, such as TIMSS and PISA, have provided further evidence with which to criticise much of what happens in school science laboratories. In 1987, for example, Keys, in *Aspects of Science Education in English Schools,* reported on the findings of the Second International Science Study (1982-1986):

> While the majority of 14 year-olds reported that their teachers normally introduced new material and went over material which had been covered previously at the beginning of each lesson, rather fewer reported that their science teachers summarized what had been taught at the end of each lesson ... About half the 14 year-olds reported copying from the blackboard often and half doing so sometimes ... Over 90 per cent of the 14 year-olds reported having science tests, about 40 per cent often and 50 per cent sometimes. (p. 159)

There is little evidence that science teaching in the UK, in terms of strategies and tactics, made significant progress between the 1970s and the mid-1980s when many of today's science teachers were themselves pupils. This state of affairs occurred despite the best endeavours of Nuffield Science, which encouraged aspirations of more creative process that, in the end, were not always met. The model that many current PGCE students or 'beginning teachers' see taught in schools may be little different from that which they experienced as pupils. This lack of alternative models in pre-service education may prove to be a major factor in limiting the professional development of many teachers. Johnson, Monk and Swain (2001) point out that teachers change in response to their environment and, in the case of teachers in England since the late 1980s, that environment has seen an increasing emphasis on assessment and testing.

Shymansky *et al*. (1997), writing about their research in Australia describe a *'typical'* classroom and science teacher:

> The classroom was a self-contained lecture-laboratory room. The teacher, a middle-aged man with a strong academic background in physical science, was an active graduate student pursuing a masters degree in science education at a local university. He expressed commitment to many constructivist ideas. He was enthusiastic about implementing ideas that he had researched at the university, and valued hands-on/minds-on activities, collaborative problem solving, and communities of learning. However, to some extent he was restricted in his teaching values and intentions by the need to complete the requisite subject matter of the unit of study within an allotted period of time. Nevertheless, within the traditional structure of the science department in his school, his lessons included strategies and activities that promoted knowledge construction and discourse opportunities. He used whole-class discussion for organization of the day's activities, and students frequently worked in small groups to complete experiments, reports, and study guides. (p. 576)

Although the *'typical'* UK science teacher would not be studying for a masters degree (although many PGCE courses are now offering some level of M-level accreditation), and, therefore, would be less aware of the discourse of *‘constructivism’*, there are many characteristics of the description above that would typify a secondary school science lesson in England. The crux of the debate about science teachers’ pedagogical development relates to the perceived need for heads of department and others to shift teachers towards challenging the orthodox ‘teaching values and intentions’ which manifest themselves in what many would describe as ‘traditional science teaching’.

In 2006, the House of Lords Science and Technology Committee identified what it said was a critical issue in school science, a reported decrease in the volume and variety of practical work caused by a range of factors related to the assessment regime. As they put it:

> Some witnesses felt that the volume and variety of practical work in schools had lessened over time. A key cause of this was the focus on *“teaching to the test”*, which squeezed out some types of practical work. As CLEAPSS pointed out, *“teachers are being required to achieve better examination results and one response to this has been to focus more on* ‘book learning’ *which is more easily managed and assessed”* than practical work. Moreover, teachers had *“insufficient opportunity ... to learn about, and practice, activities before lessons”* (p 110). Similarly, the Science Learning Centres noted, *“many teachers complain that, with pressure to get through the syllabus, they cannot find room for much practical work”* (p 176). A NESTA survey had reinforced these impressions, with *“a lack of time”* being cited by 64 per cent of teachers—more than any other issue—as a barrier to practical work. (p. 165)

The perceived lack of time to learn about and practice practical activities was compounded, according to witnesses, by teachers’ desire to maximize opportunities for their pupils to score highly in tests:

> Even when teachers can find time for practical work, there is concern about the lack of variety, particularly at GCSE level. CLEAPSS suggested that *“a desire to ensure that ... investigations can be both rigorously assessed and enable candidates to do their best has meant that schools choose only those known to work well and*

> *conform to certain specifications"*. This had led to *"perhaps as few as 10 different investigations forming the bulk of science GCSE coursework throughout the country"*. (*ibid*., p. 112)

Support for this hypothesis came from representatives of the Science Learning Centres who stated that:

> the national tests […] require teachers to assess practical skills, but the highly specific criteria against which this assessment takes place tends to lead to a formulaic approach more akin to jumping through hoops than carrying out true scientific enquiry. (*ibid*., pp. 176-177).

The Science and Technology Committee noted that *'Whilst it is to be hoped that the new GCSEs will improve the situation, these issues again emphasise the need to modify the assessment regime, allowing space for genuinely open-ended practical work'* (*ibid*., p. 28).

A related though separate issue concerns the role of practical work outdoors. As the Science and Technology Committee noted:

> The problems facing practical science are particularly serious in the case of fieldwork. The Field Studies Council warned that "fieldwork provision in science and biology is declining in British secondary schools. A minority of 11-16 students will now venture outside the classroom and even in A-level biology nearly half the students will do no fieldwork, or will only have a half-day experience near to their schools". This decline was spreading to universities and "appears to be leading to a shortfall in people with the practical skills needed to support biodiversity and teaching related careers and activities" (p 150). The British Ecological Society concurred, warning that "urgent changes are needed to policies and the level of resources available to enable students to have meaningful fieldwork experiences". (*ibid*., p. 137)

The Campaign for Science and Engineering in the UK (CaSE) argued that *'practical classes are essential in teaching science, which is an inherently practical subject.'* (*ibid*., p. 141). CaSE quoted surveys they had carried out in secondary schools in England and in Scotland which found that teachers *'were cancelling* *practical classes for a variety of reasons, the principal two being a lack of equipment, and concerns about the behaviour of individual pupils.'* (*ibid*., p. 141). According to CaSE, *'not a single teacher downplayed the importance of practical work'* (*ibid*., p. 141) adding that:

> all the interaction CaSE has had with science teachers, with universities and with employers suggests that practical work is considered crucial by all interested parties, and that all sectors at worried at the decline in practical experimentation and field work in school science courses. (*ibid*., p. 141)

The Royal Society of Chemistry argued that *'classroom practicals form an integral part of many science courses'* adding that *'studies have shown that practical and investigative work has a marked positive effect on pupils' enjoyment and learning of science'* (*ibid*., p. 48). The study referred to was carried out in primary schools in Northern Ireland by Murphy *et al.* (2004) and, in fact, the authors found it hard to disaggregate the effect of increasing investigative work and co-teaching of classes.

Another factor identified by the advocates of practical work is the quality of laboratory provision. Recently, the RSC commissioned CLEAPSS (the Consortium of Local Education Authorities for the Provision of Science Services) to investigate aspects of school science teaching. CLEAPSS sent questionnaires to every maintained secondary school in England. CLEAPSS reported that whereas 35 per cent of school laboratories in the sample were rated *'good'* or *'excellent'* by science teachers, 41 per cent were rated as *'basic'* and *'uninspiring'*, and 25 per cent were rated as *'unsafe'* or *'unsatisfactory'* (RSC, 2005). Improving the quality of school science laboratories is a key aspect of the *Building Schools for the Future* initiative (HM Government, 2008).

Ofsted (2005), commenting on the provision of science laboratories in secondary schools commented that:

> Where accommodation is less than satisfactory, it hinders teaching and learning in a number of ways. Where classes are not taught in specialist rooms, the opportunities to investigate and engage in practical work are reduced, as is the effectiveness of teaching. Such timetabling

> difficulties make the sequence of science learning more difficult to manage. There is a clear need for the standards of accommodation to be improved. Although recent funding from the DfES has had some impact on improving laboratory stock, there is a continuing need for the upgrading and refurbishment of laboratories, and for new laboratories to be built in schools. (unnumbered).

The Institute of Physics evidence to the Science and Technology Committee stated that *'another issue that may be putting students off continuing with science post-16 is the quantity and quality of practical work taking place in schools.'* The IoP's belief in the value of practical work is that it *'plays a vital role in physics education'* in that *'as well as developing skills that are required for further study and employment in physics, practical work can help students to understand concepts; it can also be a powerful motivational tool'* (House of Lords, 2006, p. 57).

The IoP identified five *'barriers to effective practical work in physics'*:

- too many students in practical classes and the associated behavioural problems;
- inappropriate assessment of practical work;
- insufficient funding being devolved to science departments;
- under resourced and old fashioned laboratories in schools and colleges; and
- teachers who are not confident teaching physics.
  (*ibid*., p. 57)

The Royal Society asserted that:

> Open-ended investigative work, particularly of a long-term nature, should be promoted as the most appropriate way of engendering experimental and investigative skills at all ages. But the impact investigative work has on young people, as in all things, is dependent on the competence and confidence of the science teacher, adequate resourcing and good technician support. (*ibid*., p. 60)

The Royal Society elaborated on its position that *'"hands-on" experience in the laboratory or field is a distinctive and fundamental element in learning science'* as follows:

> The Royal Society considers that the skills and knowledge developed through fieldwork can be integral to the purposes of science education: to train experts able to serve science and society through research; to educate all young people in the fundamental processes of scientific investigation; and to prepare citizens of the future for responsible management of their environment. The Society is therefore concerned that the available research data (from small scale studies) suggest that fieldwork is being diminished throughout the education system by a number of pressures on schools, colleges and universities. (*ibid*., p. 63)

The Royal Society pointed to the dearth of empirical research into practical work in school when it stated that:

> Such evidence as exists suggests some cause for concern about the current teaching of practical science in schools. For example, while reports from Ofsted on trends in Primary science have linked high standards of achievement to good use of scientific enquiry, they also caution that: *". . . scientific enquiry remains the most variable and vulnerable part of the science curriculum. Science is largely taught in relatively short afternoon sessions . . .* [and this] *. . . seriously constrains teachers' ability to develop investigative activity. As a result, many investigations have become highly structured and give insufficient freedom for pupils to contribute their own ideas or reflect on outcomes."* The picture in Secondary schools is similarly mixed: *"Scientific enquiry and investigative practical work in particular remain issues in many schools. The Key Stage 3 strategy has led to significant improvement in Years 7 and 8, but beyond this, much investigation is narrow in range and sharply concentrated on the perceived demands of coursework assessment."* (*ibid*., p. 63)

The Biosciences Federation reported that *'the reduction in practical work is causing a significant* *impediment to inspiring the next generation of scientists and equipping students for a research career.'* In their experience, *'school students that attended summer schools at universities enjoyed hands-on practical work and that it enthused them.'* The Federation claimed that *'being able to offer a wide range of practicals in the sciences would make a huge difference in student attitude towards the subject, but few schools seem able to offer this now, making for mundane practicals and uninspired students.'*

The Biosciences Federation argued that:

> newly qualified science teachers are entering the profession ill-prepared to deliver lessons with practical work or field experiences as they themselves are not receiving the training in the delivery of these important aspects of science teaching. Practical work and especially fieldwork is increasingly seen as the province of older, more experienced teachers. (*ibid*., p. 66)

The Federation's statement was based on anecdotal evidence reported by its members (Assinder, personal communication).

The Nuffield Foundation noted that it had *'supported investigative science teaching for many years'* (House of Lords, 2006, p. 185) and pointed out that *'practical and experimental science continues to feature largely in new courses developed by the Nuffield Curriculum Centre'* (*ibid*., p. 185). Nuffield noted that in their experience, *'health and safety regulations have not prevented us building into courses a wide range of appealing practical work'* (*ibid*., p. 185).

However, unlike many of those who provided evidence to the Science and Technology Committee, the Foundation noted a caveat, *'practical work is not inherently good. It can lead to time wasting unless included in a course for a clear purpose'* (*ibid*., p. 185). The Nuffield Foundation identified four purposes for practical work which varied with the context:

- giving students experience of phenomena in ways that lead to new conceptual understanding;
- the development of hands-on practical skills;
- offering experience of the methods of science and the evaluation of data, as well as; and

- providing the challenge of investigations planned and carried through by students. (*ibid*., p.185)

5.2 Strategies to improve the quality of practical work

Strategies for improving the effectiveness of practical work have been identified by many authors. Millar, noting that students need to think as well as act, pointed out that Duckworth (1990) had noted that effective tasks are those where students are not only *‘hands on’* but also *‘minds on’* (Millar, 2004, p. 12). In Millar’s opinion, improving the quality of practical activities:

> requires first that teachers become more aware that making links between the domain of objects and observables and the domain of ideas is demanding, and then helping them to design practical tasks which take this demand more explicitly and fully into account – tasks which ‘scaffold’ students’ efforts to make these links. This in turn requires that teachers analyse more carefully the objectives of the practical tasks they undertake, and become more aware of the cognitive challenge for their students. The starting point for improving practical work is therefore to help teachers become much clearer than many are at present about the learning objectives of the practical tasks they use. (*ibid*., p. 12)

Hart *et al.* (2000) describe a successful intervention in Australia which was unusual in that the teacher’s purpose in conducting the investigation was not elaborated at the start of the activity. The teacher’s aim was:

> to develop students’ [girls aged 14-15] understanding about the way scientific facts are established with little expectation that they would understand the science content involved in the experiments. The unit was very successful from both a cognitive and affective perspective. An important feature was the way in which students [n=30] gradually came to understand the teacher’s purpose as they proceeded through the unit. (p. 655)

Hand *et al.* (2004) developed a Science Writing Heuristic that *'encourages students to examine laboratory activities much more carefully in terms of having to justify their research questions, claims and evidence'* (p. 131). The authors found that students (n=93), aged 12-13, who used the heuristic *'performed better as a group than students who did not, and that students who completed a textbook explanation as a write-up performed better as a group than those who completed a more traditional write-up format'* (*ibid*.) (see, also, Rudd *et al.*, 2001)

Wynne Harlen, writing for a US committee, pointed to the work of Supovitz and Turner (2000). In a 1997 study of a local systemic change initiative, data was collected from 24 US projects. Drawing on questionnaire data from 787 schools and 4,903 teachers which asked about teachers' attitudes, beliefs and teaching practices, *'they linked the amount of PD experienced [among other teacher variables] to the indicators of teachers' inquiry-based teaching practice and levels of investigative classroom culture'* (Harlen, 2004, p. 16). Supovitz and Turner (2000) reported that *'it was only after approximately 80 hours of professional development that teachers reported using inquiry-based teaching practices significantly more frequently … than the average teacher'* (p. 973). They, like others who have studies teachers' professional development (Adey *et al.*, 2004; Guskey, 2000; Joyce and Showers, 1995), concluded that much short-term professional development was ineffective.

Supovitz and Turner (2000) also noted that teachers from schools with low socio-economic status (SES) students tended to use more traditional teaching methods than those with students of higher SES backgrounds. They, like Adey *et al.* (1995), also noted the importance to the success of the professional development of the headteacher.

The challenge of changing science teacher pedagogy, despite the existence of the National Network of Science Learning Centres is daunting. Harlen and Altobello (2003) showed that professional development for inquiry-based science for primary and middle school science teachers *'could be delivered with equal effect on-line as face-to-face, given a carefully crafted on-line course designed to provide experience of learning through inquiry'* (Harlen, 2004, p. 16). In the study carried out in the US, Harlen and Altobello looked at how teachers fared when taught on-line and when taught face-to-face. They reported that:

> About half of the course time was spent learning science content through inquiry and half in studying aspects of inquiry-based teaching. In all parts of the courses, participants worked in groups. On-line participants were formed into groups of six or seven, each member exchanging asynchronous messages with the others every week. On-line participants conducted investigations or analysis of evidence of teaching from videos or case studies off-line and then went on-line to report their results or ideas to their group. (Harlen, 2004, pp. 16-17)

Harlen and Altobello found that:

- The *Try Science* course, when delivered both on-line and on-campus successfully involved participants in scientific investigation in which they regularly used science inquiry skills.
- For both sets of course participants, there were changes in their understanding of the science content of the course, but this was significantly greater for the on-line participants.
- There was little change in the participants' understanding of inquiry evident in their pre- and post-course definitions, but those in both courses considered that their understanding of inquiry in science had been increased.
- The main difference in experience between the on-line and on-campus was that the former were involved more frequently than the latter in reflecting on their learning and on the process of inquiry.
- The confidence that teachers expressed in their capacity to teach science through inquiry increased during the course, significantly more for the on-line than for the on-campus participants.

(Harlen, 2004, p. 17)

In summary, the science education community is not lacking in knowledge of what works in terms of science activities, or at least, what might work better. What is lacking is adequate training and an assessment regime that might facilitate change.

6. The role that information technology can and might play in supporting teaching and learning in practical work

This section provides an examination of the role that information technology can and might play in supporting teaching and learning in practical work, particularly the use of computer simulations and the use of primary data obtained from the internet or other research sources is examined. This is an area that is constantly changing as new hardware and software become available. Lunetta *et al.* (2007) point out an added challenge:

> To complicate matters, science education studies have not always helped to distinguish between and link important ends (learning outcomes that are sought) and means to those ends (teaching resources and strategies such as specific kinds of investigative activities in the laboratory). For example, significant changes in technologies since the 1980s have offered new resources for teaching and learning, but insufficient attention has been directed to examine critically how these new technologies can enhance or confound experiences in the school laboratory. (p. 396)

Rapid advances in technology have been claimed to offer a wide range of new opportunities for innovative science education (Barton, 1998; Lunetta, 1998). The opportunities include the use of sensors, simulations and the internet (Braund and Reiss, 2006). Millar (2004) notes that *'computer-based simulations may also help to reduce the* 'noise' *of the laboratory bench and focus attention on important aspects of experimental planning and data interpretation (Millar, 1999)'* (p. 19). He also notes that *'computer-based tools (for example, Bell and Linn, 2000; Sandoval, 2003) can help to engage students more actively in thinking about issues of theory choice'* (Millar, 2004, p. 19).

Computers and their peripherals can be used to aid long-term investigations, for example in data-logging experiments (Friedler *et al.*, 1990; Lunetta, 1998; Krajcik *et al.*, 2000; Dori *et al.*, 2004). Computers can also be used in visualizing data and modelling scientific phenomena (see, for example, Reiser *et al.*, 2002). Lunetta *et al.* (2007, p. 412) summarise recent research findings when they say:

> When teachers and students properly use inquiry empowering technologies to gather and to analyze data, students have more time to observe, reflect, and construct conceptual knowledge that underlies their laboratory experiences. The associated graphics also offer visualization resources that can enhance students' experiences with authentic activities while promoting deeper conceptual understanding (Edelson, 2001). When students have the time and when the activity is valued by the teacher and by high-stakes assessment, students can examine functional relationships and the effects of modifying variables; they can also make and test predictions and explanations. Technologies that offer instantaneous display of data as it is gathered can offer opportunities through which students may be helped to understand systemic functional relationships and more holistic relationships among variables. Using appropriate high technology tools can enable students to conduct, interpret, and report more complete, accurate, and interesting investigations. Such tools can also provide media that support communication, student – student collaboration, the development of a community of inquirers in the laboratory-classroom and beyond, and the development of argumentation skills (Zembal-Saul *et al.*, 2002).

Nelson and Ketelhut (2007) recently reviewed research into the challenge of implementing *'authentic'* scientific inquiry into US schools and looked at the developing use of Multi-User Virtual Environments (MUVEs) (see, also, Zacharia, 2007). Three recurrent themes emerged:

> (1) with careful design and inclusion of virtual inquiry tools, MUVE-based curricula can successfully support real-world inquiry practices based on authentic interactivity with simulated worlds and tools, (2) Educational MUVEs can support inquiry that is equally compelling for girls and boys, and (3) research on student engagement in MUVE-based curricula is uneven. (p. 265)

Based on their review, the authors *'urge'* researchers to investigate whether:

> (1) MUVE-based curriculum can help teachers meet state and national standards with inquiry curricula; and (2) scientific inquiry curricula embedded in MUVE environments can help teachers learn how to integrate interactive scientific inquiry into their classroom. (*ibid*.)

However, many researchers have caveats about the inappropriate use of technology as Lunetta *et al.* (2007, p. 411) make clear:

> Much evidence now documents that using appropriate technologies in the school laboratory *can* enhance learning, and important research on learning empowering technologies is the focus of this section. That said, an initial cautionary note is fitting since evidence also documents that inappropriate use of even simple technology tools has interfered with meaningful science learning (Olson and Clough, 2001; Hofstein and Lunetta, 2004). When a device is introduced prematurely, before students have made sense of the underlying science concepts, there is evidence that device or tool may serve as a *"black-box"* that interferes with students' perceptions of what is happening and hinder their understanding of important scientific ideas.

The internet is increasingly being seen as a potential resource for science education. However, as Linn (2000) notes: *'The internet provides a rich, confusing, chaotic, informative, persuasive set of scientific information'* (p. 785). In terms of utilising the internet to promote and support practical work in science, the House of Lords Science and Technology Committee recommended that the *'Government assess the feasibility of a unified and comprehensive central website dedicated to practical work in all the sciences'* (2006, p. 33). Such a website, the Committee suggested *'should offer health and safety advice and exemplar practicals that can stimulate students'* (ibid, p. 33).

Subsequently, several of the learned societies have supported the development of websites that promote practical work, although these are in relatively early phases (see, for example, www.practicalbiology.org). The *'Practical Physics'* website (http://www.practicalphysics.org/) is more advanced and already contains more than 400 experiments aimed at the 14–19 age range.

The Government's response to the recommendation noted that:

> The Secondary National Strategy provides guidance and lesson materials to encourage effective and engaging practical work in the classroom and to ensure that teachers link this to learning objectives and development of subject knowledge. They also encourage practical work to be used with other learning tools such as ICT. As one of our *'Next Steps'* commitments, the Government has also asked the Secondary National Strategy to promote effective practice in interactive teaching including imaginative use of practical work. (HM Government, 2007, para 6.11)

In terms of strategies to encourage teachers to see the benefits of blending ICT into their lessons, Zacharia (2003) reports on a study involving 13 pre-service teachers designed to investigate the effect of interactive computer-based simulations, the use of laboratory inquiry-based experiments and the use of combinations of both in a physics course on science teachers' beliefs about and attitudes toward the use of these learning and teaching tools, as well as the effect on their intentions to incorporate these tools in their own future teaching practices. The study found that, at the end of the study, *'beliefs affect attitudes and these attitudes then affect intentions, and showed that science teachers' attitudes toward physics and the use of the teaching approaches were highly positive'* (p. 792). A blended approach to simulations and laboratory work was found to be effective with Finnish elementary (aged 11-12) students (n=66) by Jaakkola and Nurmi (2007, unnumbered) who reported that:

> the simulation–laboratory combination environment led to statistically greater learning gains than the use of either simulation or laboratory activities alone, and it also promoted students' conceptual understanding most efficiently.

A recent, unpublished, study of the impact of a London Science Challenge initiative, suggests that, in terms of the use of ICT in schools, supply far outweighs demand. There appears to be little evidence of sustained, focused use of ICT in science lessons on any significant scale. While examples of good practice exist, teachers appear to prioritise other approaches to the teaching of science. It is difficult to see the situation changing substantially in the near future despite evidence that appropriate use of ICT in science can lead to higher attainment and more positive attitudes to science.

7. Research and researchers at the cutting-edge

This section examines research, comparative or otherwise, which is exploring the practical work in science in other countries and research and researchers at the cutting-edge who are framing today’s debate on practical work. Many of the key researchers have been identified already so this section will focus on a range of projects which appear to be increasingly influential or typify the kind of research and development that is taking place in Europe and elsewhere.

It is evident from much of what is reported in the rest of this review that concern about the amount and quality of what is referred to as practical work in science has been a feature of school science education for some time. The title of Jerry Wellington’s (1998) edited collection, *Practical Work in School Science: Which Way Now?*, illustrates the deep concern felt by many people who witnessed science lessons in UK schools or who carried out research into students attitudes towards their science education. The problem is not one faced solely by UK science education. Successive international comparisons of knowledge and attitudes have led many countries to consider changes to their science curriculum (Osborne and Dillon, 2008). It is not surprising, then, to find that a number of projects have been looked at improving science education within the last decade or so.

Some of these projects involved international collaborations between several European institutions. *Labwork in Science Education*, funded by the European Commission, ran from 1996-1998 and involved some of Europe’s most experienced researchers including John Leach, Robin Millar, Jean-Francois Le Maréchal and Andrée Tiberghien working in seven European countries - Denmark, France, Germany, England, Greece, Italy and Spain (Leach and Paulsen, 1999). Several empirical studies emerged from the project which have led to further studies in the UK, Germany and elsewhere (Séré *et al.*, 1998, 2001; Tiberghien *et al.*, 1998, 2001; Welzel *et al.*, 1998; Séré, 2002).

The project examined *‘labwork’* in biology, chemistry and physics to students in *‘academic science streams’* at the upper secondary level and in the first two years of undergraduate study at university. The project resulted in, *inter alia*, twenty-three case-studies from five European countries which contain:

- In-depth analyses of students' thinking during standard labwork with the aim of improving the process of modelling.
- Observation of open-ended projects.
- Labwork sessions focused on unusual objectives like data handling, epistemological objectives and students using their own initiative.
- A comparison of labwork with and without computers, in order to emphasise the process of modelling.

(European Commission, 2003)

Some of the specific project findings have been reported in recent papers and articles. For example, Séré *et al.* (2001) reported findings about the images of science drawn upon in laboratory work (n=368). Students were asked to comment on laboratory investigations carried out by research scientists or by science students. The authors reported that students' reasoning often differed significantly from accepted perspectives on the nature of science. The implication for teachers appeared to be that 'explicit teaching about the various relationships that can exist between theory and data would transform labwork towards a more critical process that involves making and justifying decisions' (Séré *et al.*, 2001, p. 499).

The *Labwork in Science Education* project's key recommendations were as follows:

1. Labwork should address a broader range of learning objectives than the range currently addressed. In particular, labwork rarely addresses epistemological objectives and teachers rarely make these objectives explicit when designing labwork activities, sequences of labwork or labwork sheets. Similarly, conceptual objectives, procedures to be learnt, data collection and processing are generally left implicit in the design of labwork.
2. Labwork should be better designed with more specific targets aimed at meeting clearly defined learning objectives. There should be fewer objectives for each labwork session and a more coherent overall organisation of labwork, which should lead to improvements in student learning.

3. There is a need to improve the design of assessment along side the design of more effective targeted labwork.
4. Improvements to labwork practices need to be addressed at teacher education level. In particular, teachers should be trained to identify effectiveness by better understanding of:
   a) What is learnt
   b) What processes consciously go on in students' minds, when putting into operation procedures and methods as well as developing models and theories. This should lead to an improved image of science and a better motivation for it.
5. Collaboration between researchers, teachers and policy-makers should be one of the key aims of research in Science Education in Europe over the next few years.

A more recent policy document, *Science Education Now: A Renewed Pedagogy for the Future of Europe* (Rocard *et al.*, 2007), written by the *'High Level Group on Science Education'* and published by the European Commission, argued for *'A reversal of school science-teaching pedagogy from mainly deductive to inquiry-based methods'* (p. 8) on the grounds that such an approach would provide the means to increase interest in science. The report claimed that:

> inquiry-based science education (IBSE) has proved its efficacy at both primary and secondary levels in increasing children's and students' interest and attainments levels while at the same time stimulating teacher motivation. IBSE is effective with all kinds of students from the weakest to the most able and is fully compatible with the ambition of excellence. Moreover IBSE is beneficial to promoting girls' interest and participation in science activities. Finally, IBSE and traditional deductive approaches are not mutually exclusive and they should be combined in any science classroom to accommodate different mindsets and age-group preferences. (Rocard *et al.*, 2007, p. 8)

One of the five recommendations in the report was that:

> Improvements in science education should be brought about through new forms of pedagogy: the introduction of inquiry-based approaches in

> schools, actions for teachers training to IBSE, and the development of teachers' networks should be actively promoted and supported. (*ibid.* p. 9)

The report drew on the experience of two projects, Pollen and Sinus-Transfer, which were specifically referred to in another recommendation:

> The articulation between national activities and those funded at the European level must be improved and the opportunities for enhanced support through the instruments of the Framework Programme and the programmes in the area of education and culture to initiatives such as Pollen and Sinus-Transfer should be created. The necessary level of support offered under the Science in Society (SIS) part of the Seventh Framework Programme for Research and Technological Development is estimated to be around 60 million euros over the next 6 years.

Pollen, which is based on previous work in France ('la main à la pâte') and the US (Folco and Léna, 2005), operates in 12 cities in 12 countries (see, http://pollen-europa.net/?page=WkdXK8w8jtI%3D). In the UK, the city taking part is Leicester. The UK National Coordinator for Pollen is Tina Jarvis (University of Leicester). The objectives of the Pollen Project – City of Leicester (Year 1) were to:

- Help schools do more practical investigative work.
- Support teachers to be more creative and make better links between subjects.
- Use the environment and facilities within the city to enhance science.
- Identify and disseminate good practice to all Leicester city schools, throughout the UK through the Regional Science Learning network and to teachers in other European countries.
- Help teachers and pupils to share and understand science activities being done in other EU countries.

(Pollen, 2007)

SINUS-Transfer is a dissemination programme which draws on the experiences gleaned from the SINUS project. SINUS was set up after the publication of the TIMSS study in the late 1990s. The results of the

German students were deemed by many to be worse than expected in both the mathematics and science assessments. Around 180 schools were involved in the SINUS project which was originally projected to last five years. Teachers played a key role in the project:

> The SINUS Programme basically focussed on the cooperation of teachers. Various schools all over the country were linked (in so-called Sets) and the teaching staffs improved their teaching methods considerably. Discussing and evaluating their own math and science lessons was the main issue of the project. The school Sets received both advice and practical support from so-called coordinators, who again cooperated closely not only within the individual federal states but also throughout the whole of the Federal Republic. Scientifically they were permanently supported by the Leibniz Institute for Science Education (IPN) at Kiel University, the Math Department of Bayreuth University and the State Institute of School Education and Educational Research in Munich (ISB).
> (SINUS-Transfer, 2007)

SINUS-Transfer aims to improve attainment in mathematics and science by disseminating the results of the SINUS programme. By 2005, almost 1,800 schools were involved in the project. The experience gained from the SINUS projects has helped make the Leibniz Institute for Science Education (IPN) at Kiel University one of the leading science education centres in Europe. However, other German researchers also have substantial experience in carrying out research in science classrooms including Claudia von Aufschnaiter (Justus-Liebig-University Giessen), Hans Fischer (University of Duisburg-Essen) and Manuela Welzel (University of Education Heidelberg).

Other institutions engaged in research into practical science activities include the University of Oslo where Carl Angell and Ellen Henriksen are involved with the FUN project (see, http://www.fys.uio.no/skolelab/fun/english.html) and FYS21 (Physics Education for the 21st century) (see, http://www.fys.uio.no/skolelab/FYS21/index2.htm).

In the USA, Eleanor Abrams (University of New Hampshire), Sherry Southerland (Florida State University) and Peggy Silva (Souhegan High School) have recently published an edited collection, *Inquiry in the Classroom* (2008). The book contains articles by some of the US's leading researchers including Sandra Abell (University of Missouri, Colombia), Valarie Akerson (Indiana University), Norman Lederman (Illinois Institute of technology), Larry Yore (University of Victoria), John Tillotson (Syracuse University), John Settlage (University of Connecticut).

Elsewhere in the US, Cuevas *et al.* (2005) recently reported that an inquiry-based instructional intervention on elementary school children's ability to conduct science inquiry overall and to use specific skills in inquiry:

> enhanced the inquiry ability of all students regardless of grade, achievement, gender, ethnicity, socioeconomic status (SES), home language, and English proficiency. Particularly, low-achieving, low-SES, and English for Speakers of Other Languages (ESOL) exited students made impressive gains. (p. 337)

The level of investment in science education research in the US is of an order of magnitude greater than anywhere else in the world. The National Science Foundation's Centers for Learning and Teaching programme supported around 15 collaborative projects, each lasting up to five years (see, http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5465).

The most recent UK study relevant to this review was carried out by Abrahams and Millar (2008, forthcoming). In a study of 25 'typical' science lessons they noted that:

> The teacher's focus in these lessons was predominantly on developing students' substantive scientific knowledge, rather than on developing understanding of scientific enquiry procedures. Practical work was generally effective in getting students to do what is intended with physical objects, but much less effective in getting them to use the intended scientific ideas to guide their actions and reflect upon the data they collect. There was little evidence that the cognitive challenge of linking observables to ideas is recognized by those who design practical activities for science lessons.

In conclusion, a significant number of researchers are studying aspects of practical work in Europe, the US and elsewhere. Much of the work is driven by the results of international comparisons such as PISA and TIMMS or by a desire to increase the number of students studying science at university, or both.

8. Conclusions

> Perhaps then it is time to consider the inconceivable – that the laboratory is only an adjunct and not a necessity. That the learning of science is not dependent on a practical offering for every lesson … (Osborne, 1998, p. 172)

Osborne's provocative challenge might find support amongst those who acknowledge that much of what happens under the guise of practical work is frequently a relatively ineffective use of teaching time and has repeatedly failed to train students in the science skills needed for the 21st century and has failed to provide learners with an adequate understanding of scientific theories or of how science works.

This review began by noting (*Foreword*) that though is often argued that practical work is central to teaching and learning in science, there are growing concerns that schools in general are not doing enough practical work and that its quality is uneven. In this concluding section, the key issues and evidence are drawn together and some suggestions are made for future research.

It is clear from looking at the National Curriculum documentation, at reports from stakeholders and at statements made by members of the broader science education community that there is confusion about the definition of 'practical work'. This confusion makes discussions about the value of 'practical work' difficult. A variety of terms exist to describe practical work many of which are frequently used with little clarification. For example, *Science in the National Curriculum* uses several terms with little attempt to explain their meaning: *'Practical and enquiry skills'*, *'practical and investigative activities'*, *'independent enquiry'* and *'experimental work'* (QCA 2007a/b).

Part of this confusion, which can make discussions about the topic frustrating, is that there are many espoused purposes for doing practical work in school science. Some of the most frequently stated are: to encourage accurate observation and description; to make phenomena more real; to arouse and maintain interest; to promote a logical and reasoning method of thought. There is a clear need for the broader science education community to agree, more than is now the case, on the value and purpose of ‘practical work’ in school science. Without an agreement about the purpose of science education and shared understandings about what kind of activities we want to school students engaged in, we are in danger of repeating yesterday’s mistakes tomorrow.

We know, too, that although practical activities appear to be popular with most teachers and many students, there are some caveats. The quality of practical work varies considerably not just in the UK but elsewhere in the world. Having said that, there is strong evidence that *‘When well planned and effectively implemented, science education laboratory and simulation experiences situate students’ learning in varying levels of inquiry requiring students to be both mentally and physically engaged in ways that are not possible in other science education experiences’* (Lunetta *et al*., 2007, p. 405). We must not lose sight of this message. Indeed, there is a growing body of research that shows the effectiveness of ‘hands-on’ and ‘brains-on’ activities in school science inside and outside the laboratory. Together with developments in technology-enhanced media, not to mention students’ growing facility with modern technology, the future of practical activity in school science might be very promising.
However, it is clear that there are significant barriers standing in the way of schools and teachers. There are concerns about health and safety issues although there is strong evidence to suggest that such concerns are both misunderstood and exaggerated to the continued detriment of student learning and enjoyment. There are significant equity issues involved here. Some students enjoy access top engaging practical activities and challenging outdoor activities whereas others do not, for no good reason.

The major barrier to improving the quality and variety of practical activity is the constraints felt by teachers in terms of two interrelated factors: time and the demands of the national assessment framework, particularly after Year 8. There is substantial evidence, teachers’ and students’ voices’ as well as independent research evidence, that the assessment regime, as it is currently constructed and conceived, is narrowing the range of activities carried out in schools and reducing the learning on offer to students. This situation has to change if we are serious about providing world-class science education for our students to prepare all of them for the future. This is the key message of this review.

Having said that, the existing cadre of school science teachers is probably insufficiently trained in planning, carrying out and evaluating the kind of practical activities that would provide maximum learning opportunities to students. There is a little evidence to suggest that the training that science teachers receive in this area, both pre-service and in-service is adequate. Any change in the assessment system must be supported by a concomitant change in CPD.

In terms of what training is required, Lunetta *et al.* (2007) note that that:

> Inquiry investigations conducted by novices in school science laboratories differ in important ways from authentic scientific investigations conducted by expert scientists, and to enable development of the science education field, it is important for teachers and researchers in science education to define and use central technical terms precisely and consistently. (p. 396)

Given what we know about learning in science (Bybee, 1997; Bransford *et al.*, 2000), we are in a position to identify which activities, practical or otherwise, are likely to engage students and help them to develop an understanding of what science is and how science works. Once we are clear about the purpose of science in schools, and practical work in particular, the design of new activities, new teaching (and assessment) methods and new teacher training should become more easier.

Teaching is a complex endeavour (Clough, 2003) and, particularly in the UK that complexity is exaggerated by the demands of high-stakes testing and accountability. There is a danger that little will change in the classroom unless change takes place in the assessment system.

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