Literature Review in Science Education and the Role of ICT: Promise, Problems and Future Directions

Jonathon Osborne, Sara Hennessy

FUTURELAB SERIES

futurelab

REPORT 6:

Literature Review in Science Education and the Role of ICT: Promise, Problems and Future Directions

Jonathon Osborne, King's College London
Sara Hennessy, University of Cambridge

REPORT 6:

Literature Review in Science Education and the Role of ICT: Promise, Problems and Future Directions

Jonathon Osborne, King's College London
Sara Hennessy, University of Cambridge

FOREWORD

"Science education in the UK stands poised to make the second fundamental change in its nature. Having won the battle that science education should be a compulsory element of all children's education, it is now attempting to develop a curriculum which is appropriate for all."

Today, what 'counts' as science and science teaching is in a state of flux. This, however, is not new – for 150 years there have been debates about the purpose, nature and role of science education in our society. Any designer of resources and tools for the teaching of science therefore needs to be able to understand these debates, and to be aware of the origins and reasons for the changes that are currently taking place.

This review is intended as a useful component in raising that awareness. It is a guide to the history, principles, debates and practices of science teaching in the 21st century and an introduction to the roles that digital technologies, as key new resources for scientific endeavour and communication today, might play in the changing practices of science teaching in our schools.

While the importance of informal learning is recognised, this review describes and contextualises the changes that are taking place in science education specifically in UK secondary schools. It should be noted that Futurelab's partner publication 'Primary Science and ICT' (2003) explores the development of primary science while a further Futurelab report to be published in early 2004 will address the key role of informal learning in science education.

We are keen to receive feedback on the Futurelab reports and welcome comments at research@futurelab.org.uk.

Martin Owen
Director of Learning
Futurelab

CONTENTS:

EXECUTIVE SUMMARY

WHY DOES SCIENCE EDUCATION MATTER?

Science education has its roots in the recognition by Victorian society that it had changed – changed from an agrarian society to one dominated by, and reliant on, scientific and technological expertise. In1851, the Great Exhibition brought the realisation that this new society could only be sustained by ensuring that a body of people were educated in science and technology. However, whilst there was little disagreement about the necessity for incorporating science into the curriculum, the form and content of that science education has since that time been a matter of considerable debate.

The opposing camps have lain between, on the one hand, those who would emphasise the need for science education to develop a knowledge and understanding of the **basic scientific principles** – the foundation on which the edifice rests – and, on the other, those who would argue for an emphasis on the processes of **scientific thinking**. The latter contend that the value of science education lies in the critical and evaluative habits of mind it develops that are of ubiquitous value for all individuals in all domains.

A retrospective view shows that as a rule, the dominant model of the curriculum has been one which has seen science education as a pre-professional form of **training** for the minority of today's youth who will become the scientists of tomorrow. This characteristic has arguably been responsible for the undervaluing of science within the British establishment who have historically regarded it as a lesser form of knowledge than the humanities which, in contrast, were often seen as offering an **education** of the complete individual.

Current research would suggest, however, that there are four common rationales for science education:

- the utilitarian: the view that a knowledge of science is practically useful to everyone. However this view is increasingly questionable in a society where most technologies are no longer remediable by any one other than an expert
- the economic: the view that we must ensure an adequate supply of scientifically trained individuals to sustain and develop an advanced industrial society
- the cultural argument: the view that science and technology are one, if not the greatest, achievement of contemporary society, and that a knowledge thereof is an essential prerequisite for the educated individual
- the democratic: the argument that many of the political and moral dilemmas posed by contemporary society are of a scientific nature. Participating in the debate surrounding their resolution requires a knowledge of some aspects of science and technology. Hence, educating the populace in science and technology is an essential requirement to sustain a healthy democratic society.

THE CHANGING CONTEXT

Two factors have led to calls for change in the nature of school science education.

a. The changing relationship between science and society. The past 30 years have seen a transformation in society's view of science. 30 years ago, the then Prime Minister, Harold Wilson, was able to offer a vision of the 'white heat of the technological revolution', men were landing on the moon, and iconic symbols such as Concorde heralded a new dawn. In contrast, today, after a long litany of environmental and technological disasters such as Chernobyl, global warming, ozone depletion, Bhopal, BSE and more, science is seen as a source of threat as well as a source of solutions.

In addition, recent research has transformed our understanding of science by highlighting the ways in which culture and values impact upon the development of scientific ideas and practices. The perception of scientific progress today is, therefore, more ambivalent than 30 years ago both in terms of its 'impacts' on society, and in terms of its claims to act as a value-neutral domain.

b. In the 1980s, the economic case for science education was successful in arguing that science should be a compulsory part of all school science curricula in many countries across the globe. The outcome, however, was the imposition of a model of science education designed for the small minority of children who would go on to become scientists. In recent years, however, it has been increasingly argued that compulsory science education can only be justified if it offers something of universal value to all. Hence, in the last decade the democratic and cultural arguments have come to the fore to argue that a complete science education should give a much more holistic picture of science, concentrating less on the details and more on the broad explanatory themes that science offers. In addition, a much more comprehensive treatment of a set of ideas about how science is done, evaluated and functions is required.

The most significant product of this debate so far has been the development of a new AS curriculum entitled Science for Public Understanding which has attempted to articulate a model of school science which meets these two challenges. This course addresses a collection of themes in the life science and physical sciences through a set of topics which cover the major ideas of science, ideas about data and explanations, the social influences on science and technology, causal links, risk and risk assessment, and decisions involving science and technology. This model is now being extended to the GCSE curriculum with the development of a pilot scheme – 21st Century Science – a course which will consist of a similar, but simplified core, and then a set of optional modules for those who wish to continue with the more academic or applied science.

MEETING THE CHALLENGE OF CHANGE

The changes embodied in these courses are radical. Traditionally school science has ignored any treatment or exploration of its nature as such knowledge is considered to be either largely irrelevant to its contemporary practice, or to be best acquired en passant. Hence, the pedagogy of school science has tended to be didactic, authoritarian and non-discursive with little room for autonomous learning or the development of critical reasoning. In addition, science teachers, themselves the product of the standard model of science education, often have naïve views about the nature of science. Teaching about science rather than teaching its content will require a significant change in its mode of teaching and an improved knowledge and understanding in teachers.

THE POTENTIAL ROLE OF ICT IN TRANSFORMING TEACHING AND LEARNING

While there are changes in the views of the nature of science and the role of science education, the increasing prevalence of Information and Communication Technologies (ICT) also offers a challenge to the teaching and learning of science, and to the models of scientific practice teachers and learners might encounter.

ICTs, for example, offer a range of different tools for use in school science activity, including:

- tools for data capture, processing and interpretation – data logging systems, databases and spreadsheets, graphing tools, modelling environments
- multimedia software for simulation of processes and carrying out 'virtual experiments'
- information systems
- publishing and presentation tools
- digital recording equipment
- computer projection technology
- computer-controlled microscope.

These forms of ICT can enhance both the practical and theoretical aspects of science teaching and learning. The potential contribution of technology use can be conceptualised as follows:

- expediting and enhancing work production; offering release from laborious manual processes and more time for thinking, discussion and interpretation
- increasing currency and scope of relevant phenomena by linking school science to contemporary science and providing access to experiences not otherwise feasible
- supporting exploration and experimentation by providing immediate, visual feedback
- focusing attention on over-arching issues, increasing salience of underlying abstract concepts
- fostering self-regulated and collaborative learning
- improving motivation and engagement.

ICT USE AND PEDAGOGY – AN INEXTRICABLE LINK

Current research would suggest, however, that it is not appropriate to assume simply that the introduction of such technologies necessarily transforms science education. Rather, we need to acknowledge the critical role played by the teacher, in creating the conditions for ICT-supported learning through selecting and evaluating appropriate technological resources, and designing, structuring and sequencing a set of learning activities. Pedagogy for using ICT effectively includes:

- ensuring that use is appropriate and 'adds value' to learning activities
- building on teachers' existing practice and on pupils' prior conceptions
- structuring activity while offering pupils some responsibility, choice and opportunities for active participation
- prompting pupils to think about underlying concepts and relationships; creating time for discussion, reasoning, analysis and reflection
- focusing research tasks and developing skills for finding and critically analysing information
- linking ICT use to ongoing teaching and learning activities
- exploiting the potential of whole class interactive teaching and encouraging pupils to share ideas and findings.

THE REALITY OF ICT USE IN THE SCHOOL SCIENCE LAB

Teachers' motivation to use ICT in the classroom is, at present, adversely influenced by a number of constraints including: lack of time to gain confidence and experience with technology; limited access to reliable resources; a science curriculum overloaded with content; assessment that requires no use of the technology; and a lack of subject-specific guidance for using ICT to support learning. While this technology can, in principle, be employed in diverse ways to support different curriculum goals and forms of pedagogy, such constraints have often stifled teachers' use of ICT in ways which effectively exploit its interactivity. Consequently, well-integrated and effective classroom use of ICT is currently rare.

Research shows that even where technology is available, it is often under-used and hindered by a set of practical constraints and teacher reservations. Whole class interactive teaching is also under-developed. At present, effective use of ICT in science seems to be confined to a minority of enthusiastic teachers or departments.

On the whole, use of ICT in school science is driven by – rather than transformative of – the prescribed curriculum and established pedagogy. In sum, teachers tend to use ICT largely to support, enhance and complement existing classroom practice rather than re-shaping subject content, goals and pedagogies. However, teacher motivation and commitment are high and practice is gradually changing. The New Opportunities Fund (NOF) scheme for training teachers in using ICT in the classroom appears to have had more success in science than in other subjects. Teachers are now beginning to develop and trial new strategies which successfully overcome the distractions of the technology and focus attention, instead, on their intended learning objectives.

To conclude, teachers are currently working towards harnessing the powerful potential of using ICT to support science learning as far as possible, given the very real operational constraints. Further development depends on providing them with more time, consistent access to reliable resources, encouragement and support, and offering specific guidance for appropriate and effective use. Assessment frameworks (and their focus on end products) may also need to change in order to evaluate – and thereby further encourage – ICT-supported learning.

PERSPECTIVES ON THE AIMS OF SCIENCE EDUCATION

CONCLUSION

To meet the new aims for science education, the science curriculum is poised to move in a new direction. The approach taken by the proposed new science curriculum for all pupils is eminently well-suited to the supportive use of interactive digital technology. As the school curriculum begins to forge links with the external scientific and social communities, opportunities arise for ICT use to play a central and core role in supporting development of scientific reasoning and critical analysis skills. Those in the process of developing new digital tools for use in the science classroom need, therefore, to engage with the new aims of science education and the science curriculum, and to develop resources that can be used by teachers both in facilitating key aspects of scientific thinking and in building bridges between schools and with the wider social and scientific communities.

1 PERSPECTIVES ON THE AIMS OF SCIENCE EDUCATION

THE ROOTS OF SCIENCE EDUCATION

The Great Exhibition of 1851 was a significant milestone in Victorian society. The technological marvel displayed both in the structure of Crystal Palace, and the exhibits within, brought home to society at large the transformation that had occurred in their society in the past 100 years from an agrarian to an industrial society. The very landscape itself had been transformed by the arrival of railways, canals and the factories that were to become the foundation of the world's leading economy and its expanding Empire. However, then, just as now, there were significant worries about how this prosperity could be sustained. Other nations, such as France, appeared to have more advanced systems of scientific instruction that provided for the mass of the population. Great Britain, in contrast, had no universal system of education for its young and, even where it did exist, there was no requirement for any science education.

> in the Victorian era the principal aim of such a 'scientific' education was to "educe a love of nature"

Such concern led the government of the day to propose that science education should form part of the elementary school curriculum. The form that it should take was one that emphasised the 'science of common things' – essentially an education which should aim to 'foster a taste for science'. Lyon Playfair, the then senior civil servant in the Department of Science and Art (there being no Department of Education at the time), argued that "the sciences of observation such as zoology, botany and physiology, are more suitable to the children of primary schools". The principal aim of such an education was to "educe a love of nature", and the only intellectual development recognised as an objective for science teaching was a training in observation (Layton 1973). Any aspects of physical science were considered inappropriate.

Such a view was controversial then, as it would be now. Thomas Huxley and others, in contrast, saw the function of science education as a means of intellectual development providing opportunities to engage in the exercise of reasoning by analysing and interpreting data, and using evidence-based arguments for appropriate scientific theories. In addition, it also permitted the testing of speculation. For Huxley then, science offered a discoverable order revealed by the application of standard processes. What mattered was not so much the content of any science education but the unique capacity that science offered for a training of the mind – in short that the process of engaging with scientific enquiry was much more significant than the content per se.

Such debates, between the value of the content of science versus its processes, ie scientific modes of thinking, were to play themselves out repeatedly in debates about the function and purpose of science education. They can be seen in Armstrong's advocacy of the significance of process (Armstrong 1891), in particular, in his advocacy of an approach to teaching which came to be known as 'guided discovery', and were to emerge again in the 1980s (Millar & Driver 1987). However, 100 years later, writing a personal view of UK primary science from 1950-82, Jean Conran provides a view of elementary science education which is still remarkably consistent with Playfair's view.

"We started the year with a 'Seaside Room'. Ready beforehand were displays of shells, pebbles, and sand; aquaria with live crabs and sea anemones; seaweeds; boxes and tables for collections made during the summer holidays; drawing materials, paper for labelling and selection of named specimens, reference books and pictures. We then followed the seasons with an ever-changing set of exhibits, a growing family of resident plants and animals, and a flow of temporary visitors brought in by the children. They marvelled at the unfamiliar and became confident in handling and caring for the familiar... Animals and plants were kept at home and books were purchased or borrowed from the library. Research was undertaken into cats and dogs. Diaries were kept. Expeditions to parks, museums and zoos were made on Saturdays and the children brought along parents, siblings and friends." (Conran 1983, p18)

In secondary education, in contrast, the arguments for the centrality of science in education met the combined opposition of advocates of the Classics and of Christianity who argued that the humanities were to be more highly valued than scientific and technological education for the development of a rounded individual (Barnett 2001). From the Victorian era, until at least the 1970s, this view was forcefully articulated, particularly by the public school community.

Thus, in spite of the centrality of science and technology to the success of two world wars and the industrial revolution, the values that predominated in formulating the school science curriculum echoed Matthew Arnold's view that scientific training as a form of education would produce only a 'useful specialist' and not a

for Huxley, scientific enquiry was much more significant than the content per se

PERSPECTIVES ON THE AIMS OF SCIENCE EDUCATION

'a frogmarch across the scientific landscape'

truly educated man. Over this period, science education and its curriculum were predominantly seen as essentially a pre-professional preparation for those who were interested in pursuing scientific or technical careers and had no value as part of the cultural education of the rounded individual.

The science education, essentially a scientific 'training', which emerges from such a view inevitably emphasises the foundational or vocational aspects of the subject and offers a curriculum that consists of the fundamental concepts of well-established, consensually-agreed science. However, as was argued recently:

"In focusing on the detail (for example, by setting out the content as a list of separate 'items' of knowledge as does the English and Welsh National Curriculum), we have lost sight of the major ideas that science has to tell. To borrow an architectural metaphor, it is impossible to see the whole building if we focus too closely on the individual bricks. Yet, without a change of focus, it is impossible to see whether you are looking at St Paul's Cathedral or a pile of bricks, or to appreciate what it is that makes St Paul's one the world's great churches. In the same way, an over concentration on the detailed content of science may prevent students appreciating why Dalton's ideas about atoms, or Darwin's ideas about natural selection, are among the most powerful and significant pieces of knowledge we possess. Consequently, it is perhaps unsurprising that many pupils emerge from their formal science education with the feeling that the knowledge they acquired had as much value as a pile of bricks and that the task of constructing any edifice of note was simply too daunting – the preserve of the boffins of the scientific elite."
Beyond 2000: Science Education for the Future (Millar & Osborne 1998)

Such a 'training', as opposed to an education, is essentially dogmatic and authoritarian, requiring its young acolytes to learn and assimilate a body of well-established knowledge which is essential for understanding the nature of the discourse and the contemporary problems facing scientists. In addition, it neglects any exploration of the nature of the subject itself or its history. The former is ignored, as it is assumed that such knowledge will be acquired en passant, and the latter neglected as it is assumed that the retrospective study of the history of sciences and its methods offers no insights into the questions that will face the prospective entrant to the scientific community. In short, such a science education is dominated by an emphasis on the content or 'facts' of science rather than its processes consisting, at its worse, of a 'frogmarch across the scientific landscape' (Osborne & Collins 2000). Where any exploration or teaching about the processes of science does take place, it tends to give the impression that there is a singular scientific method (Bauer 1992; Hodson 1996). Not surprisingly, therefore, the evidence suggests that most students emerge from such a science education with very naïve views of the nature of science (Driver et al 1996; Lederman 1992) where science is seen as a process of conducting experiments to derive data from which unambiguous generalisations or laws are made.

Unfortunately, the dominant view that science education is a pre-professional preparation for a scientific career has been unwittingly reinforced over the years by politicians concerned by the so-called 'flight from science' of contemporary youth (Dainton 1968; House of Commons Science & Technology Committee 2002). For the basis of their concerns lies in the threat posed by the poor recruitment to the supply line of scientific and technological personnel, rather than a concern that one of the greatest cultural achievements of Western society fails to engage the interest of young people.

Nevertheless, during the 1980s, policy arguments (DES 1987; DES/Welsh Office 1981; 1982) made both here and in other countries, managed to persuade politicians that science was so central to contemporary culture that it should be a compulsory element for all children from age 5 to 16. This process culminated in the implementation of compulsory 'science for all' in the first version of the National Curriculum (DES 1989). Science now found itself at the curriculum high table (House of Commons Science & Technology Committee 2002; Osborne & Collins 2000) alongside mathematics and English. Yet this structural change had been undertaken without any explicit consideration of the aims and values of science education. The model of scientific training that had been reasonably well suited to the minority who chose to continue with science post-14 of their own accord was, overnight, imposed on **all** children.

Arguably, however, the only justification for a requirement for all children to study science can be if the science curriculum offers something that is of universal value to all children. The failure to consider what might be appropriate to their needs laid the seeds for the failings and discontents of the next decade.

Another contextual factor that has driven the shape and nature of science education, and which has arguably undermined its quality, has been the development of a system of measuring the performance of schools through their examination results. The current system, which emphasises pencil and paper tests, gives pre-eminence to that which can be easily assessed – essentially students' knowledge of the content of science. However, as has been pointed out, when an indicator is selected for its ability to represent the quality of the service, and then used as the sole index of quality, the manipulability of these indicators destroys the relationship between the indicator and the indicated (Wiliam 1999). In short, the high stakes nature of the assessment distorts the nature, and quality, of the experience that is offered to pupils. Teachers feel under pressure to deliver the curriculum, and as a corollary over-emphasise content over process, removing or minimising opportunities to discuss issues raised by students or explore the more marginal but potentially interesting parts of the curriculum. The consequence is that testing, rather than being an integral component of science education with a benign effect on pedagogy has, instead, begun to have a malign effect on the teaching of science (Hacker & Rowe 1997; Wadsworth 2000).

A particular problem confronting the science curriculum has been the requirement to both undertake practical work and assess students' competence and skill in this domain. The first version of the National Curriculum embodied a model of scientific enquiry that, in the light of contemporary scholarship, was far too limited and restrictive. As Donnelly et al (1999) argued:

science, one of the greatest cultural achievements of Western society, fails to engage the interest of young people

SECTION 1

PERSPECTIVES ON THE AIMS OF SCIENCE EDUCATION

"The central elements of the model of science embedded in the 1991 Order are descriptive headings and quasi-algorithmic protocols. Professional scientists, or those who actually do experimental work, no doubt undertake activities which could be called 'hypothesising', 'observation' and so on. No doubt they also make use of variable handling schemes of various kinds. But there is nothing about such approaches which is specific to science, and thus explanatory of its power. Characterising the practice of natural science requires an altogether more complex framework, if indeed it can be done."

Such then is a brief picture of science education and some of its discontents at the turn of the millennium. Some of the dissatisfactions voiced in this account have emerged from the increasing understanding of science and its practices, which is emerging from the burgeoning body of scholarship in the field known as science studies. It is to this research we shall now turn in order to explore its implications for the teaching of science in secondary schools.

A CONTEMPORARY PICTURE OF SCIENCE

In contrast to the picture commonly presented in school science, the reality is that there is no singular method in science. A fundamental division exists between those working in the exact sciences of physics, chemistry, and to some extent biology, where the hypothetico-deductive method predominates, and where the aim is to develop explanatory models of the physical and biological world, and those sciences which are attempting a historical reconstruction of the past such as evolutionary biology, cosmology and the Earth sciences (Rudolph 2000). The goal of these sciences, in contrast, is the construction of a set of chronological sequences of past natural occurrences. The immediate goal is not the development of a model, but rather the establishment of a reliable record of what has occurred and when. At a more detailed level, the methods of the paleontologist and the nuclear physicist are as different as chalk and cheese, sharing in common only a commitment to evidence as a means of resolving disputes. And, moreover, as Norris (1997) has pointed out, "merely considering the mathematical tools that are available for data analysis immediately puts the study of method beyond what is learnable in a lifetime".

The other transformation of our understanding of science that has occurred in the past four decades is a consequence of the work of historians, philosophers and, in particular, sociologists of science. 40 years ago, the last lingering remnants of logical positivism – essentially the view that science was a set of logically deducible statements derived from observable entities – still held a strong influence within the scientific community. However, the work of Popper (1959), who argued that theories were believed not because experiments confirmed them but because they survived simply through scientists failing to falsify them, began to change both scientists' and the wider public's understanding of science. The real transformation in our understanding of science came with the work of Kuhn who argued that the work of scientists was a cultural product. In essence, scientists were portrayed as working in paradigms where ideas were so radically different as to be incommensurable. Every so often, the thinking of scientists would undergo a paradigm shift. Kuhn's essential contribution was to highlight that science was not the disinterested study of the natural world, as scientists would have it, but that science was indistinguishable from all other cultural activities consisting of a set of social actors embedded in a body of social networks and governed by sets of implicit and explicit rules. Once perceived this way, Kuhn's work opened the floodgates to the sociologists to study science in much the same way that such lenses had been applied to other social activities (Bloor 1976; Collins & Pinch 1993; Gross 1996; Latour & Woolgar 1986; Pickering 1984; Taylor 1996; Traweek 1988). The view of science that they offered was radical and contentious – at its most extreme some researchers argued that scientific knowledge was socially rather than objectively determined (Gross & Levitt 1994). This led to an acrimonious debate that at its height in the mid 1990s was characterised as the 'science wars'. Now that the dust has begun to settle, the outcome is one where the social dimension of science is clearly recognised. Science is a cultural activity, albeit an important one, which is governed by a set of structures and agencies that have well-defined mechanisms for inducting and accrediting its members (such as the Royal Society) and for communicating and recognising new knowledge claims advanced by its members (such as peer review). This is not to suggest that science is a social construct but merely to recognise the social dimension in the construction of scientific knowledge.

Historical and sociological studies show that such aspects are particularly salient for science-in-the-making. This last point is particularly important, as most of the political and moral dilemmas posed by contemporary science are a product of the uncertainties surrounding new scientific knowledge – eg the mechanism for the transmission of BSE, the effects of GM crops on the environment or the long-term impact of mobile phones. Steve Fuller (1997), a prominent sociologist, goes further to argue "that most of what non-scientists need to know in order to make informed public judgments about science fall under the rubric of history, philosophy, and sociology of science, rather than the technical content of scientific subjects." Given that school science education all but ignores this dimension of science, such a perspective offers a different vision of the aims and function of science education. What then are the differing functions and purposes of science education?

THE PURPOSES OF SCIENCE EDUCATION

Broadly speaking, there are four arguments for the purposes of science education which can be found in the literature (Layton 1973; Millar 1996; Milner 1986; Thomas & Durant 1987). These are called the utilitarian argument, the economic argument, the democratic argument and the cultural argument.

The utilitarian argument

This is the view that learners might benefit, in a practical sense, from learning science – that is that scientific knowledge enables them to wire a plug or fix their car; that a scientific training develops a 'scientific attitude of mind', a rational mode of thought, or a practical problem-

the political and moral dilemmas posed by contemporary science are a product of the uncertainties surrounding new scientific knowledge

PERSPECTIVES ON THE AIMS OF SCIENCE EDUCATION

there is little evidence that scientists are any more or less rational than the rest of humanity

solving ability that is unique to science and essential for improving the individual's ability to cope with everyday life. It is also claimed that science trains powers of observation, providing an ability to see patterns in the plethora of data that confront us in everyday life. Such arguments may well resonate with the reader — they are after all the stock-in-trade responses that are part of the culture of science teaching. Sadly, however, they do not stand up to close examination.

First, there is little evidence that scientists are any more or less rational than the rest of humanity. As Millar (1996) argues, "there is no evidence that physicists have fewer road accidents because they understand Newton's laws of motion, or that they insulate their houses better because they understand the laws of thermodynamics." Second, the irony of living in a technologically advanced society is that we become less dependent on scientific knowledge, for the increasing sophistication of contemporary artefacts makes their functional failure only remediable by the expert, whilst simultaneously their use and operation is simplified to a level that requires only minimal skill. Electrical appliances come with plugs pre-wired whilst washing machines, computers, video recorders, etc require little more than intuition for their sensible use. Even in contexts where you might think that scientific knowledge would be useful, such as the regulation of personal diet, recent research on pupils' choice of foods shows that it bears no correlation to their knowledge of what constitutes a healthy diet (Merron & Lock 1998).

The inevitable conclusion to be drawn from such work is that a utilitarian argument for knowledge is open to challenge on a number of fronts. In short, an argument that does not justify science's claim to such a large slice of precious curriculum time.

The economic argument

From this perspective, school science provides a pre-professional training and acts essentially as a sieve for selecting the chosen few who will enter academic science, or follow courses of vocational training. The 'wastage' is justified by the fact that the majority will ultimately benefit from the material gains that the chosen few will provide. The data on the skills and proficiencies needed for the world of work, however, raises some concerns with this argument. In the most systematic and comprehensive analysis of what scientists or scientifically-based professionals **do** in the UK, carried out by the Council of Science and Technology Institutes (1993), 46 occupations where science was a main part of the job (such as a medical technician), or a critical part of their job (such as a nurse) were itemised. Some 2.7 million people fell into these categories, a figure which represents only 12% of the UK work force. A further million people have their work enhanced or aided by a knowledge of science and technology. Coles (1998) estimates that the needs of this group represents, at most, a further 16% of the total UK workforce.

Coles' analysis of scientists and their work, their job specifications and other research summarises the important components of scientific knowledge and skills needed for employment as:

- general skills
- knowledge of explanatory concepts
- scientific skills:
  - application of explanatory concepts
  - concepts of evidence
  - manipulation of equipment
- habits of mind:
  - analytical thinking
- knowledge of the context of scientific work.

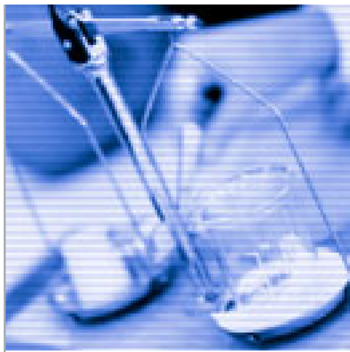
Coles' data, collected from interviews with a range of 68 practising scientists, suggests that a knowledge of science is only **one** component amongst many that are needed for the world of work. Furthermore, his data shows that knowledge that they **do** need is quite specific to the context in which they are working. The scientists in this research, in contrast to the need for specific content knowledge, stressed the importance of the skills of data analysis and interpretation; and general attributes such as the capacity to work in a team and an ability to communicate fluently, both in the written word and orally.

Yet these are aspects which are currently undervalued by contemporary practice in science education. Baldly stated, it would suggest that even our future scientists would be better prepared by a curriculum that reduced its factual emphasis and covered less but uncovered more of what it means to practice science. Coles' findings suggest that the skills developed by opportunities to conduct investigative practical work, such as that required in the UK – the ability to interpret, present and evaluate evidence, the ability to manipulate equipment, and an awareness of the scientific approach to problems – are outcomes which are to be valued as much as any knowledge of the 'facts' of science.

The cultural argument

There is an argument that science is one of the great achievements of our culture – a shared heritage that forms the backdrop to the language and discourse that permeate our media, conversations and daily life (Cossons 1993; Millar 1996). In a contemporary context, where science and technology issues increasingly permeate the media (Pellechia 1997), this is a strong argument, succinctly summarised by Cossons. Essentially this view would contend that the distinguishing feature of modern Western societies is its scientific and technological knowledge base which, arguably, is the most significant feature of our culture. And, in order to decode that culture and enrich our participation – including protest and rejection – an appreciation/understanding of science is desirable.

The implication of such a view is that science education should be more of a course in the appreciation of science, developing an understanding not only of what it means to do science, but of what a hard-fought struggle and great achievement such knowledge represents. However, understanding the culture of science requires some science history, science ethics, science argument and scientific controversy — with more emphasis on the human dimension and less emphasis on science as a body of reified knowledge. In short, a reduction of the factual emphasis with more emphasis on the broad 'explanatory themes' that science offers and the development of a better understanding of a range of 'ideas-about-science' (Millar & Osborne 1998).



the ability to interpret, present and evaluate evidence, the ability to manipulate equipment, and an awareness of the scientific approach to problems are to be valued

PERSPECTIVES ON THE AIMS OF SCIENCE EDUCATION

understanding the culture of science requires some science history, science ethics, science argument and scientific controversy

The democratic argument

The essence of this argument is that the political and moral dilemmas posed by contemporary society are increasingly of a scientific nature. For instance, do we allow cloning of human beings? Should we prevent the sale of British beef? Should we allow electricity to be generated by nuclear power plants? Participation in such debate requires some knowledge of science and its social practices. However, as disciplinary knowledge becomes increasingly specialised and fragmented, we become ever more reliant on expertise. Social systems such as hospitals, railways, and air travel gain a complexity beyond the comprehension of any individual. Consider, for instance, the number of individuals and systems involved in ensuring the safe flight of one aircraft between London and Paris. In such a context, trust in expert systems and their regulatory bodies is an essential requirement in our faith that they will function effectively (Giddens 1990). Worryingly, though, the increasing reliance on expertise undermines a basic tenet of democratic societies that all citizens should be able to participate in the process of decision making. Yet, this is only likely if individuals have at least a basic understanding of the underlying science, and can engage both critically and reflectively in a public debate. As the European Commission (1995) has argued:

"Clearly this does not mean turning everyone into a scientific expert, but enabling them to fulfill an enlightened role in making choices, which affect their environment and to understand in broad terms the social implications of debates between experts." (p28)

Most contemporary scholarship would argue that public debate about socio-scientific issues would benefit if our future citizens held a more critical attitude towards science (Fuller 1998; Irwin 1995; Norris 1997) – essentially one which, whilst acknowledging the strengths of science, also recognised its limitations and ideological commitments. However, it is difficult to see how this can be done by a science education which offers no chance to develop an understanding of how scientists work, that fails to explore how it is decided that any piece of scientific research is 'good' science, and which, in contrast to the controversy and uncertainty that surrounds much contemporary scientific research, offers a picture of science as a body of knowledge which is "unequivocal, uncontested and unquestioned" (Claxton 1997).

SCIENCE EDUCATION FOR THE 21ST CENTURY?

Faced with these competing functions, science education is effectively caught between a rock and a hard place, neither fulfilling the task of educating the future scientist nor the future citizen very well (House of Commons Science & Technology Committee 2002). What kind of science education would be more appropriate to the diverse needs of its students and the expectations of society?

The radical view advanced in the influential report, Beyond 2000: Science Education for the Future, was that the needs of the majority, who will not continue with formal science education post-16, must be foremost in formulating a curriculum. For the majority of young people, the 5-16 science curriculum will be an end-in-itself, which must provide both a good basis for lifelong learning and a preparation for life in a modern democracy – essentially a course which aims to develop 'scientific literacy'. Its content and structure must be justified in these terms, and not as a preparation for further, more advanced study.

This position is radical as, so far, all school science curricula have been dominated by the needs of the scientific community. Thus the content of science A-levels has been determined by the needs of university undergraduate courses and, likewise, the content of GCSE has been determined by the requirements of A-level. Whilst it is worth noting that the UK system is quite successful at this form of education, achieving high rankings on both the recent TIMSS (Beaton et al 1996) and PISA (Harlen 1999) international comparisons of achievement in school science, the substance of the case against the status quo is that this form of education is not appropriate to the needs of the majority.

Nevertheless, school science does need to cater for those young people who choose to pursue the formal study of science beyond age 16. Meeting the heterogeneous needs of young people requires a choice amongst science curricula, as it does for other personal and socially valuable choices and interests, rather than a one-size fits all homogeneous offering. In short, the mantra of the science education community 'science for all' does not mean one science for all.

What kind of education would help our future citizen to decide, for instance, whether cloning of human cells should be permitted? Gee (1996) argues that becoming 'literate' means becoming knowledgeable and familiar with the discourse of the discipline. That is the "words, actions, values and beliefs of scientists", their common goals and activities and how they act, talk, and communicate. Such knowledge has to be acquired through exposure to the practices of scientists and explicitly taught so that children can become critically reflective. Rather as learning a language requires children to develop a knowledge of the form, grammar and vocabulary, so becoming scientifically literate would require a knowledge of science's major explanatory themes, the reasons for belief in at least some of its content and, in particular, its uses and abuses.

The articulation of these ideas have been developed first in the AS course Science for Public Understanding (AQA 1999) and its associated textbook (Hunt & Millar 2000). At the time of writing, it is this course which is likely to form the framework for the new GCSE '21st Century Science' (further details of which can be found on http:// www.21stcenturyscience.org/home/) which will be offered initially as a pilot in 2003, and then universally to all schools in 2005. Contrary to reports in the press, this does not mean that it will be compulsory, but merely one option amongst several. Hence separate GCSEs in the sciences will still be available as will double science GCSEs. This innovative course includes a single GCSE core aimed at providing students with a 'toolkit' of knowledge to help them make sense of the modern world.

The AS course consists of two basic components – a set of ideas about science and a set of science explanations which are taught through a set of teaching topics. Fig 1 shows how these are interrelated. The science explanations, which are the major explanatory components underlying much of science are:

future citizens should hold a more critical attitude towards science

- the particle model of chemical reactions
- the model of the atom
- radioactivity
- the radiation model of action at a distance
- the field model of action at a distance
- the scale, origin and future of the universe
- energy: its transfer, conservation and dissipation
- cells as the basic unit of living things
- the germ model of disease
- the gene model of inheritance
- the theory of evolution by natural selection
- the interdependence of living species.

Whilst such a list is open to contention, for instance there is no treatment of the Earth Sciences, it represents a list of the broad themes that hopefully a young person would carry away from their experience of school science.

The 'Ideas-about-Science' component consists of four sub-components which, because of their relative unfamiliarity, are listed in more detail in Table 1. Evidence that it is an understanding of these aspects of the processes and practices of science that matter comes from a series of studies conducted with the public in different contexts, eg sheep farmers resolving how to deal with field contaminated from the fallout from Chernobyl (Wynne 1996); parents of Down's syndrome children dealing with

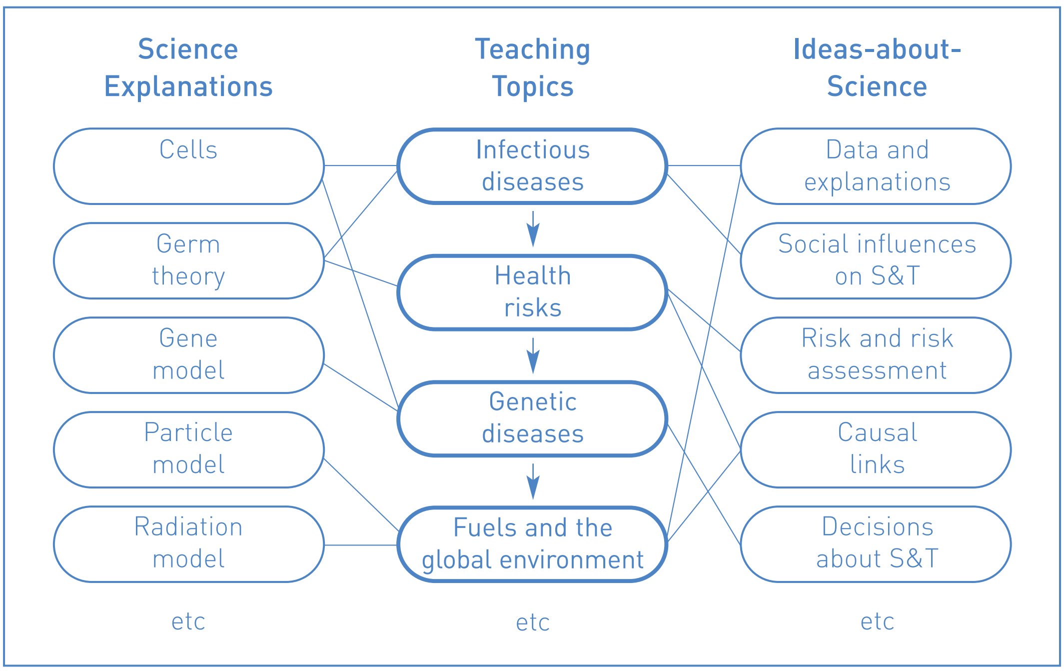


Fig 1: Diagram showing relationship between the teaching topics and the two major themes of the Science for Public Understanding course – Science Explanations and Ideas-about-Science

the mantra of the science education community 'science for all' does not mean one science for all the doctors (Layton et al 1993); the community around Sellafield and their attempts to understand the dangers posed by radiation (Layton et al 1993). Much of the implications of this work has been well-articulated by Irwin (1995) in his book Citizen Science. Further evidence comes from interview studies conducted with scientists and science educators by Abd-el-Khalick and Lederman (2000), and a Delphi study undertaken by Osborne et al (2001). All of these latter studies show that there is consensual agreement that what might be termed a 'vulgarised' account of the nature of science should form part of the compulsory school science curriculum.

An evaluation of the AS Science for Public Understanding Course conducted by Osborne et al (2002) has shown that the course has been successful in attracting more girls than boys – a remarkable feat for a course, which contains a large component of physical science – and that overwhelmingly students enjoy the course. This can be seen a considerable achievement in the light of the strong negative reaction to much of GCSE science (House of Commons Science & Technology Committee 2002; Osborne & Collins 2000). However, the course poses significant pedagogical challenges for many teachers, demanding a more extensive knowledge base and requiring the use of unfamiliar techniques such as the management of small group discussion.

Thus, science education in the UK stands poised to make the second fundamental change in its nature. Having won the battle that science education should be a compulsory element of all children's

the new AS course attracted more girls than boys

Table 1: The components of 'Ideas-about-Science'

Theme	Details
Data and Explanations	The idea that any measurement always has an element of uncertainty associated with it and that confidence is increased with repetition and replication. The idea that any experiment requires the identification and control of variables. That explanations require the use of creative thought and invention to identify what are underlying causal relationships between variables. Such explanations are often based on models that cannot be observed. That the goal of science is the elimination of alternative explanations to achieve a single, consensually agreed account. However, data shows only that a single explanation is false not that it is correct. Nevertheless, our confidence in any explanation increases if it offers predictions which are shown to be true. All new explanations must undergo a process of critical scrutiny and peer review before gaining wider acceptance.

Theme	Details
Social Influences on Science and Technology	Recognise that the focus of much research is influenced by the concerns and interests of society and the availability of funding. That scientists' views and ideas may be influenced by their own interests and commitments. That the personal status of scientists and their standing in the field is a factor which, wisely or not, is often used in the judgement of their views and ideas.
Causal Links	To recognise that many questions of interest do not have simple or evident causal explanations. Rather, that much valuable scientific work is based on looking for correlations and that such a relationship does not imply a causal link. To recognise that confidence in correlational links is dependent on the size of the sample and its selection. Events with very low frequency are particularly difficult to explain causally. To recognise that eliminating causal factors for a correlational link is highly problematic. Rather that much scientific work relies on the identification of plausible mechanism between factors which are correlated.
Risk and Risk Assessment	To have a knowledge of different ways of expressing risk and an awareness of the uncertainties associated with risk measurement. To be aware that there is a variety of factors which impinge on people's assessment of risk. That risk assessment is central to many of the decisions raised by science in contemporary society.
Decisions about Science and Technology	To recognise that whilst the application of science and technology has made substantial contributions to the quality of life of many people, there has been a set of unintended outcomes as well. That technology draws on science in seeking solutions to human problems. However, a distinction should be drawn between what can be done and what should be done. Decisions about technical applications are subject, therefore, to a host of considerations such as technical feasibility, economic cost, environmental impact and ethical considerations. That certain groups or individuals may hold views based on deeply held religious or political commitments and that the tensions between conflicting views must be recognised and addressed in considering any issue.

education, it is now attempting to develop a curriculum which is appropriate for all. The history of curriculum change is undoubtedly strewn with all kinds of false tracks and failures. The outcome of this reform remains to be seen – but it is at least attempting to steer the ship of science education, which behaves more like a supertanker than a dinghy, in a more morally justifiable direction.

2 THE POTENTIAL OF ICT IN SUPPORTING SCIENCE EDUCATION

THE USE OF ICT TO SUPPORT SCIENCE TEACHING AND LEARNING

So far, this review has attempted to summarise the differing perspectives of the aims of science education and the significant choices that have to be made of what and how we teach. Currently, the curriculum is still driven by the agenda of the professional scientific community with a well-established pedagogy which is primarily based upon transmission of predefined, value-free content knowledge. However, the demands for change embodied in new curricula such as 21st Century Science will require teachers to adapt and adopt a different set of pedagogic practices. Its goal of fostering 'scientific literacy' involves developing a knowledge not only of the broad explanatory themes of science but also of some of the discourse and practices of scientists, including the processes of theory construction, decision making and communication, and the social factors that influence scientists' work, albeit highly simplified.

Another force for pedagogic change in science education is the new modes of enquiry afforded by computer-based tools and resources, now known collectively as 'Information and Communication Technologies' (ICT). The advent of this educational technology, and its more widespread access in schools, potentially has an important part to play in re-shaping the curriculum and pedagogy of science. In particular, it offers easy access to a vast array of internet resources and other new tools and resources that facilitate and extend opportunities for empirical enquiry both inside and outside the classroom. Thus, in a very real sense, it offers opportunities to dissolve the boundaries that demarcate school science from contemporary science by facilitating access to a wide body of data, such as real-time air pollution measurements, epidemiological statistics, or providing direct links to high quality astronomical telescopes, and providing ready access to a wealth of information about science-in-the-making.

Access to such secondary resources and data, however, places greater emphasis on the need to provide a science education which gives pre-eminence, as its ultimate goal, to developing the higher order cognitive skills of evaluation and interpretation of evidence requiring critical assessment of the validity of theories and explanations. Such an education would seek to support and develop students' scientific reasoning, critical reflection and analytic skills. What, then, is the potential of using ICT to support and nurture such a science education? In the following sections of this review, we now examine this potential – particularly that envisioned by the current trend in science education which seeks to develop scientific literacy. We also explore the teacher's role in exploiting this potential, and the outcomes

another force for change in science education is the new modes of enquiry afforded by computer-based tools and resources

so far, concluding with a consideration of the implications for further development.

The potential role of ICT in transforming teaching and learning

Classroom use of ICT became a statutory requirement in all subjects with the introduction of a National Curriculum in 1989. This obligation has been somewhat elaborated with successive curriculum documents but its role is described in broad terms, in the form of tentative notes in the margins of the Science National Curriculum (and a very brief outline within the recent framework for Key Stage 3 science: DfES 2002a). Suggestions for 'opportunities' in the curriculum include "pupils could use simulation software to investigate and model circuits" and "pupils could use data loggers to investigate relationships" (DfEE/QCA 1999). Outline schemes of work produced by the QCA/DfEE (2000) for ages 11-14 provide some further non-statutory suggestions for using ICT.

The established model of using ICT to support school science assumes an iterative, investigative approach, as embedded in the National Curriculum, and incorporates simultaneous learning about scientific theory and process (see Frost et al 1994, for detailed examples of classroom activities which exploit ICT in this way).

The main forms of ICT which are relevant to school science activity include:

Tools for data capture, processing and interpretation
data logging systems, data analysis software (eg 'Insight'), databases and spreadsheets (eg 'Excel'), calculators, graphing tools, modelling environments

Multimedia software
for simulation of processes and carrying out 'virtual experiments' - CD-Roms, DVDs (eg 'Science Investigations 1', 'Chemistry Set', 'Multimedia Library for Science')

Information systems
CD-Roms (eg 'Encarta'), internet, intranet

Publishing and presentation tools
(eg 'Word', 'PowerPoint')
Digital recording equipment – still and video cameras

Computer projection technology
interactive whiteboards, data projector + screen, external monitor or TV

The first category of tools – those which can support practical activities or 'scientific enquiry' – is currently the most significant form of ICT application for science teaching and learning (Barton 2002). Its centrepiece is the **data logging system**, comprising a set of sensors or probes to convert the quantity to be measured (eg temperature, light level, humidity, sound, time, position, acceleration, pH, oxygen, current, energy) into a voltage recognisable by the computer; an interface to pass information from sensors to computer; and a computer program to control the interface and presentation of data on the screen. Sensors can be used remotely for collecting data over time from outside the laboratory, for example for monitoring weather. The versatility of the data logging system means that it can be used within a range of activities to support any of the substantive curriculum areas of study (life processes, materials, physical processes) as well as the processes of scientific enquiry.

Data handling tools (generic or task-specific) allow pupils to tabulate pre-stored data or that derived from computer logging or practical experiments; carry out calculations using built-in formulae; sort, search and graph/chart data; generate new datasets. Spreadsheets and modelling environments are particularly useful for both static and dynamic modelling of physical phenomena; in the first case, changing a variable in the model (eg driver's reaction time) generates a new output (eg vehicle stopping distance), and in the second, an iterative calculation models a system (eg harmonic motion) as a function of time, while initial parameters (eg amplitude) can be varied. Specific modelling environments (eg for exploring generational trends in predator-prey relationships) handle complex mathematical principles more readily than spreadsheets. Pupils can also use these tools to predict and test theories, constructing their own models and then employing them in their investigations. The latest generation of data logging software provides a common interface for comparing logging- and model-generated data (Rogers 2002b).

Multimedia software may include video and audio explanatory sequences, animated graphics, tutorials or interactive tasks, slide shows and/or an interactive database/encyclopaedia (simulations most frequently concern the solar system, the human body, the periodic table and physical forces). Some contain innovative analytic software which renders the simulated motion interactive and quantifiable; pupils can, therefore, manipulate variables (eg changing temperature or the mass of a moving object) or mark points and then process the data either by calculation or display in graphical form (see Wellington, in press, for details). Some multimedia CD-Roms also offer a virtual microscope enabling pupils to see exactly what they should see through a real microscope.

Information systems are typically used to support conceptual learning in the three substantive curriculum areas. Intranets storing a limited range of web content on a local network server are increasingly being used to provide an information resource which is safer, more quickly accessible and pre-filtered compared to the internet. **Word processing** can support an iterative approach to planning or analysis and **presentation tools** can be used to present findings of research or investigations in any topic area. A further kind of tool is the **computer-controlled microscope** where still, moving or time-lapse images can be captured, labelled, enlarged etc and used in conjunction with laboratory or field work (eg for live dissection of a micro-organism such as a seed, or analysis of pond life). Increasingly popular are multi-purpose **digital still and video cameras**. These can supply images for incorporation in teaching materials/presentations, or experiments can be recorded by pupils themselves. Finally, **projection technology** has become central to science education; access is rapidly increasing and it can be used with any of the other tools for whole class interaction – demonstration, lecturing, or collating and discussing class results. Interactive whiteboards are a special case and can encourage new forms of active student participation in science activities, as discussed later on.

Other common modes of using ICT include using a single computer or data logger with a small group (eg as part of a 'circus' of rotated activities in the lab or for

entering experimental results into a spreadsheet); half a class using a few machines (the other half might use conventional resources and compare results); a whole class using a computer suite or set of portable computers in the laboratory; and independent use (at home or in the school library/resource area). Certain learning purposes and resource levels clearly lend themselves more to certain modes of use (Wellington, in press), and use of particular tools is associated with certain pupil learning modes, eg receiver or revisor of knowledge, explorer of ideas, creator of reports/presentations (Newton & Rogers 2001, ch3).

Where's the 'C' aspect of ICT in this? For example, video conferencing? Or e-mail? Or linking schools/children/scientists together to discuss? Or 'mass' experiments linking numbers of different computers together? There are examples of these activities, some highlighted below, and they are directly relevant to the arguments in the first section of the review. Drawing on some prominent examples of recent research, we now examine how the above forms of ICT can potentially enhance both the practical and theoretical aspects of science teaching and learning, and explore the uses of ICT in the school laboratory [1]. In particular, two recent books – one by Newton and Rogers (2001) and an edited collection by Barton (in press-b) – offer an overview of the field as well as extensive practical guidance to teachers wanting to develop their practice in teaching with ICT. We also make use of ongoing research by the second author and her colleagues which is concerned with analysing and documenting effective ways of using ICT to support subject teaching at secondary level [2]. In conjunction with the wider research literature, the findings converge on the following conceptualisation of the potential contribution of technology use to science teaching and learning (throughout the five Key Stages of primary and secondary schooling).

Expediting and enhancing work production; release from laborious processes

The use of ICT, particularly tools for data handling and graphing, can speed up and effect working processes, notably the more arduous and routine components. This frees pupils from spending time setting up experiments, taking complex measurements, tabulating data, drawing graphs by hand, and executing multiple or difficult calculations. It enables rapid plotting of diverse variables within a short period, or collection of and comparison between a larger number of results (including merging of results from different classes). Hence it is possible to significantly increase the productivity of pupils within a single lesson and improving the quality of work they produce (Ruthven et al, submitted). Using the versatile software tools which are now linked to data logging is particularly helpful in allowing pupils to explore and present data in different ways with a low investment of time and effort (Newton 2000). Such tools free experimentation from the time constraints of the standard one-hour lesson, allowing data to be collected over several days, or even several weeks. Interactive computer simulation can help pupils to avoid getting 'bogged down' with the mechanics of simply setting up equipment, for example constructing and testing a circuit where the proliferation of wires involved can make it difficult to see what is happening, and minor faults in physical connection can pose a complete impediment.

ICT-supported procedures are not only faster and more efficient, but are also considered more precise, reliable and accurate. They yield less 'messy' data and illustrate phenomena without the 'noise' of unwanted variables and human error in measurement – in contrast with some practical experiments! Digital still and video cameras can offer high quality images of fieldwork sites, practical demonstrations or experiments. Finally, interactive worksheets can incorporate diagrams and text created in other applications. This saves time and improves accuracy by removing the need for students to copy them by hand before using them for conceptual activities (Hitch 2000). The worksheets can include automatic 'hyperlinks' allowing rapid access to pre-selected information on the internet or in an encyclopaedic database such as 'Encarta'. Interactive whiteboards offer similar facilities and the ability for the teacher in a whole class situation to move instantly between multiple kinds of prepared resources stored on a single computer or network.

Conflicting opinions arise regarding whether time for discussion and reflection upon activity can be easier or more difficult to find when using ICT, but a 'time bonus' is commonly reported. Teaching with ICT is said to offer more time for teacher interaction and intervention with pupils and greater sharing of class results, permitting more time for pupils to observe, think and analyse rather than being pre-occupied by gathering and processing data (Barton 1997; Finlayson & Rogers 2003).

Thus, in this sense, ICT does create the space to develop the kinds of analytical skills demanded of contemporary science education. Moreover, in conjunction with prompt teacher intervention, real-time data display can be a powerful stimulus for discussion and interpretation, particularly where large sample sizes are involved, or complex interactions between a number of variables may be evident. Real-time data display also enables the teacher to demonstrate instantly the link between an event and its formal representation. For example, the ability to produce graphs of the motion of objects as it happens strengthens the association between the phenomenon and its scientific representation.

To conclude, the use of ICT changes the relative emphasis of scientific skills and thinking; for example, by diminishing the mechanical aspects of collecting data and plotting graphs – particularly beneficial for low ability pupils – while enhancing the use of graphs for interpreting data, spending more time on observation and focused discussion, and developing investigative and analytic skills (Hennessy 1999; McFarlane & Friedler 1998; Rogers, in press-b; Rogers & Wild 1996). Research also suggests that using computer modelling and simulation allows learners to understand and investigate far more complex models and processes than they can in a school laboratory setting (eg review by Cox 2000; Linn 1999; Mellar et al 1994).

1 See June 2003 issue of School Science Review on the use of ICT in science teaching.

2 The findings of a series of departmental group interviews (Hennessy et al, submitted; Ruthven et al, submitted) and classroom observational case studies (Deaney & Ruthven, in preparation; Hennessy et al 2003) are drawn upon here. Also contributory is a current ESRC-funded project investigating pedagogy for effective use of ICT in science and mathematics.

SECTION 2

THE POTENTIAL OF ICT IN SUPPORTING SCIENCE EDUCATION

ICT may support teachers in rising to the new pedagogical challenges emerging as the curriculum begins to shift

Increasing currency and scope of reference and experience

Use of ICT, especially the internet, can open up access to a broader range of up-to-date tools and information resources, and increase the currency and authenticity of schoolwork far beyond that which textbooks and other resources can offer. It allows pupils to relate their work more closely to the outside world – to obtain live news or real data, for example concerning an earthquake. Pupils can even ask questions of 'real' scientists, or collaborate or pool results with peers elsewhere.

A topical example of reported use was accessing the Roslin Institute website during a research project on the cloning of 'Dolly' the sheep. Likewise the TERC Centre in Cambridge, Mass. (www.terc.edu) coordinates a wide range of projects linking schools to each other and to professional scientists. A prominent example is the GLOBE project (www.globe.gov) involving 12,000 schools collaborating with a community of scientists to collect, analyse, validate and interpret shared research data concerning climate change. Such exploration of pressing global questions promotes students' awareness of environmental issues and the Earth as a dynamic system. A further example is the Jason Project (www.jasonproject.org), a series of real-life and real-time internet-based science explorations designed for students who can engage with the work of research scientists exploring the geology and biology of dynamic and eco-systems throughout the planet.

Contact with wider ideas can extend high ability pupils and is perceived to increase opportunities for learning beyond that anticipated by the teacher or prescribed by the curriculum. One recent application, a CD-Rom called 'Ideas and Evidence', uses ICT to raise pupils' awareness of the uncertainties which surround the construction of scientific knowledge, especially the validity and consequences of different scientists producing different results and interpretations. This tool can be used to support role play and group discussions of topical social and ethical issues, including media bias and oversimplification in presenting science news stories (eg concerning health scares such as BSE or mobile phone transmissions). Tools like this may, therefore, support teachers in rising to the new pedagogical challenges emerging as the curriculum begins to shift.

Using ICT can provide access to new forms of data previously unavailable. Data logging can offer measurements of transient phenomena, remote and long term monitoring and increased sensitivity; for example, it is commonly used to measure the speed of a moving object by measuring the time taken to pass through a light gate and combining this with manual measurement of its stopping distance. Using ICT further allows teachers and pupils to observe or interact with simulations, animations or phenomena in novel ways that may be too dangerous, complex or expensive for the school laboratory. Use of a data logger can facilitate otherwise impossible demonstrations, such as measuring energy transfer as a hot liquid cools. Digital video capture offers an alternative to data logging; repeated and slow motion playback allows phenomena which are difficult for a whole class to view, or events otherwise too slow (eg plant growth) or fast (eg sound waves or the behaviour of two different masses dropped from the same height), to be captured. The internet also offers some unique opportunities for pupils to experience phenomena such as viewing the Earth from a moving satellite.

A particularly accessible and popular way of exploiting the power of visual representations to develop understanding – particularly of abstract phenomena like electricity flow – is the direct use of video clips from interactive simulation CD-Roms. Examples include 'seeing' an electron going around a nucleus or a white cell ingesting bacteria, simulating launch of a space shuttle, and rotating a 3D model of molecules and atoms in motion. Another multimedia tool is the 'Interactive Microscope Laboratory' (Baggott & Nichol 1998), which facilitates active investigation of the sub-optical living world (eg measurement of the heart rate of a water flea) through simulating the functionality of advanced microscopy. Virtual reality 'field' trips (eg to remote animal habitats) and surrogate walks (eg through a rainforest) are beginning to offer further possibilities which other local resources cannot provide. Interactions with virtual phenomena can be repeated as often as necessary for the learner – impossible during a live practical.

Supporting exploration and experimentation

The use of graphing or modelling tools provides dynamic, visual representations of data collected electronically or otherwise. Like the interactive simulations described above, use of these tools offers immediate feedback to pupils, and introduces a more experimental, playful style in which trends are investigated and ideas are tested and refined. Through providing an immediate link between an activity and its results, the likelihood is increased that pupils will relate the graphical or diagrammatical representation of relationships to the activity itself. In particular, the key pedagogical technique of Predict – Observe – Explain [3] is greatly facilitated through viewing a graph or model on screen soon after making a prediction.

Rapid data presentation and interactive computer models representing a scientific phenomenon or idea not only provide immediate opportunities for study and analysis; they can also encourage pupils to pose exploratory ("what if…") questions and to pursue these by conducting follow-up activities (Barton 1998; Finlayson & Rogers 2003; Newton 2000; Wardle, in press). Immediate display of experimental results in a simple spreadsheet template can even guide the course of data collection through structuring their subsequent actions and predictions about the related variables (for instance when investigating heat loss and surface area/volume ratios). The facility to overlay several graphs can encourage further prediction and, where hypotheses need to be reassessed, more, perhaps different data, can be collected and processed quickly. Thus, the provisional, interactive and dynamic nature of ICT tools such as spreadsheets supports this iterative approach to learning (ibid). Another example is the use of simulation software for building and testing circuits. Whereas circuit diagrams on paper are static and give no feedback, using ICT can enable

ICT can provide access to new forms of data previously unavailable

[3] This technique is valuable because it forces the student to hypothesise, drawing on their existing knowledge about what they think the outcome of an investigation will be, eg which will fall faster – a penny or a brick). Having observed the phenomenon and the outcome (they both fall at the same rate), it forces them to re-evaluate their own knowledge.

THE POTENTIAL OF ICT IN SUPPORTING SCIENCE EDUCATION

using ICT to support practical investigation can help pupils to experience the entire process as holistic and cyclical

pupils to visualise what happens if components are connected wrongly and learn from their mistakes.

Focusing on overarching issues

The interactive and dynamic nature of tools such as simulations, data analysis software and graphing technologies can be influential in: allowing pupils to visualise processes more clearly and derive qualitative or numeric relationships between relevant variables; focusing attention on overarching issues; increasing salience of underlying features of situations and abstract concepts, (eg current and voltage in the circuit example); helping students to access ideas more quickly and easily, to formulate new ideas and transfer them between contexts. In particular, a graph evolving in real time actually serves to focus pupils' attention on the screen and thus on the behaviour of the data, especially where it is unexpected (Barton 1998). Contemporary analysis software which integrates table, chart, graph and model display allows seamless interchange – and hence conceptual linking – between them (Rogers 2002b).

Thus, computer analytic facilities are advantageous over manual methods in allowing a more holistic and qualitative approach to pupil analysis of trends and relationships between variables in a graph rather than individual data points (Barton 1997). Using ICT to support practical investigation can in fact help pupils to experience the entire process as holistic and cyclical, whereas time constraints on conventional laboratory work tend to isolate – and hence obscure the links between – planning, practical work, writing up and evaluation (Baggott la Velle et al 2003).

We saw above how use of ICT could facilitate or automate subsidiary tasks – typically those involving routine data handling, calculating and graphing. However, freeing users to give their attention to more overarching matters is not an automatic process. In order to understand what an experiment is all about, pupils also need to appreciate the fundamental nature of the procedures being carried out by the computer, for example so that they grasp that a data logging activity is using a probe like a thermometer, measuring temperature over time. The pivotal role of the teacher in this is discussed later.

Fostering self-regulated and collaborative learning

ICT is infinitely more than a surrogate tutor; its use for exploratory and experimental purposes offers teachers a powerful means of stimulating active learning and it offers learners more responsibility and control. Pupils carrying out research or practical activity using ICT may work more (but not completely) independently of the teacher. To develop the concepts central to science teaching and to counter intuitive conceptions, pupils need to think for themselves.

"Their ideas need to be made explicit and challenged by new experiences. ICT tools have great potential to encourage this style of learning… Software can present many choices and alternatives to the pupil, providing an interactive experience which is well suited to individual exploration." (Rogers, in press-b, p2)

It is worth noting that 'independence' does not mean pupils working alone. Peer collaboration between students working together on tasks, sharing their knowledge and expertise, and producing joint outcomes is becoming a prevalent model for the use of educational technology. This is partly because lack of hardware resources means that machines are often shared. However, a growing body of research evidence has accumulated for the cognitive benefits of technology-supported collaborative learning (eg O'Malley 1995); teachers too perceive that using ICT offers a stimulus and a medium for discussion between pupils. Note, however, that teachers themselves play a critical role in fostering, supporting and sensitively managing pupil collaboration as an effective vehicle for subject learning (Hennessy & Murphy 1999; Scrimshaw 1997).

There are a few examples of where self-regulated use can play a part in actually structuring pupil thinking, shaping activity and broadening knowledge. For instance, graphing technology can act as a cognitive prop, provoking spontaneous investigations of relationships between variables or between numerical data and graphs, which would never be worthwhile manually. Another example is the CSILE/Knowledge Forum, a collaborative, networked learning environment whose use enabled a scientific 'learning community' of Canadian primary pupils working in small groups to design, execute and report their own experiments and research activities, and to generate and engage in depth with meaningful research questions and complex problems – the natural progression of their ideas determining the curriculum sequence (Caswell & Bielaczyc 2001; Caswell & Lamon 1999). They also consulted expert scientists, acting not merely as recipients of their knowledge, but sharing their own knowledge, theories and predictions, and critically examining these.

Future development in using ICT within school science may perhaps take a similar collective approach to knowledge building. These examples illustrate how the introduction of ICT has the potential to change the way in which scientific inquiry is perceived. When learners using ICT encounter and accept a rebalancing of the benefits and constraints of inquiry, this typically results in some modification of their investigative strategies. Similarly, existing cultural practices and values realted to inquiry, and the proficiencies of pupils in regulating their own learning and in exploiting new forms of digital technology, can affect how effectively ICT will be used.

Improving motivation and engagement

Related to all of the above are the well-documented motivational effects of using ICT, which seems to be intrinsically more interesting and exciting to pupils than using other resources (eg Cox 1997; Deaney et al, in press). ICT offers the opportunity to greatly enhance the quality of presentation, incorporating the use of movement, light, sound and colour rather than static text and images, which is attractive and more authentic. Above all, using ICT can increase pupils' persistence and participation through enhancing the appeal of laboratory activity, not only in terms of novelty and variety, but by providing immediate, accurate results and reducing the laboriousness of work. Pupils are also observed to be more motivated to participate in science activity and discussion when using tools such as interactive whiteboards, modelling and simulations which permit active engagement and offer pupils a degree of control over their own learning.

'independence' does not mean pupils working alone

THE POTENTIAL OF ICT IN SUPPORTING SCIENCE EDUCATION

future developments in using ICT within school science may take a collective approach to knowledge building

ICT USE AND PEDAGOGY[4] – AN INEXTRICABLE LINK

Just as when using any other tool, certain features of the socio-cultural setting in which ICT is used are highly influential[5]. These diverse influences include the nature and purpose of the activity, age and ability of pupils, their degree of participation, curriculum requirements, wider educational and political agendas, etc. Teachers' established pedagogic approaches need to adapt accordingly. The teacher plays a critical role in creating the conditions conducive for learning through selecting and evaluating appropriate technological resources and designing, structuring, sequencing, supporting and monitoring learning activities using ICT (eg Scrimshaw 1993; Selinger 2001). It is that role which is explored in this section.

The first issue to be tackled is whether to use ICT at all. There is a shared concern among educators that use of ICT in the teaching and learning of any subject needs to be appropriate, discerning and oriented towards the learning goals of the subject itself[6]. Teachers are understandably resistant to the notion of 'bolting on' ICT to the curriculum or using it simply because it is available or its use is encouraged or expected. Rather, they perceive that selective use, which 'adds value' to learning activities, is essential.

Potential software needs to be evaluated for the suitability of its content to the science curriculum, its intended level of use, and scope for differentiation according to pupils' needs. Quality of video clips and animations, and their potential for misleading pupils, need to be assessed. According to Rogers (in press-b), if the learning objective lies in conceptual development, the software should support investigative activity and foster analytical and divergent thinking. Wellington (in press) extends this role to include encouraging problem solving, modelling, classifying, sorting, questioning, pattern finding, data exploring, researching, groupwork and out of class work.

A critical constraint on adoption of ICT is that it must fit with teachers' existing conceptions of pedagogy. The interim report of a major British evaluation, ImpaCT2[7], indicated that 'relatively few teachers are integrating ICT into subject teaching in a way that motivates pupils and enriches learning or stimulates higher-level thinking and reasoning' (p14). As other studies have detected, these few tended to be teachers who already had an innovative pedagogic outlook. Niederhauser and Stoddart (2001), and a prominent study of primary teachers by Moseley et al (1999), found that teachers choose ICT applications, activities and approaches to fit their own perspectives on teaching and learning. Rogers (2002a) observed that limited resources (an oft

4 The term 'pedagogy' denotes the complex relations between teacher, learning context, subject knowledge, purposes, teacher's view of enhancing learning, selection of learning and assessment activities, learning about learning, and learner characteristics such as age and knowledge (Watkins & Mortimore, 1999).

5 Thus research which aims to isolate the role of ICT in raising attainment (on standardised assessment measures) is not reviewed here; McFarlane (2001) discusses the complex issues involved in this endeavour.

6 For example, the framework for Key Stage 3 science provides a checklist for appropriate use (DfES 2002a, p47).

7 ImpaCT2 is a DFES/Becta large-scale longitudinal study of ICT and student attainment across the curriculum: www.becta.org.uk/impact2.

cited complaint) were less of an obstacle to teachers' use of ICT than the science teachers' reluctance to abandon their existing pedagogy.

Before they will use ICT, teachers have to first recognise the potential benefits of computer-supported science teaching and learning, and its specific role in meeting their classroom aspirations (Barton, in press-a). Successful integration of ICT depends then on development of an appropriate pedagogy – which is best begun with incorporation and adaptation within teachers' conventional practice, and then going beyond it. The collegiality evident in science departments strongly influences individual teachers' development, and colleagues who exemplify and share good pedagogy in teaching with ICT make a valuable contribution (Finlayson et al 2002). However, evidence would suggest that only if ICT provides activities (rather than mere 'opportunities') with a clear and concrete curriculum focus which support and enhance learning will its use be initially adopted and integrated into departmental schemes of work and all teachers' lessons.

Using ICT to support self-regulated learning does not diminish the importance of the science teacher, but it clearly challenges their beliefs to some extent. A major constraint is prevailing classroom practice which clashes with the culture of student exploration, collaboration, debate and interactivity within which much technology-supported activity is said to take place (Schofield 1995). For instance, Ruthven et al (submitted) noted a marked lack of reference by science teachers to trialling and refinement of ideas with ICT (compared to English and mathematics teachers). This may be a consequence of their tendencies both to pre-structure investigations (seeking a single outcome such as verification of a known relationship) and to treat writing as a means of recording results rather than forming or evaluating ideas. It reflects a culture uneasy with 'uncertainty', and a pedagogy correspondingly emphasising coverage of content over development of reasoning (Donnelly 1999). It also reflects a tendency toward a didactic, whole class teaching approach which may simply subsume the computer (and/or interactive whiteboard) by using it mainly for demonstration. The outcome is that, so far, the potential for using ICT to support exploration and experimentation has not been exploited by the majority of teachers.

Current pedagogy does not draw extensively on the well-established literature on pupils' prior conceptions and experiences (Driver et al 1985; Osborne 1985), nor on the more recent literature on the significance of small group discussion to learning (Kuhn 1993; Mercer & Wegerif 1999). Nor does it appreciate the importance of making prior conceptions and implicit reasoning explicit so as to highlight any inconsistency – either with simulated phenomena or between conflicting theories, which can co-exist within children's own minds. In such a context, computer simulations do need then to present viable and convincing alternatives to children's everyday beliefs if their thinking is to move on (Hennessy et al 1995).

In summary, using ICT in limited and constrained ways can curtail the potential offered by ICT for learning science and developing the skills required by contemporary curricula. To progress, teachers need not only to evaluate

computer simulations need to present viable and convincing alternatives to children's everyday beliefs

THE POTENTIAL OF ICT IN SUPPORTING SCIENCE EDUCATION

the teacher's role is critical in structuring tasks and interventions in ways which prompt pupils using ICT to think about underlying concepts and relationships

critically the benefits of using ICT – both beforehand and afterwards – but they need deliberate strategies to mediate the interactions between pupils and technology; these they are beginning to develop, as elaborated in what follows.

Structuring activity and supporting active, reflective learning

Learners and teachers using ICT are often portrayed as creators, collaborators and decision makers (Loveless et al 2001), yet overly mechanical uses of ICT can obstruct the process of learning. The automaticity of processes previously carried out by hand which ICT offers can hinder reflection, analysis and understanding of the underlying scientific processes. Science teachers are concerned, for example, that pupils may use technology to produce many different kinds of graphs and bar charts, or to collect data automatically, without actually understanding what is represented.

The term 'interactive' (commonly applied to internet, CD-Roms, DVD) needs a particular note of caution. Digital technology has rendered many forms of information more provisional and fluid, ie open to intervention and improvement by learners. However some technologies actually provide little opportunity for exploration and manipulation of underlying models. Even those that provide more can be used to reinforce existing didactic approaches (teacher as knowledge provider) and perpetuate laborious or routinised learning (Ellis 2001).

Genuine interactivity requires active learner contribution and engagement, ie an element of reflection on choices and their effects, and it may include prediction, trial and evaluation (Rogers, in press-b). 'Open' simulations and modelling software support this engagement by offering students significant choices of variables and types of data generation (within an experimental range or with a randomised element), whereas 'closed' simulations concentrate on concept development through demonstrating an idealised system (McFarlane & Sakellariou 2002). They absolve the student from any responsibility for the investigative aspects – planning, design, data collection and display.

Although development of pupils' investigative skills is a key objective of science activity, use of software such as interactive simulations here is in its infancy. There are some exceptions which offer pupils a significant degree of control in manipulating variables themselves. For instance, 'open' genetics simulation software can be used to substitute for complex selective breeding operations over several generations. Multimedia simulations clearly illustrate the effects of processes such as dissolving, diffusion or bonding atoms and can foster exploration of rates of reaction, or properties of solids, liquids and gases. Many simulation and modelling activities involve the learner 'exploring' someone else's ideas, however, rather than expressing or evaluating their own (Mellar & Bliss 1994).

Simulations, models and virtual experiments are a particular danger zone in that they represent 'cleaned-up' versions of the complex and messy real world. These are helpful in focusing attention on particular abstract concepts or isolating variables, which are normally combined. However there is some indication that pupils attribute a great deal of authority to the computer and may develop misconceptions by taking animations and images of abstract concepts too literally (Wellington, in press). A key example is the creation of a frictionless virtual world; while this can be powerful in many ways, reflection upon experience of both the natural world and the simulation is an essential pre-cursor to exploring pupils' conceptual difficulties and dealing with their general disbelief in simulations (Hennessy & O'Shea 1993). Teacher intervention in this and similar contexts needs to investigate and challenge pupils' own ideas, and use discussion to move them towards a consensual model of understanding (ibid, Wardle, in press).

More generally, the teacher's role is critical in structuring tasks and interventions in ways which prompt pupils using ICT to think about underlying concepts and relationships. For example, pupils using graphing software first need to understand the nature of the data and how to make an appropriate choice of graph type from those on offer. Then they can appreciate the significance of graph shape, describe the behaviour of variables, compare sets of data, make predictions, and so on. With simulated experiments and measuring tools, they need a rationale for purposeful investigations, controlling variables, fair testing and so on. Pupils will, ideally, then move on to planning their own tasks and asking their own questions (Rogers, in press-b). With data logging, it is important to encourage pupils to remain active while the machine is collecting data, using the 'time bonus' purposefully to think critically about and discuss the experiment in more depth. The teacher can probe pupils about issues such as whether it is a fair test, what they expect to happen, what controls would be useful, etc. (Newton 2000).

The teacher's mediating role is also important in the context of pupils' interactions with multimedia simulations of scientific processes, especially where these are 'closed'. The following account illustrates how a skilful teacher exploits the power of a biology simulation, using it to stimulate questioning for investigation and requiring pupils to discuss and reflect on the underlying processes in some depth:

"You can actually... see a red blood cell squeezing its way through a capillary and see it in action, and you can discuss what is actually happening here, what is it going through... why not just go through the biggest route, what's the reason that the red blood cells have to be routed through these capillaries? What's it doing as you are watching it that you can't see? What's being picked up? What liquid is it in?" (From Hennessy et al, submitted)

Such experiences, coupled with enough time for discussion, analysis and reflection, provide valuable opportunities for enriching learning.

Retaining some use of manual processes is a necessary strategy for tackling perceived problems concerning the automaticity of some forms of ICT (and for meeting examination needs). Examples from teacher reports include using an ordinary thermometer and drawing graphs and lines of 'best fit' by hand – although well known conceptual and physical difficulties in drawing these may both reflect and reinforce misconceptions since inaccurate representations can lead to erroneous interpretations (Barton 1997;

Hennessy 1999). Using a manual system of data recording can be perceived as allowing pupils to see and understand what is going on more easily. However, experience shows that manual data recording can also be a mechanical process (Barton 1998). Whether it is with ICT or by hand, the teacher's skill in constructing tasks and making interventions which highlight the meaning underlying the data collected is the crucial factor.

Developing an investigative approach

As pupils' roles become more autonomous, teachers need to decrease their overt direction and instead facilitate information finding and development of understanding, for example by providing sufficient opportunities for experimentation. The teacher role is emerging as one of prompting pupils with the aim of encouraging them to reason for themselves, to ask lots of questions about the data, and to find their own solutions and interpretations, rather than giving these directly. Rogers & Wild (1996, p143) suggest that:

> "Pupils might be encouraged to compare sets of data; they can look at each other's graphs, discuss the differences and similarities or compare their graph with that of sample data. Hopefully... they might take a broader view of what constitutes relevant and useful information."

Rogers (in press-b) points out that pupils using an investigative approach to practical science already need 'to question, plan, design, decide, predict, observe, measure, record, draw conclusions and generally think for themselves'. Complementary to these investigative pupil skills are facilitatory teacher strategies; the most effective strategies highlighted by Millar et al in the EPSE study[8] were asking open questions, supporting small group discussion of ideas and evidence, and focusing on 'how' rather than 'what' we know. These kinds of pupil and teacher skills are just as pertinent and important when using ICT, but crucial interactions and lesson aims can be undermined by technical problems with equipment. Nevertheless, technological advances in both hardware and software have widened access to ICT and reduced the level of operational skill required. Furthermore, user-friendliness and connectivity are expected to improve further in future so that developing the necessary operational skills should no longer hinder subject learning (Rogers, in press-a). However, observation indicates that technical difficulties and time-consuming troubleshooting remain a reality for teachers – and for many, a significant impediment to using ICT.

In such a context, the need for constructive learning-focused interventions (as opposed to technology focused) becomes even more apparent, and according to Rogers, these include:

- building on what pupils have learnt already
- prompting pupils to make links between observations or some other knowledge
- helping to avoid 'early closure' of pupils' own discussion

[8] The Evidence-based Practice in Science Education (EPSE) network worked with 11 science teachers over a year to develop approaches and resources for teaching Key Stage 2-4 pupils about the nature of science (www.york.ac.uk/depts/educ/projs/EPSE).

- prompting pupils to make a prediction and compare it with actuality
- helping to interpret the implications for science.

These and other forms of teacher guidance can be used in the context of focused enquiry to support a strategic balance between carefully structured activity and a degree of pupil responsibility for regulating their own learning. Achieving this balance is particularly important for research-based activity, as discussed in what follows.

Focusing research tasks for pupils

While the internet offers more up-to-date and wide-ranging information, freedom and excitement for students, the information they obtain from open-ended 'surfing' is generally less focused, less age-appropriate, less ability-specific, and less reliable than that from other sources (including CD-Roms), where information has been carefully checked and pre-filtered. Research activity therefore needs to be channelled and goal-directed in order to be productive, especially for low ability pupils. Setting clear parameters – and even time limits – for electronic searches, and pre-selecting websites helps pupils to obtain more useful, accessible, focused and relevant information.

In practice it is difficult to obtain a balance between being over-directive (providing more security but limiting imagination, decreasing motivation and risking similar task outcomes) and under-directive (providing opportunity for independent learning but risking floundering due to pupils' confusion about task requirements); both scenarios are sometimes observed.

Offering a degree of choice within a pre-selected range of sites can provide a compromise solution here. Deliberate teaching and reinforcement of generic search strategies (eg formulation of keywords) has also been found to be important.

Developing 'critical literacy'

Pupils additionally need to develop skills for selecting and processing information derived from the internet and similar sources. Its potential complexity and unreliability mean that simply accessing information is insufficient, and the speed and ease of downloading and printing out chunks of material has in fact rendered plagiarism more of an issue than children copying chunks of information from a book or encyclopaedia has been. The notion of 'critical literacy' (eg Collins et al 1997) describes the need for interpretation, analysis and evaluation – including an assessment of the author's agenda and authority.

Despite increasing recognition of its critical importance (eg Hammond 2001), there is little indication that schools are strategically tackling this issue yet. Evidence from Ofsted (2001) indicates that pupils lack strategies for obtaining ICT-based information efficiently and are not yet moving beyond the location of information as an end in itself, continuing to present unprocessed information. While this is problematic in any subject involving research activity, the importance of developing analytic and critical skills may be even greater in science, dependent as it is on data and evidence rather than values, and where students need to learn how to collate, weigh up and synthesise such evidence, and judge its likely validity. Children's lack of skill in scientific reasoning can be observed to hinder their

pupils need to develop skills for selecting and processing information derived from the internet and similar sources

THE POTENTIAL OF ICT IN SUPPORTING SCIENCE EDUCATION

progress in evaluating scientific models; ICT does offers a useful medium for developing this skill through the critique and analysis of extensive electronic information sources (McFarlane & Sakellariou 2002). However, the complexity of the analytic skills required may be under-estimated and there is little evidence that pupils are learning them without support. Some helpful strategies which teachers already employ include requiring pupils to highlight key points, rework original text into a different form or prepare a class presentation or poster. Explicitly developing pupils' understanding of the relationship between evidence and conclusions, the skills for forming and defending their own ideas, and for interpretation and critical analysis are essential pre-cursors for evaluating the plethora of information available electronically.

explicit links can be made between theoretical computer models and reality

Linking ICT use to ongoing teaching and learning

It is important to stress that although simulations and other tools can provide a virtual alternative to practical work in some situations, using ICT is not perceived – by pupils, teachers or educators – as a replacement for other activities. The balancing and integration of use of ICT resources with other teaching and learning activities, is desirable in many situations; indeed it often provides the greatest benefits (Ofsted 2002a). Rather than using ICT in isolation, for example, the products of web searching or simulation-based activity can be linked with other class activities before, during and after the computer-based lesson (Finlayson & Rogers 2003; Hennessy et al 1995). This means that explicit links can be made between theoretical computer models and reality, whilst practical demonstration and development of pupils' investigative skills retain some importance. Likewise, handling a physical model or employing visual aids can also enhance learning during ICT-supported modelling activity.

Many teachers employ use of ICT after spending several lessons introducing and exploring the topic area; students are then familiar with key concepts, terms or procedures (Barton & Still, in press). Some feel that simpler experiments, at least, should be carried out in the conventional way, with the power of multimedia technology reserved for cases where it significantly enhances the activity. Others prefer all feasible experiments to be carried out manually first with subsequent use of ICT. For instance, one such approach is to use sketch graphs to make predictions about outcomes before using the computer to plot graphs of actual data. This provides immediate corroboration (or not) for predictions and is an effective catalyst for discussion. This approach enables teachers to pose questions and pupils to express their ideas by drawing on the data visible on screen (ibid). Conversely, software for carrying out virtual experiments can be used for prediction and planning purposes before practical work (Walker 2002). In either case, important manipulative skills can be developed through a combination of expecting pupils to execute manually some tasks involving, for example, graph plotting, but also (subsequently or even first) exploiting the power of the technology to plot many graphs in succession. Ideally, teachers will develop a balanced approach between 'hands on' and computer methods and the intricacies of this relationship form a fruitful basis for further research.

Whole class interactive teaching

The role of whole class teaching is potentially very significant. Research shows that it is still the predominant mode of classroom interaction (Newton et al 1999), yet a forum where ICT is currently underused. There is a higher level of teacher-pupil interaction and a lower level of information dispensing associated with using ICT, but whole class teaching of science tends to use the computer or data logger as a demonstration tool (even where logistics favour individual activity), and fails to exploit the **interactive** potential of software (Finlayson & Rogers 2003).

Whole class interactive teaching can potentially be used to establish a clear task focus, to clarify the focus of investigation, to predict and hypothesise, to interpret findings and assess their significance, to discuss key concepts and 'procedural learning' objectives (Gott & Duggan 1995), eg notions of what constitutes evidence, to conduct 'fair tests', to repeat measurements, and to explore the accuracy of measurements. Creating time for discussion of these issues is extremely important. Question-and-answer sessions are particularly valuable in assessing understanding and enabling sharing of ideas.

ICT itself can also be an effective medium for whole class interaction; increasing availability of interactive whiteboards and other forms of computer projection not only facilitates demonstration, revision and collation of class results but additionally offers the potential for more interactive modelling of complex processes, skills and techniques, including scientific reasoning. In particular, a whiteboard goes beyond the interactive worksheet in enabling students to participate directly in whole class tasks by labelling a diagram, identifying or measuring organisms, categorising or manipulating images (eg linking elements in a food chain). Use of these approaches will hopefully increase as availability of projection technology – and teacher confidence to move out of simple demonstration mode – becomes more widespread. This use could further facilitate the processes of analysis, reflection and consolidation, which are of particular importance to science teachers using ICT (Stodolsky & Grossman 1995).

The strategies outlined above illustrate the pivotal role of the teacher in determining how effectively ICT is used in practice to motivate pupils and enrich science teaching and learning. They describe ways of overcoming potential drawbacks of using ICT without due care and attention to underlying learning aims. The success of the emerging strategies depends on continuing to engage pupils in thinking through, discussing and evaluating scientific ideas or applications – and consciously developing the subject-specific and generic information handling skills that they require. All of the teacher strategies discussed above require deliberate, thoughtful and systematic planning. Effective employment of ICT also requires new approaches and roles for both teachers and pupils. In particular, it points to developing a classroom culture which more strongly encourages pupils to explore and share ideas, reflections and findings – with working partners, with the teacher, and during whole class discussion (Hennessy et al 2003; Rogers & Wild 1996). In short, it calls for a transformation of the culture of science teaching.

THE POTENTIAL OF ICT IN SUPPORTING SCIENCE EDUCATION

USE OF ICT IN THE SCHOOL SCIENCE LAB - A REALITY CHECK

External constraints on teachers' use of ICT

Teachers' motivation to integrate use of ICT is undoubtedly influenced by the working contexts – physical, socio-political and educational – in which teachers find themselves. While classroom practice is currently developing as outlined above, there are some notable obstacles. Innovation and adaptation are costly in terms of time, especially in the present climate when 'initiative overload' makes many competing demands on teachers' time and energy. Indeed lack of time was the most significant constraint on use quoted by (86-88%) of primary and secondary science teachers surveyed by Dillon, Osborne, Fairbrother and Kurina (2000).

In addition to the new interpersonal and pedagogic skills which teachers require to use ICT in their classrooms, other contextual factors which can act as barriers include: teachers' lack of confidence, experience and training; lack of a supportive organisational culture within the school; limited access to resources and timetabled use of dedicated ICT suites; unreliability of equipment and lack of adequate technical support (Dawes 2001; Schofield 1995). A recent Ofsted report (2002b) noted a significant combined effect of government ICT initiatives in terms of improved access by science departments and increased teacher confidence in classroom use, but access to computers in science areas, stocks of reliable data logging equipment and teacher expertise remain patchy.

External pressure from the national assessment regimes further constrains the use of ICT and the development of pedagogy. For example, compulsory tests in core subjects at ages 7, 11, 14 involve no use of ICT. There is also a culture clash between an overloaded National Curriculum for science which is based on knowledge 'delivery' in a highly prescriptive way, and the opportunities afforded by ICT which have more potential for developing pupils' reasoning skills. Moreover, classroom teachers have historically had little say in developing how ICT should be deployed within their schools, and for defining its role within subject curricula (Cuban 2001: ch6). Imposed policy decisions can, therefore, result in a lack of 'ownership'. Another tension is pressure to teach ICT technical skills through science activity and the desire to use ICT to facilitate the learning of science. The time needed to help inexperienced pupils develop their ICT skills can further diminish the opportunity for subject-specific work.

More optimistically, the government's recent (New Opportunities Fund) teacher training intiative for serving teachers (TTA 1999), and the National Curriculum for trainee teachers (DfEE 1998), are based on the premise that appropriate, indeed critical, use of ICT is a medium to support subject teaching and attainment of its learning objectives; this is a welcome shift away from technology-driven use. The latter document provides a reasonably detailed outline of the generic ways in which trainees are expected to use ICT effectively within subject teaching.

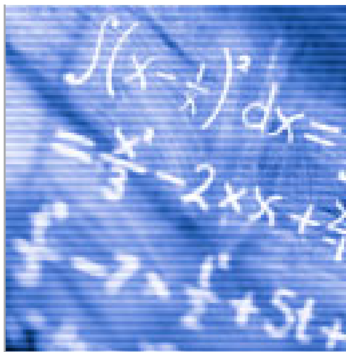
However, despite massive investment in ICT initiatives (£1.8 billion has been spent by the government since 1997) and the prominent iconic and ideological status of ICT, there remains a marked lack of specific guidance and support for practitioners in incorporating ICT in appropriate ways directly related to the prescribed subject curriculum (Selwyn 1999). Other research has confirmed that while teachers are motivated to integrate appropriate uses of ICT into their classroom practice, their understanding of how it enhances learning is still developing, and pedagogy for effective use has not yet been clearly established (Hennessy et al 2003). Teachers themselves desire more knowledge in this area (Williams et al 2000). In particular, there is a lack of suggestions for productive internet use.

Training is a major issue here as teachers try to get to grips with new tools and new ways of teaching they require. For example, many schools have recently acquired interactive whiteboards but lack of time available for training means that teacher confidence in using the new tools is currently inconsistent (House of Commons Science and Technology Committee 2002). However, there is evidence that the ambitious NOF-funded training scheme for teachers in using ICT in the classroom has had more success in science than in other subjects where the impact has been minimal (Ofsted 2002b). The Science Consortium was the only provider geared exclusively towards secondary science and the first national programme to promote a pedagogy for ICT use in science. It encouraged teachers to participate in an iterative cycle of reflective teaching using a carefully prepared framework of lessons and associated software and sharing written evaluations of their routine classroom use. The vast majority of the evaluation reports on 22,000 science lessons were positive (Finlayson & Rogers 2003).

Consequences of practical constraints

The research literature provides very little support for the popular (though perhaps unrealistic) notion of a technological revolution in teaching and learning as a consequence of introducing ICT. Similarly, Ofsted (2001) has observed that appropriate and effective classroom use of ICT is in fact rare. Available technology is often underused and poorly integrated into classroom practice. Last year about two thirds of primary and secondary teachers in English secondary schools reported 'some use' of ICT in science, and only 26-29% reported 'substantial use' (DfES 2002b)[9]. Similar percentages of teachers perceived substantial or some beneficial effects of using ICT in science. Despite numerous reported examples of effective use, clarification of what pupils should learn using ICT – and how teachers should facilitate this – is said to be needed (Ofsted 2002a).

It is becoming clear that having the requisite equipment and software does not guarantee its effective use or even 'take-up'. Research shows that virtually all secondary schools possess data logging equipment and some level of connection to the internet but practical constraints and uncertainty about pedagogical relevance and scope hinder regular and effective use (Hammond 2001; Newton 2000). A recent ImpaCT2 report[10] concludes that home



training is a major issue as teachers get to grips with the new tools and new ways of teaching they require

[9] This has changed radically since the McKinsey (1997) report of a survey carried out a decade ago (1993-4), when less than 5% of science teachers were using ICT regularly in their teaching compared with 34% of mathematics teachers. In 2002, frequency of use was slightly higher in secondary science than in the other core disciplines of mathematics and English, while use at primary level was considerably lower in science (DfES 2002b).

[10] http://www.becta.org.uk/research/reports/docs/ImpaCT2_strand_2_report.pdf (section 4: Pupils' and Teachers' Perceptions of ICT in the Home, School and Community).

use of internet-linked computers is in fact likely to have a much greater impact on many pupils' learning than use at school. Another example is the computer-controlled microscope provided free to each UK secondary school during Science Year (2002). In many cases, the micro-scopes remain in cupboards as teachers are uncertain how to exploit them.

Exceptional use can be found – for instance, one special school in Northern Ireland uses the microscope innovatively like an underwater camera brought into the classroom, offering its physically disabled students a rich experience through investigating the teeming life in samples of local pond water (Cole 2002). Nevertheless, it seems that at present effective use of ICT in science is confined to a minority of enthusiastic teachers or departments.

As well as lack of use, there is some evidence for the passive or inappropriate uses of ostensibly interactive forms of ICT previously discussed, including pupil presentation of unprocessed information and inappropriate graphical presentation. Ofsted (2001, p12) complains that too many core subject teachers "select software packages for their visual appeal rather than their relevance to lessons" giving, as an example, the domination of a primary lesson by passive viewing of a simulation of materials dissolving. Simulations or multimedia information resources which make too few cognitive demands on pupils, and are used to replace rather than complement practical experiments (and skills), highlight the danger that software applications may become the curriculum itself rather than tools for problem solving, research, knowledge and text creation (CTGV 1996).

Transformation of science activity and pedagogy

Some of the examples described in this report – such as activities based on interacting with sophisticated simulations or the integration of software supporting scientific enquiry with practical investigations – characterise the extent to which the practice, tools and methods of science teaching are beginning to adapt and change. There are some isolated examples of innovation. However, traditional learning goals and values seem to remain mostly intact – in line with the prescribed curriculum. ICT, so far, has radically transformed the nature of science itself for professional scientists, whose research activity has become dependent on routine access to sophisticated computer-based tools and resources.

In contrast, the use of ICT in school science, on the whole, has yet to establish its transformative role. The research literature converges on the conclusion that teachers tend to use ICT largely to support, enhance and complement existing classroom practice rather than actually re-shaping subject content, goals, activities and pedagogies (Hennessy et al, submitted; Kerr 1991; Watson et al 1993). As Goodson and Mangan (1995, p119) put it, there is "evidence of reshuffling the pack of cards, but little evidence of anybody trying a new game". Since the same tools can be used in different modes, it is natural for teachers initially to design activities, which imitate traditional methods or experiments. For example, computer projection technology may be used as a substitute for an overhead projector before animations and hot-links to internet sources are incorporated. Despite the extraordinary scope offered by the internet, pupil activity can be narrowly channelled during research or 'exploration'. Similarly, research for the Interactive Education Project [11] indicates that using a simulation to simply replicate – and sanitise – directed (rather than investigative) laboratory work involves no pedagogical shift and may yield little learning gain (Baggott la Velle et al 2003). Pedagogic change is inevitably slow and to fully exploit new software takes time (Rogers, in press-b), especially if pupils are to capitalise upon its powerful use in evaluating, constructing and reformulating new ideas and concepts.

However, a gradual process of 'pedagogical evolution' is now evident as the teacher's role develops to encompass supporting pupils' learning with ICT. Experiences arising in the course of getting to grips with new tools offered by ICT, which are themselves continually evolving, have led learners to develop new strategies for learning, and teachers to begin to re-evaluate and modify aspects of their practice and thinking (Ruthven & Hennessy 2002).

The teacher's role could be described as changing from that of 'sage on the stage' to 'guide on the side'. Teachers are already beginning to develop and trial new strategies which both positively exploit the new opportunities arising, and focus attention away from the distracting nature of sophisticated features of the technology itself, and onto intended science learning objectives. While teachers are motivated and committed to using ICT in the classroom, they are simultaneously developing a reflective and critical outlook. Evidence would suggest then, that teachers are working towards harnessing the potential of ICT to support science learning as far as possible, given the very real operational constraints.

IMPLICATIONS FOR FUTURE DEVELOPMENT

Implications for teachers

Educational technology can be exploited further in science education by building on – and disseminating – actual exemplars of successful practice and pedagogy. This means moving towards structured forms of exploratory use, which becomes more feasible as science teachers gain experience and confidence in integrating ICT within their teaching.

Increasing availability of interactive linking between software means that electronic worksheets or tutorials can be employed to structure tasks and to guide pupils along certain pathways (eg areas of a database, customised spreadsheets, computer models, or pre-selected websites). Instructions for discussing an idea with their teacher or peers could even be built in to such resources (Rogers, in press-a), since increasing dependence on the computer is not, of itself, a desirable goal. Indeed, an essential feature of successful teaching with ICT is expecting and fostering **active participation of pupils** – particularly in research and practical work which provides most opportunities for pupil responsibility and engagement with tasks, but also in teacher-led discussion and demonstration (Newton & Rogers 2001, ch3).

exploratory use becomes more feasible as science teachers gain experience

[11] The science subject design team of the ESRC-funded Interactive Education Project are exploring how the mutual interaction between ICT and pedagogy can drive knowledge transformation, aiming towards specifying an effective pedagogy for using ICT (www.interactiveeducation.ac.uk).

CONCLUSION

The roles of whole class interactive teaching and the use of ICT to develop investigative skills are currently under-developed and an increased focus on these may prove fruitful. Explicitly developing new pupil skills such as 'critical literacy' is necessary so that pupils can access, discuss and evaluate information derived from scientific sources. It is also important to offer strategies for overcoming potential pitfalls (such as 'black box', or overly passive, approaches). Insisting upon a clear rationale for each form of ICT use where identified learning outcomes remain paramount is the first and foremost step to advancing the contribution that ICT can make to the learning of science – particularly a science education which seeks to develop 'critical science literacy'.

Teachers are progressing steadily and the use of ICT is permeating to more classrooms. Further development, however, depends on providing them with more time, access to reliable resources, encouragement and support, and offering specific guidance for appropriate and effective use. In short, on a programme of sustained professional development.

Implications for assessment

Currently there is almost exclusive assessment of the curriculum via written tests of content knowledge which do not capture the educational outcomes associated with using ICT. Computer-based instruments bring their own problems, but it can be argued that assessment frameworks themselves need to alter to reflect changes in the way that teaching and learning are conducted when supported by ICT (McFarlane 2001). Within the context of a science education which seeks to place more emphasis on the critical evaluation, analysis and interpretation of evidence and data, the present focus on the outcome rather than the process itself exerts a malign rather than a benign effect on teachers' pedagogy and their use of ICT.

Assessment could instead, or as well, examine the appropriate use of methods (Barton & Still, in press) and this would involve greater use of teacher assessment. Interim records may be useful indicators for assessment of understanding, reasoning or analytic skills, which may now take place during the activity. For instance, the teacher could circulate, asking probing questions of pupils about predicted or annotated graphs, drafts of written work or research outputs visible on their screens, making judgements against well-defined criteria of performance. Whilst identifying individual contributions in collaborative work is recognised as problematic, the benefits of this style of working suggest that we adapt our styles and modes of assessment to match our desired pedagogy rather than the converse.

CONCLUSION

This paper has attempted to review the state of science education today, the impact of ICT use on the curriculum, pedagogy and learning, and the implications for future practice.

The first section outlined a range of perspectives on the aims of science education and the associated choices concerning curriculum and pedagogy. It showed that science education within the UK is in the second phase of a two-part revolution. The first phase, in the 1980s, achieved the implementation of compulsory science education for all from 5-16. The second phase, begun in the mid 1990s, has attempted to argue for, and develop, a curriculum which genuinely meets the needs of all pupils rather than the few who will enter the corridors of science. Its goal of fostering 'scientific literacy' will require a new pedagogic approach, one that moves away from knowledge delivery towards involving pupils more actively in engaging with scientific ideas and developing the skills necessary for appraising evidence, handling risk and uncertainty, and recognising social and other influences on (and consequences of) decision making and research.

The second section has described the potential role which ICT may play in revitalising science education to meet such aspirations. It has shown that this powerful tool can be employed flexibly to support different curriculum goals and forms of pedagogy; that there are diverse ways of linking ICT use to existing classroom teaching (including supporting, extending or replacing it); and that there are different modes of using the same tools.

Yet, whilst the appropriate use of ICT clearly has a transformative potential for science education and student learning, this is often found only in isolated pockets of innovation and associated with enthusiastic individuals. As such, ICT still needs to embed itself in the 'habitus' and culture of the ordinary classroom teacher.

Part of the problem lies with the current content-laden National Curriculum and associated assessment measures which reinforce a cultural perspective on teaching science through a process of transmission (Hacker & Rowe 1997). These impediments have served to stifle the development of classroom use of ICT in ways which effectively exploit its interactivity and potential for supporting active pupil participation, exploration and collaboration in science activity.

By contrast, the values of the new emergent science curricula for all pupils which give more emphasis on developing critical and analytical skills are more likely to foster and support the use of ICT. For instance, Osborne et al (2002) found in their evaluation of the new AS Science for Public Understanding that use of the internet was reported as a feature of approximately 50% of all lessons.

As the school curriculum begins to forge a stronger link between science-as-it-is-taught and science-as-it-is-practised, a major constraint currently affecting the integration of ICT use within the curriculum may be lifted. In short, access to information and data, its interpretation and critical evaluation, will become central features of any new syllabi. Such a shift would encourage a change in pedagogy and the interactive use of ICT to support and develop students' scientific reasoning and analytic skills. The use of ICT will then, perhaps, lie at the core of science teaching and learning rather than languishing on the margins.

new emergent science curricula put more emphasis on developing critical and analytical skill

ACKNOWLEDGEMENTS

We are very grateful to Roy Barton and Laurence Rogers for their pioneering work on the use of ICT in science and their helpful feedback on an earlier draft of this report. The contributions of other colleagues and the teachers who participated in the research reviewed here are also acknowledged with thanks.

BIBLIOGRAPHY

Abd-el-Khalick, F & Lederman, N (2000). Improving science teachers' conceptions of the nature of science: a critical review of the literature. International Journal of Science Education, 22(7), pp665-702

AQA (Assessment and Qualifications Alliance) (1999). Science for Public Understanding: Advanced Subsidiary 5401. Manchester: Assessment and Qualifications Alliance

Armstrong, HE (1891). The teaching of the scientific method. The Education Times

Baggott, L & Nichol, J (1998). Multimedia simulation: a threat to or enhancement of practical work in science education?, in: J Wellington (Ed) Practical Work in School Science. London, New York: Routledge

Baggott la Velle, LM, McFarlane, A & Brawn, R (2003). Knowledge transformation through ICT in science education: a case study in teacher driven curriculum development. British Journal of Educational Technology (in press), 34(2)

Barnett, C (2001). Prelude to an industrial defeat from the 1944 Education Act to the 1956 White Paper on Technological Education. London: Royal Society of Arts

Barton, R (1997). Computer-aided graphing: a comparative study. Journal of Information Technology for Teacher Education, 6(1), pp59-72

Barton, R (1998). IT in practical work: assessing and increasing the value-added, in: J Wellington (Ed) Practical Work in School Science. London, New York: Routledge

Barton, R (2002). Learning Science with the Aid of Computers. Cambridge: Homerton College 23/10/02

Barton, R (in press-a). Introduction, in: R Barton (Ed) Teaching Secondary Science with ICT. Cambridge: Hill McGraw

Barton, R (in press-b). Teaching Secondary Science with ICT. Cambridge: Hill McGraw

Barton, R & Still, C (in press). Planning, teaching and assessment using computer-aided practical work (ch4), in: R Barton (Ed) Teaching Secondary Science with ICT. Cambridge: Hill McGraw

Bauer, HH (1992). Scientific Literacy and the Myth of the Scientific Method. Chicago: University of Illinois Press

Beaton, A, Martin, MO, Mullis, I, Gonzalez, EJ, Smith, TA & Kelley, DL (1996). Science Achievement in the Middle School Years: IEA's Third International Mathematics and Science Study. Chestnut Hill, MA: Boston College

Bloor, D (1976). Knowledge and Social Imagery. London: Routledge and Kegan Paul

Caswell, B & Bielaczyc, K (2001). Knowledge forum: altering the relationship between students and scientific knowledge. Education, Communication and Information, 1(3), pp281-305

Caswell, B & Lamon, M (1999). Development of scientific literacy: the evolution of ideas in a knowledge-building classroom, in: J Leach & B Moon (Eds) Learners and Pedagogy. London: Paul Chapman/Open University

Claxton, G (1997). A 2020 vision of education, in: J Thomas (Ed) Science Today. London: Routledge

Cognition and Technology Group at Vanderbilt (CTGV) (1996). Looking at technology in context: a framework for understanding technology and education research, in: DC Berliner & RC Calfee

(Eds) Handbook of Educational Psychology. New York: Macmillan Library Reference

Cole, G (2002). Make the most of your minibeasts. TES Teacher, 17/05/02, pp20-21

Coles, M (1998). The Nature of Scientific Work: a study of how science is used in work settings and the implications for education and training programmes. London: Institute of Education

Collins, H & Pinch, T (1993). The Golem: What Everyone Should Know About Science. Cambridge: Cambridge University Press

Collins, J, Hammond, M & Wellington, J (1997). Teaching and Learning with Multimedia. London: Routledge

Conran, J (1983). Primary science 1950-82: a personal view, in: D Holford (Ed) The Teaching of Primary Science: Policy and Practice. Lewes: Falmer Press

Cossons, N (1993). Let us take science into our culture. Interdisciplinary Science Reviews, 18(4), pp337-342

Council of Science and Technology Institutes (1993). Occupational Mapping and Initial Functional Analysis of Occupations in Science. London

Cox, MJ (1997). The Effects of Information Technology on Students' Motivation: summary report. London: Kings College London/NCET

Cox, MJ (2000). Information and Communications Technologies: their role and value for science education, in: M Monk & J Osborne (Eds) Good Practice in Science Teaching: What Research has to Say. Buckingham: Open University Press

Cuban, L (2001). Oversold and Underused: Computers in the Classroom. Cambridge: Harvard University Press

Dainton, FS (1968). The Dainton Report: An Inquiry into the Flow of Candidates into Science and Technology. London: HMSO

Dawes, L (2001). What stops teachers using new technology?, in: M Leask (Ed) Issues in Teaching using ICT. London: Routledge

Deaney, R & Ruthven, K (in preparation). Teachers' Developing Practical Theories of Technology-integrated Pedagogy

Deaney, R, Ruthven, K & Hennessy, S (in press). Secondary school students' perspectives on information and commun-ication technology in subject learning and teaching. Research Papers in Education

DES (1987). The National Curriculum 5-16 - a Consultation Document. London: HMSO

DES (1989). Science in the National Curriculum. London: HMSO

DES/Welsh Office (1981). The School Curriculum. London: HMSO

DES/Welsh Office (1982). Science Education in Schools: A Consultative Document. London: DES

DfEE (1998). Teaching: High Status, High Standards. Requirements for Courses of Initial Teaching Training. Circular 4/98, Annex B: Initial Teacher Training Curriculum for the Use of ICT in Subject Teaching. London: Stationery Office

DfEE/QCA (1999). The National Curriculum. London: QCA, HMSO

DfES (2002a). Framework for Teaching Science: Years 7, 8 and 9. London: DfES

DfES (2002b). Statistics of Education: Survey of Information and Commuications Technology in Schools, England 2002

Dillon, J, Osborne, J, Fairbrother, R & Kurina, L (2000). A Study into the Professional Views and Needs of Science

Teachers in Primary and Secondary Schools in England. London: King's College London

Donnelly, J (1999). Interpreting differences: the educational aims of teachers of science and history, and their implications. Journal of Curriculum Studies, 31(1), pp17-41

Driver, R, Guesne, E & Tiberghien, A (Eds) (1985). Children's Ideas in Science. Milton Keynes: Open University Press

Driver, R, Leach, J, Millar, R & Scott, P (1996). Young People's Images of Science. Buckingham: Open University Press

Ellis, V (2001). Analogue clock/digital display: continuity and change in debates about literacy, technology and English, in: A Loveless & V Ellis (Eds) ICT Pedagogy and the Curriculum - Subject to Change. London: Routledge

European Commission (1995). White Paper on Education and Training: Teaching and Learning — Towards the Learning Society. Luxembourg: Office for Official Publications in European Countries

Finlayson, H & Rogers, L (2003). Does ICT in science really work in the classroom? Part 1: The individual teacher experience. School Science Review, in press

Finlayson, H, Wardle, J & Rogers, L (2002). Integration of ICT within science lessons (grades 5-10). National Association for Research in Science Teaching Conference, New Orleans

Frost, R, McFarlane, AE, Helmsely, K, Wardle, J & Wellington, J (1994). Enhancing Science with IT. Coventry: National Council for Educational Technology

Fuller, G (1998). Cultivating science: negotiating discourse in the popular texts of Stephen Jay Gould, in: R Veel (Ed) Reading Science. London: Routledge

Gee, J (1996). Social Linguistics and Literacies. London: Taylor and Francis

Giddens, A (1990). The Consequences of Modernity. Cambridge: Polity Press

Goodson, IF & Mangan, JM (1995). Subject cultures and the introduction of classroom computers. British Educational Research Journal, 21(5), pp613-628

Gott, R & Duggan, S (1995). Investigative Work in the Science Curriculum. Buckingham: Open University Press

Gross, AG (1996). The rhetoric of science Cambridge, MA: Harvard University Press

Gross, P & Levitt, N (1994). Higher Superstition: The Academic Left and its Quarrels with Science. Baltimore: The John Hopkins University Press

Hacker, RJ & Rowe, MJ (1997). The impact of National Curriculum development on teaching and learning behaviours. International Journal of Science Education, 19(9), pp997-1004

Hammond, M (2001). Using the Internet in Secondary Schools: Implications of a Case Study. Coventry: Centre for New Technologies Research in Education Occasional Paper, University of Warwick

Harlen, W (1999). The Assessment of Scientific Literacy in the OECD/PISA Project. Speech given at the European Science Education Research Association Conference, Kiel, Germany

Hennessy, S (1999). The potential of portable technologies for supporting graphing investigations. British Journal of Educational Technology, 30(1), pp57-60. Full article available at http://edu.leeds.ac.uk/research/groups/cssme/graphCalc.html

Hennessy, S, Deaney, R & Ruthven, K (2003). Pedagogic Strategies for Using ICT to Support Subject Teaching and Learning: An Analysis Across 15 Case Studies. Faculty of Education, University of Cambridge, Research Report 03/1

Hennessy, S & Murphy, P (1999). The potential for collaborative problem solving. D&T, International Journal of Technology and Design Education, 9(1), pp1-36

Hennessy, S & O'Shea, T (1993). Learner perceptions of realism and 'magic' in computer simulation. British Journal of Educational Technology, 24(2), pp125-138

Hennessy, S, Ruthven, K & Brindley, S (submitted). Teacher Perspectives on Integrating ICT into Subject Teaching: Commitment, Change and Caution

Hennessy, S, Twigger, D, Driver, R, O'Shea, T, O'Malley, CE, Byard, M, Draper, S, Hartley, R, Mohamed, R & Scanlon, E (1995). A classroom intervention using a computer-augmented curriculum for mechanics. International Journal of Science Education, 17(2), pp189-206

Hitch, M (2000). Another dimension: introducing ICT into science lessons is easy, time-saving and enjoyable. Times Educational Supplement Curriculum Special, Spring 2000, pp18-19

Hodson, D (1996). Laboratory work as scientific method: three decades of confusion and distortion. Journal of Curriculum Studies, 28(2), pp115-135

House of Commons Science & Technology Committee (2002). Science Education from 14 to 19. London: The House of Commons: Stationary Office

Hunt, A & Millar, R (Eds) (2000). Science for Public Understanding. London: Heinemann Educational

Irwin, A (1995). Citizen Science. London: Routledge

Kerr, ST (1991). Lever and fulcrum: educational technology in teachers' thought and practice. Teachers College Record, 93(1), pp114-136

Kuhn, D (1993). Science as argument: implications for teaching and learning scientific thinking. Science Education, 77(3), pp319-337

Latour, B & Woolgar, S (1986). Laboratory Life: The Construction of Scientific Facts Princetown, NJ: Princetown University Press

Layton, D (1973). Science for the People: The Origins of the School Science Curriculum in England. London: Allen and Unwin

Layton, D, Jenkins, EW, McGill, S & Davey, A (1993). Inarticulate Science? Perspectives on the Public Understanding of Science. Driffield, Nafferton: Studies in Education

Lederman, NG (1992). Students' and teachers' conceptions of the nature of science: a review of the research. Journal of Research in Science Teaching, 29, pp331-359

Linn, MC (1999). The impact of technology on science instruction: historical trends and current opportunities, in: Fraser & K Tobin (Eds) International Handbook of Science Education. Kluwer Academic Publishers

Loveless, A, DeVoogd, GL & Bohlin, RM (2001). Something old, something new... is pedagogy affected by ICT?, in: A Loveless & V Ellis (Eds) ICT, Pedagogy and the Curriculum. London and New York: Routledge Falmer

McFarlane, A (2001). Perspectives on the relationships between ICT and assessment. Journal of Computer Assisted Learning, 17(3), pp227-234

McFarlane, A & Friedler, Y (1998). Where you want IT when you want IT - the role of portable computers in science education, in: K Tobin (Ed) International Handbook of Science Education. Amsterdam: Kluwer

McFarlane, A & Sakellariou, S (2002). The role of ICT in science education. Cambridge Journal of Education, 32(2), pp219-232

McKinsey and Company (1997). The Future of Information Technology in UK Schools. London: McKinsey and Company

Mellar, H & Bliss, J (1994). Introduction: modelling and education, in: H Mellar, J Bliss, R Boohan, J Ogborn & C Tompsett (Eds) Learning with Artificial Worlds: Computer-based Modelling in the Curriculum. London: Falmer

Mellar, H, Bliss, J, Boohan, R, Ogborn, J & Tompsett, C (1994). Learning with Artificial Worlds: Computer-based Modelling in the Curriculum. London: Falmer Press

Mercer, N & Wegerif, R (1999). Children's talk in the development of reasoning. British Educational Research Journal, 25(1), pp95-111

Merron, S & Lock, R (1998). Does knowledge about a balanced diet influence eating behaviour? School Science Review, 80(290), pp43-48

Millar, R (1996). Towards a science curriculum for public understanding. School Science Review, 77(280), pp7-18

Millar, R & Driver, R (1987). Beyond processes. Studies in Science Education, 14, pp33-62

Millar, R & Osborne, JF (Eds) (1998). Beyond 2000: Science Education for the Future. London: King's College London

Milner, B (1986). Why teach science and why to all?, in: B Nicholl (Ed) The ASE Science Teacher's Handbook. London: Hutchinson

Moseley, D, Higgins, S, Bramald, R, Hardman, F, Miller, J, Mroz, M, Harrison, T, Newton, D, Thompson, I, Williamson, J, Halligan, J, Bramald, S, Newton, L, Tymms, P, Henderson, B & Stout, J (1999). Ways Forward with ICT: Effective Pedagogy using Information and Communications Technology for Literacy and Numeracy in Primary Schools. Newcastle: Newcastle University, Durham University and CEM Centre, Durham University

Newton, LR (2000). Data logging in practical science: research and reality. International Journal of Science Education, 22(12), pp1247-1259

Newton, LR & Rogers, L (2001). Teaching Science with ICT. London: Continuum

Newton, P, Driver, R & Osborne, J (1999). The place of argumentation in the pedagogy of school science. International Journal of Science Education, 21(5), pp553-576

Niederhauser, D & Stoddart, T (2001). Teachers' instructional perspectives and use of educational software. Teaching and Teacher Education, 17(1), pp15-31

Norris, S (1997). Intellectual independence for nonscientists and other content-transcendent goals of science education. Science Education, 81(2), pp239-258

O'Malley, C (1995). Computer Supported Collaborative Learning. New York: Springer-Verlag

Ofsted (2001). ICT in Schools: The Impact of Government Initiatives, An Interim Report April 2001. London: Office for Standards in Education

Ofsted (2002a). ICT in Schools: Effect of Government Initiatives. London: Office for Standards in Education

Ofsted (2002b). ICT in Schools: Effect of Government Initiatives - Secondary Science. London: Office for Standards in Education

Osborne, JF & Collins, S (2000). Pupils' and Parents' Views of the School Science Curriculum. London: King's College London

Osborne, JF, Duschl, R & Fairbrother, R (2002). Breaking the Mould: Teaching Science for Public Understanding. London: Nuffield Foundation

Osborne, JF, Ratcliffe, M, Collins, S, Millar, R & Duschl, R (2001). What Should we Teach about Science? A Delphi Study. London: King's College

Osborne, RJ (1985). Building on children's intuitive ideas, in: RJ Osborne & P Freyberg (Eds) Learning in Science: The Implications of Children's Science. Auckland: Heinemann

Pellechia, M (1997). Trends in science coverage: a content analysis of three US newspapers. Public Understanding of Science, 6, pp49-68

Pickering, A (1984). Constructing Quarks Edinburgh: Edinburgh University Press

Popper, K (1959). The Logic of Scientific Discovery. London: Hutchinson

QCA/DfEE (2000). Science: a Scheme of Work for Key Stage 3. London: Qualifications and Curriculum Authority

Rogers, L (2002a). Learning science with ICT: how do teachers make a difference?, The CeNTRE Seminar Series on the Relationship between ICT and Specific Subject Disciplines, Coventry

Rogers, L (2002b). Physics in new fields and modern applications. Groupe International de Recherch sur l'Enseignment de la Physique (GIREP), Lund

Rogers, L (in press-a). The future of ICT in science education (ch10), in: R Barton (Ed) Teaching Science with ICT. Cambridge: Hill McGraw

Rogers, L (in press-b). Integrating ICT into the curriculum (ch9), in: R Barton (Ed) Teaching Secondary Science with ICT. Cambridge: Hill McGraw

Rogers, LT & Wild, P (1996). Datalogging: effects on practical science. Journal of Computer Assisted Learning, 12, pp130-145

Rudolph, JL (2000). Reconsidering the 'nature of science' as a curriculum component. Journal of Curriculum Studies, 32(3), pp403-419

Ruthven, K & Hennessy, S (2002). A practitioner model of the use of computer-based tools and resources to support mathematics teaching and learning. Educational Studies in Mathematics, 49(1), pp47-88

Ruthven, K, Hennessy, S & Brindley, S (submitted). Teacher Representations of the Successful Use of Computer-based Tools and Resources in Teaching and Learning Secondary English, Mathematics and Science

Schofield, JW (1995). Computers and Classroom Culture. Cambridge: Cambridge University Press

BIBLIOGRAPHY

Scrimshaw, P (1993). Cooperative writing with computers, in: P Scrimshaw (Ed) Language, Classrooms and Computers. London: Routledge

Scrimshaw, P (1997). Computers and the teacher's role, in: B Somekh & N Davis (Eds) Using Information Technology Effectively in Teaching and Learning. London: Routledge

Selinger, M (2001). Information and communications technologies in representations of mathematics, in: A Loveless & V Ellis (Eds) ICT, Pedagogy and the Curriculum. London: Routledge

Selwyn, N (1999). Why the computer is not dominating schools: a failure of policy or a failure of practice? Cambridge Journal of Education, 29(1), pp77-91

Stodolsky, SS & Grossman, PL (1995). The impact of subject matter on curricular activity: an analysis of five academic subjects. American Educational Research Journal, 32(2), pp227-249

Taylor, C (1996). Defining Science: A Rhetoric of Demarcation. Madison, WI: University of Wisconsin Press

Thomas, G & Durant, J (1987). Why should we promote the public understanding of science?, in: M Shortland (Ed) Scientific Literacy Papers. Oxford: Oxford Department of External Studies

Traweek, S (1988). Beamtimes and Lifetimes: The World of High Energy Physicists. Cambridge, MA: Harvard University Press

TTA (1999). The Use of Information and Communications Technology in Subject Teaching: Identification of Training Needs. London: Teacher Training Agency

Wadsworth, P (2000). What's happening to science?, Primary Science Review, 61, pp31-32

Walker, D (2002). No crossed wires. TES Teacher, 22 November 2002, pp30-31

Wardle, J (in press). Handling and interpreting data in school science (ch7), in: R Barton (Ed) Teaching Science with ICT. Cambridge: Hill McGraw

Watkins, C & Mortimore, P (1999). Pedagogy: What do we know?, in: P Mortimore (Ed) Understanding Pedagogy and its Impact on Learning. London: Paul Chapman

Watson, DM, Cox, M & Johnson, D (Eds) (1993). The ImpacT Report: An Evaluation of the Impact of Information Technology on Children's Achievements in Primary and Secondary Schools. London: Department for Education and Kings College London

Wellington, J (in press). Multimedia in science teaching (ch6), in: R Barton (Ed) Teaching Science with ICT. Cambridge: Hill McGraw

Wiliam, D (1999). Inaugural Lecture: The Meanings and Consequences of Educational Assessments. London: King's College, London

Williams, D, Coles, L, Wilson, K, Richardson, A & Tuson, J (2000). Teachers and ICT: current use and future needs. British Journal of Educational Technology, 31(4), pp307-320

Wynne, B (1996). May the sheep safely graze?, in: B Wynne (Ed) Risk, Environment & Modernity. London: SAGE Publications

About Futurelab

Futurelab is passionate about transforming the way people learn. Tapping into the huge potential offered by digital and other technologies, we are developing innovative learning resources and practices that support new approaches to education for the 21st century.

Working in partnership with industry, policy and practice, Futurelab:

- incubates new ideas, taking them from the lab to the classroom
- offers hard evidence and practical advice to support the design and use of innovative learning tools
- communicates the latest thinking and practice in educational ICT
- provides the space for experimentation and the exchange of ideas between the creative, technology and education sectors.

A not-for-profit organisation, Futurelab is committed to sharing the lessons learnt from our research and development in order to inform positive change to educational policy and practice.

Futurelab
1 Canons Road
Harbourside
Bristol BS1 5UH
United Kingdom

tel +44 (0)117 915 8200
fax +44 (0)117 915 8201
info@futurelab.org.uk

www.futurelab.org.uk

Registered charity 1113051

This publication is available to download from the Futurelab website – www.futurelab.org.uk/research/lit_reviews.htm

Also from Futurelab:

Literature Reviews and Research Reports

Written by leading academics, these publications provide comprehensive surveys of research and practice in a range of different fields.

Handbooks

Drawing on Futurelab's in-house R&D programme as well as projects from around the world, these handbooks offer practical advice and guidance to support the design and development of new approaches to education.

Opening Education Series

Focusing on emergent ideas in education and technology, this series of publications opens up new areas for debate and discussion.

We encourage the use and circulation of the text content of these publications, which are available to download from the Futurelab website – www.futurelab.org.uk/research. For full details of our open access policy, go to www.futurelab.org.uk/open_access.htm.

FUTURELAB SERIES

REPORT 6

ISBN: 0-9544695-5-0